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Nuclear retinoic acid receptor alpha (RAR α): novel unconventional non-genomic effects and novel partners

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Le Récepteur Nucléaire de l'acide rétinoïque alpha (RAR α): nouveaux effets non-génomiques et nouveaux partenaires

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Nuclear Retinoic Acid Receptor alpha (RAR α): novel unconventional non-genomic effects and novel partners

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Nuclear Retinoic Acid Receptor alpha (RAR α): novel unconventional non-genomic effects and novel partners

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RESUME

L'acide rétinoïque (AR), dérivé actif de la vitamine A, régule de nombreux processus biologiques comme la prolifération et la différenciation des cellules, l'embryogénèse et l'homéostasie des tissus. L'AR agit en se fixant à des récepteurs nucléaires appelés RAR pour lesquels 3 sous-types α , β et γ ont été caractérisés et qui se comportent comme des facteurs de transcription inductibles par le ligand. Selon le modèle classique, la transcription des gènes cibles induite par l'AR, nécessite la fixation des RAR au niveau de séquences spécifiques des promoteurs et met en jeu des changements conformationnels des récepteurs qui, en initiant l'association/dissociation de toute une panoplie de corégulateurs, vont permettre le recrutement de la machinerie transcriptionnelle. Cependant, en plus de ce modèle génomique et nucléaire bien établi, l'équipe du Dr Cécile Rochette-Egly a montré récemment que l'AR a aussi des effets non-génomiques et induit rapidement la voie de signalisation p38MAPK/MSK1 qui ensuite cible les RAR pour des cascades de phosphorylations.

Mon travail de thèse porte sur deux nouveaux aspects de la voie de signalisation de l'AR: (i) la mise en évidence d'une sous-population de RAR α dans les membranes et impliquée dans les effets non-génomiques de l'AR (Piskunov and Rochette-Egly, 2011a), (ii) l'interaction de RAR α dans le noyau avec un nouveau partenaire, la profiline IIA, (Piskunov et al. manuscrit en preparation) et (iii) la mise en évidence d'un nouveau rôle de RAR α dans l'adhésion cellulaire.

- J'ai mis en exergue un nouveau concept, la présence de RAR α dans des microdomaines membranaires, les radeaux lipidiques ou "lipid rafts". J'ai montré que l'activation de la voie de la p38MAPK par l'AR résulte de l'interaction de RAR α présent dans ces microdomaines avec les protéines G α q. Pour mettre en évidence cette interaction *in vivo* des protéines endogènes j'ai mis au point une technique nouvelle et sensible, appelée « Proximity Ligation Assay » (PLA). Le principe de cette technique est très semblable à celui du FRET, mais exploite la capacité de dimérisation d'oligonucléotides couplés à des anticorps lorsque ceux-ci sont assez proches, comme dans le cas de deux anticorps dirigés contre deux protéines d'un même complexe. Cette technique est très spécifique et permet une amplification importante du signal avec une meilleure sensibilité.

L'interaction RAR α /G α q, comme l'activation de la p38MAPK, ont été corrélés à l'activation des gènes cibles des RAR. De tels résultats confirment l'hypothèse du laboratoire selon laquelle les effets non-génomiques interfèrent avec les effets génomiques et sont de ce fait indispensables. De manière intéressante, j'ai aussi montré que dans des cellules de cancer mammaires surexprimant le récepteur à activité tyrosine kinase erbB-2, RAR α n'interagit pas avec G α q dans les radeaux lipidiques et, par conséquent, la voie de la p38MAPK n'est pas activée. Ces résultats mettent encore en exergue l'importance des effets non-génomiques dans le mécanisme d'action des RAR. Finalement ce travail allonge encore la liste des récepteurs nucléaires présents dans les membranes.

- J'ai aussi identifié un nouveau partenaire de RAR α , la profiline IIA, en utilisant la technique du double hybride dans la levure. La profiline IIA, comme toutes les profilines, est une protéine de petite taille (14-17 kDa) aux fonctions multiples et exprimée essentiellement dans les cellules nerveuses. J'ai montré que la profiline IIA interagit spécifiquement avec RAR α (et non avec les autres RAR), et que l'interaction met en jeu le motif N-terminal riche en prolines de RAR α et le domaine SH3-like de la profiline IIA. J'ai aussi déterminé l'affinité de l'interaction en utilisant la technique Biacore. *In vivo*, cette interaction a été analysée en utilisant la technique PLA et les complexes RAR α /profiline IIA ont été détectés dans les noyaux. Finalement la profiline IIA s'est révélée être un régulateur transcriptionnel de RAR α et est recrutée avec RAR α au niveau des promoteurs des gènes cibles.

- Finalement, étant donné que RAR α n'est pas impliqué dans la différenciation neuronale des cellules souches embryonnaires de souris induite par l'AR (Al Tanoury *et al*, manuscript in preparation), j'ai mis en évidence une nouvelle fonction de RAR α dans le contrôle de l'adhésion et de l'étalement des cellules. Des expériences sont en cours pour déterminer si RAR α contrôle avec la profiline IIA l'expression des protéines d'adhésion via des effets génomiques. Cependant, de manière inattendue, j'ai identifié une nouvelle population de RAR α dans le cytoplasme de ces cellules. D'où l'hypothèse de nouveaux effets non-génomiques via l'interaction de RAR α avec des protéines d'adhésion.

En conclusion, j'ai montré que RAR α peut être exprimé dans trois compartiments subcellulaires différents, avec trois fonctions différentes.

- une population membranaire avec des effets non-génomiques (activation de kinases)
- une population nucléaire majoritaire impliquée dans des effets génomiques. Dans ce contexte j'ai identifié un nouveau partenaire transcriptionnel de RAR α , la profiline IIA
- une population cytosolique qui serait impliquée dans l'adhésion des cellules

SUMMARY

Retinoic Acid (RA) is the active metabolite of Vitamin A, which modulates a wide variety of biological processes such as cell proliferation and differentiation, embryogenesis and homeostasis. These effects are mediated by nuclear receptors (RAR α , β and γ), which act as ligand-dependent regulators of transcription. According to the classical model, RAR-mediated transcription of cognate target genes involves the binding of the receptors to specific DNA sequences located in promoters and RA-induced conformational changes that initiate cascades of protein-protein associations/dissociations leading to communication with the transcriptional machinery. However, in addition to this well-established nuclear genomic function, recent studies from the laboratory of Dr. Cécile Rochette-Egly demonstrated that RA also has non-genomic effects and rapidly induces the p38MAPK/MSK1 pathway, which then targets RARs for phosphorylation cascades.

The work of my thesis focused on three novel and original aspects of RA and RAR α signaling: (i) the characterization of a RAR α pool located in membrane lipid rafts and involved in non-genomic effects (Piskunov and Rochette-Egly, 2011a), (ii) the interaction of nuclear RAR α with a new partner profilin IIA (Piskunov *et al*, manuscript in preparation), and finally (iii) a novel role of RAR α in cell adhesion.

- I highlighted a novel paradigm, in which a fraction of the cellular RAR α pool is present in membrane lipid rafts, where it interacts with G protein alpha Q in response to RA. To explore the endogenous RAR α /G α q complexes *in vivo* and *in situ*, I set up a new technique called proximity ligation assay (PLA). The assay is similar to Fluorescence Resonance Energy Transfer (FRET), but is based on the use of two primary antibodies raised in different species that recognize the antigens of interest and on species-specific secondary antibodies attached to unique DNA strand that can hybridize when in close proximity and then be amplified. The technique is very sensitive and specific.

This interaction is the signal for the activation of p38MAPK and of the downstream kinase MSK1. Both the RAR α -G α q interaction and the p38MAPK pathway have been correlated to the activation of RA-target genes, highlighting its physiological relevance. It also corroborates the hypothesis raised by the team according to which the non-genomic effects crosstalk with the genomic ones. Remarkably, in RA-resistant breast cancer cells characterized by the overexpression of the receptor tyrosine kinase erbB-2, RAR α associated to the membrane lipid rafts does not interact with G α q and p38MAPK is not activated, outlining again the essential contribution of this non-genomic mechanism in RA signaling. Finally this work extends the long list of nuclear receptors already shown to be present in diverse membrane structures.

- I also identified a new binding partner of RAR α , profilin IIA. Profilin IIA, a small (14-17 kDa) protein with multiple functions essentially in neuronal cells. However, I found that profilin IIA is also present in mouse embryonic fibroblasts (MEF cell line) and in human breast cancer cells (MCF7 cell

line). I demonstrated that profilin IIA interacts specifically with the RAR α subtype (and not with the other RARs) and that the interaction involves the N-terminal proline-rich motif of RAR α and the SH3-like domain of profilin IIA. I also analyzed the affinity of the interaction by using the Biacore technology. The interaction of the endogenous proteins has been analyzed by using the PLA technique and found to occur in nuclei. Remarkably, I found that profilin IIA modulates positively the expression of RA-target genes and is recruited with RAR α to target genes promoters.

- Finally, in an attempt to decipher the relevance of the RAR α interaction with profilin IIA, the laboratory found that RAR α is not involved in RA-induced differentiation of ES cells into neurons (Al Tanoury *et al.*, manuscript in preparation). However, I found that RAR α controls adhesion and spreading of these cells. This might suggest a novel genomic effect of RAR α , i.e the control of the expression of genes involved in adhesion. However, preliminary experiments indicate that, in these cells, as well as in fibroblasts that are well adherent cells, a pool of RAR α is present in the cytosol, suggesting non-genomic effects. Whether RAR α controls adhesion via its interaction with profilin IIA or other proteins will require further investigations.

In conclusion, I have highlighted that RAR α can depict three different subcellular localizations with three different functions:

- A membrane pool for non-genomic effects (activation of kinase cascades)
- A nuclear pool for genomic effects. In this context I identified a new partner, profilin IIA, which acts as coregulator of RAR α -mediated transcription
- A cytosolic pool which might play a role in cell adhesion

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LIST OF ABBREVIATIONS

ABP actin-binding proteins	DGAT diacylglycerol O-acyltransferase
ACTR acetyltransferase	DHRS dehydrogenase/reductase SDR family member
AD activation domains	DR direct repeats
ADA2 adaptor protein 2	DRIP205 vitamin D-interacting protein 205
ADF actin depolymerizing factor	EB embryoid body
ADH alcohol dehydrogenase	EGF epidermal growth factor
AF activation function	Ena/VASP vasodilator-stimulated phosphoprotein
Akt serine/threonine protein kinase	ER estrogen receptor
AIB1 amplified in breast cancer I	ERK extracellular signal-regulated kinase
ANCO1 ankyrin repeats cofactor-1	ES embryonic stem
AP-1 activator protein-1	Flii flightless-1 homolog
AR Androgen receptor	FXR farnesoid x receptor
ARAT acyl-CoA retinol acyltransferase	GAC63 GRIP1-associated coactivator 63
ARNT aryl hydrocarbon receptor nuclear translocator	GPS2 G-protein pathway suppressor 2
ArpM1 actin-related protein M1	GR glucocorticoid receptor
BAF57 barrier-to-autointegration factor 57	GRIP-1 glucocorticoid receptor interacting protein
BCMO β -carotene-monoxygenase	GST glutathione S transferase
bHLH/PAS helix-loop-helix/Per/ARNT/Sim	GTFs general transcription factors
CAFs carcinoma-associated fibroblasts	HDAC3 histone deacetylase 3
CAK CDK-activating kinase	HID histone interaction domain
CAMKII calmodulin-dependent protein kinase II	HNF hepatocyte nuclear factor
CAR constitutive androstane receptor	Hox homeobox
CARM1 coactivator-associated arginine methyltransferase 1	IDs interactions domains
Cdk cyclin-dependent kinase	IUPAC-IUB international union of pure and applied chemistry – international union of biochemistry
ChIP chromatin immunoprecipitation	JNKs c-Jun N-terminal kinases
CoCoA coiled-coil coactivator	LBD ligand binding domain
CoRNR corepressor nuclear receptor	LBP ligand binding pocket
CRABP II cellular retinoic acid binding protein II	LCoR ligand-dependent corepressor
CRBP cellular retinol binding protein	LRAT lecithin retinol acyl transferase
CREB cAMP response element-binding	LXR oxysterols liver X receptor
c-Src a tyrosine kinase	MAPK mitogen-activated protein kinase
CTE COOH-terminal extension	MAT1 cyclin-dependent kinase-activating kinase (ménage à trois 1)
cycH cyclin H	MEF-2C myocyte-specific enhancer factor 2C
CYP26 cytochrome P450	MSK1 mitogen- and stress-activated protein kinase
DAD deacetylase activation domain	
DBD DNA binding domain	

NCoA nuclear receptor coactivator complex	sim single-minded protein
N-CoR nuclear receptor corepressor complex	SMN survival of motor neuron
NFmB nuclear factor-mB	SMRT silencing mediator for retinoic acid and thyroid hormone receptors
NMDA N-methyl-D-aspartate	snRNP small nuclear ribonucleoprotein
NTD N-terminal domain	SPR surface plasmon resonance
p300/CBP CREB-binding protein	SRC steroid receptor coactivators
PCAF P300/CBP-associated factor	SRF serum response factor
pCIP p300/CBP-interacting protein	SUG-1 suppressor of Gal 1
Per period	SWI/SNF SWItch/Sucrose NonFermentable
PI3K phosphoinositide-3-kinase	TACC1 transforming acidic coiled coil
PIP2 phosphatidylinositol (4,5)-bisphosphate	TBL1 transducin β -like 1
PKA protein kinase A	TBLR1 TBL1-related protein 1
PKC protein kinase C	TEF-4 transcriptional enhancer factor 4
PLA proximity ligation assay	TFIIB transcription factor IIB
PNPLA4 patatin-like phospholipase domain-containing protein 4	THIH transcription factor IIH
PPAR peroxisomal proliferator activated receptor	TIF1α/Trim24 transcription intermediary factor-1 α
PR progesterone receptor	TIF-2 transcriptional intermediary factor 2
PRAME preferentially expressed antigen in melanoma	TRAM1 thyroid hormone receptor-activator molecule I
PRM proline-rich motif	TRAP220 thyroid hormone receptor-associated protein 220
PRMT1 protein arginine N-methyltransferase 1	TTR transthyretin
PXR xenobiotics pregnane X receptor	UGT glucuronosyltransferase
RA retinoic acid	VAD vitamin A deficiency
RAC3 receptor-associated coactivator	VDR vitamin D receptor
RALDH retinaldehyde dehydrogenase	WASP/WAVE Wiskott-Aldrich syndrome family protein/WASP family Verprolin-homologous protein
RAR retinoic acid receptor	WD40 protein containing WD40 (tryptophan-aspartic acid) repeat
RAREs retinoic acid response elements	WW (tryptophan-tryptophan)
RBP retinol binding protein	XPB (Xeroderma Pigmentosum B) ATP dependent DNA helicase
RDH retinol dehydrogenase	
RETSAT all-trans-retinol 13,14-reductase	
RPE65 retinal pigment epithelium-specific 65 kDa protein	
RXR retinoid x receptor	
SDR short-chain dehydrogenase/reductase	
SH3 Src-homology-3	

THIS THESIS IS BUILT ON THE FOLLOWING PUBLICATIONS:

1. **Piskunov, A.** and C. Rochette-Egly. 2011. A retinoic acid receptor RAR α pool present in membrane lipid rafts forms complexes with G protein α_Q to activate p38MAPK. *Oncogene*. In press.
2. **Piskunov A,** Andrimoratsiresy D, Al Tanoury Z, Rochette-Egly C. Profilin IIA: a novel coregulator of the N-terminal domain of the Retinoic acid receptor alpha (RAR α). Manuscript in preparation.
3. **Piskunov, A.,** and C. Rochette-Egly. 2011b. MSK1 and Nuclear Receptors Signaling. Landes Bioscience Books, Austin, TX, USA. 2012.

OTHER PUBLICATIONS:

Ferry, C., S. Gaouar, B. Fischer, M. Boeglin, N. Paul, E. Samarut, **A. Piskunov**, G. Pankotai-Bodo, L. Brino, and C. Rochette-Egly. 2011. Cullin 3 mediates SRC-3 ubiquitination and degradation to control the retinoic acid response. *Proc Natl Acad Sci U S A*. 108:20603-8.

ORAL COMMUNICATIONS:

- Première journée des Récepteurs Nucléaires, Muséum National d'Histoire Naturelle Amphithéâtre Rouelle, 47 Rue Cuvier 75005, Paris, France, 22 April 2011. "Novel concepts of nuclear retinoic acid receptors regulation through phosphorylation".
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- The 12th Hunter Meeting Australia's Premier Cellular Biology Meeting, the Sebel-Kirkton Park, Pokolbin, Hunter Valley, NSW Australia March 2012. "The Retinoic acid receptor RAR α is present in membrane lipid rafts and activates p38MAPK through interaction with G α_q proteins".

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INTRODUCTION

CHAPTER 1: VITAMIN A AND RETINOIDS

- HEALTH BENEFITS OF VITAMIN A

Vitamin A is very important for the life of all chordates. This vitamin has a large number of functions in vision, maintenance of epithelial surfaces, immune competence, reproduction, embryonic growth and development. Therefore, in humans, insufficient consumption of vitamin A, called Vitamin A Deficiency (VAD) is characterized by ocular features (xerophthalmia) and a generalized impaired resistance to infection (Blomhoff and Blomhoff, 2006).

For children, VAD is one of the major causes of preventable blindness and increases the risk of illness and even death from serious childhood infections such as diarrheal disease and measles.

For pregnant women, VAD causes night time blindness and builds up the risk of maternal mortality. In high-risk areas, VAD occurs particularly during the last trimester of pregnancy, when demand by both the unborn child and the mother is highest. The impact of VAD on mother-to-child HIV transmission needs additional investigation.

Thus VAD is a public health problem in more than half of all countries, especially in low-income countries (Africa and South-East Asia) (Figure 1), hard-hitting small children and pregnant women.

- An estimated 250 million preschool children are vitamin A deficient and in vitamin A deficient areas a considerable percentage of pregnant women are vitamin A deficient.
- An estimated 250 000 to 500 000 vitamin A-deficient children lose their sight every year, half of them dying within one year (<http://www.who.int/en/>).

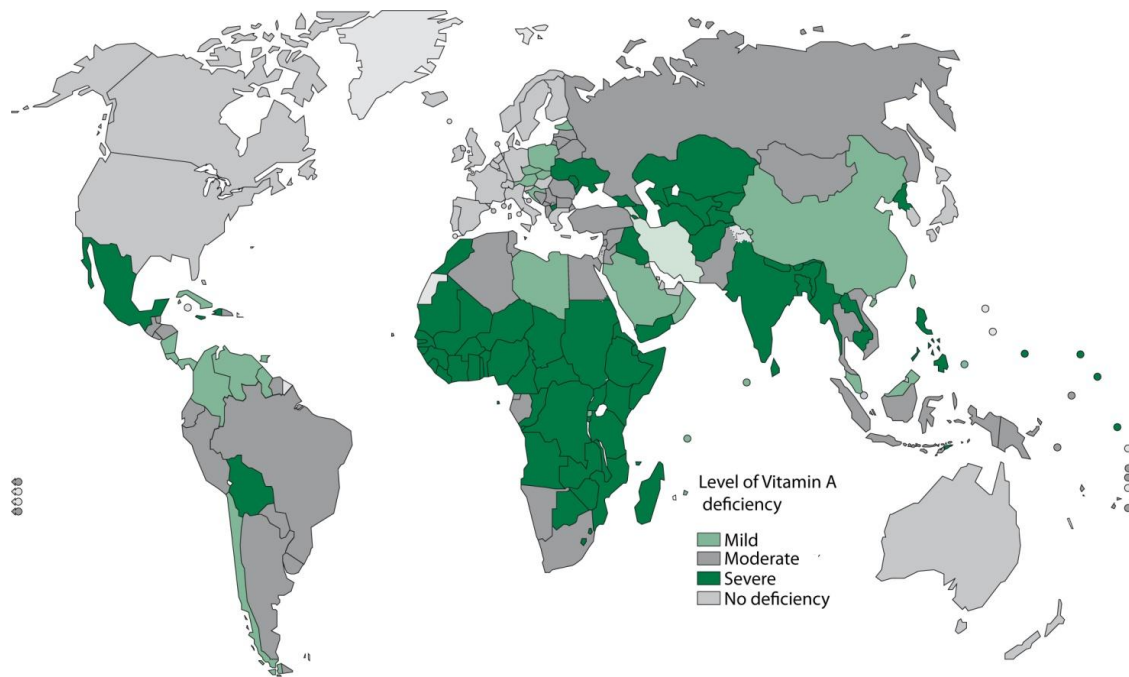


Figure 1. Map of the global prevalence of vitamin A deficiency (World Health Organization, 2009).

- ORIGIN OF VITAMIN A

No animal species have the potential for *de novo* synthesis of vitamin A (Retinol). Thus in most animals the only source is diet-derived.

Retinol is derived from carotenoids, which are present in plants and some microorganisms (bacteria and fungi) and are responsible for the yellow, orange and red colors of many vegetables, fruits, and plants (Fraser and Bramley, 2004). About 600 carotenoids are known in nature, but only 10% can be metabolized to vitamin A. Among carotenoids, β -carotene has the best biological activity (Yeum and Russell 2002).

Animals obtain vitamin A by consuming plants containing carotenoids or animal tissues that store carotenoids such as eggs, poultry and fish (Fraser and Bramley, 2004). Then they convert carotenoids to vitamin A. Alternatively, animals can also obtain vitamin A by ingesting animal tissues that have already transformed carotenoids into retinol. In general, retinol is stored as retinyl esters in fish, avian, and mammalian livers.

- NOMENCLATURE, STRUCTURE, AND CHEMICAL PROPERTIES OF RETINOIDS

The term “retinoids” was introduced by Sporn et al. in 1976 and later was designated by the International Union of Pure and Applied Chemistry – International Union of Biochemistry (IUPAC-IUB) as a class of compounds consisting of four isoprenoid units joined in a head-to-tail manner. All retinoids may be formally derived from a monocyclic parent compound containing five carbon-carbon double bonds and a functional terminal group at the terminus of the acyclic portion.

Retinoids include retinol as well as its analogs and derivatives (Figure 2A). There are six biologically active isoforms of vitamin A that include all-trans, 11-cis, 13-cis, 9, 13-di-cis, 9-cis, and 11, 13-di-cis retinol, all-trans being the main physiological form. The active metabolites of retinol include all-trans Retinoic Acid (RA), 9-cis RA, 11-cis retinaldehyde, 3,4-didehydro RA, and perhaps 14-hydroxy-4, 14-retro retinol, 4-oxo RA, and 4-oxo retinol (Achkar et al., 1996; Buck et al., 1991; Napoli, 1996).

However, some synthetic compounds (Figure 2B) that do not fit with this chemical definition are much more active than retinol or retinoic acid in several assays for vitamin A or retinoid activity. Therefore it has been proposed that retinoids should be outlined as substances eliciting a particular biologic response via binding to and activating a specific receptor or set of receptors (Sporn and Roberts 1985). Today the definition of the retinoid term includes not only retinol analogues and derivatives (with or without biologic activity), but also a number of compounds that are not structurally related to retinol but elicit biological vitamin A or retinoid activity (Blomhoff and Blomhoff 2006).

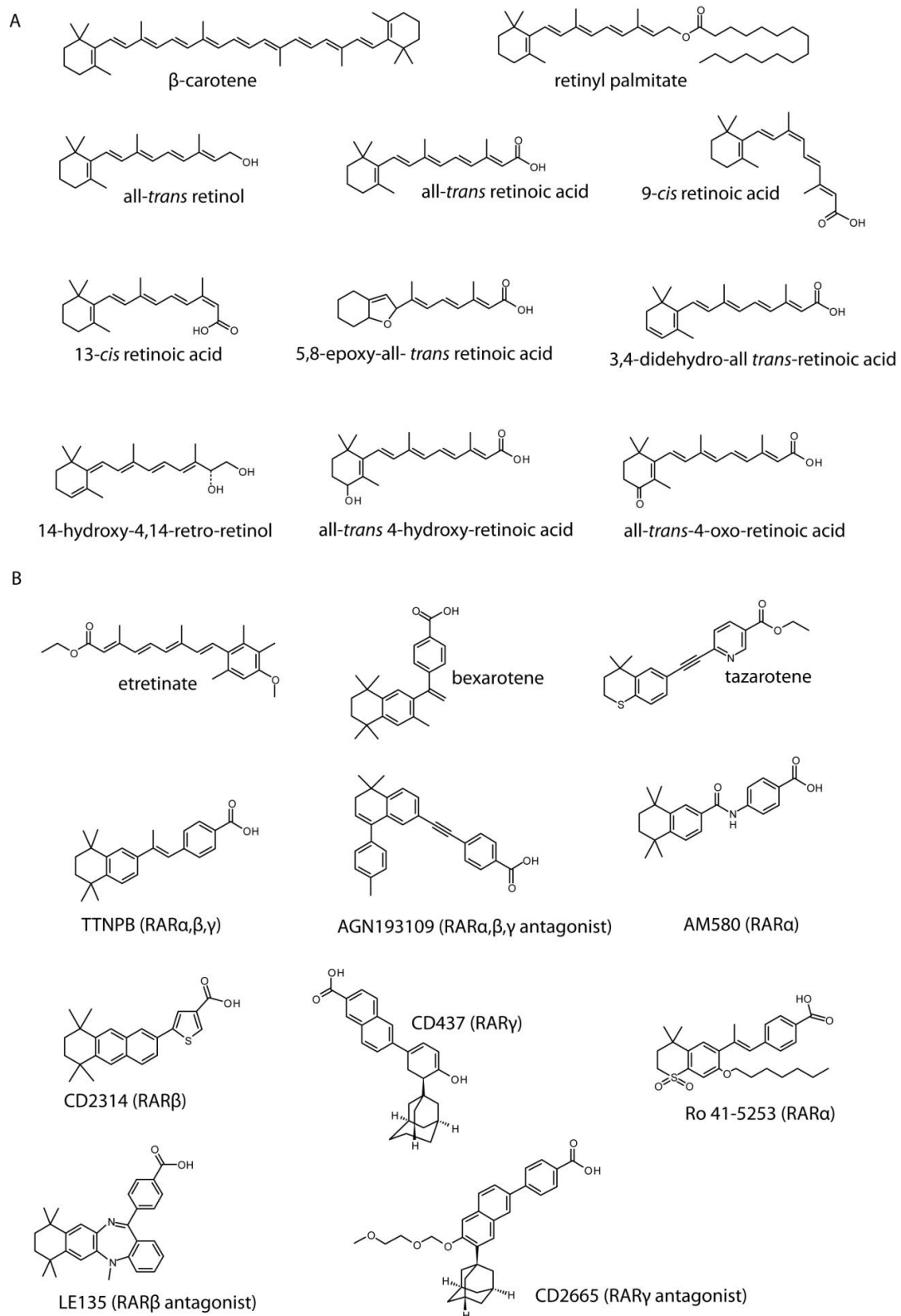


Figure 2: Chemical structure of natural (A) and synthetic (B) retinoids.

Chemically, retinoids are composed of a β -ionone ring, a polyunsaturated side chain and a polar end group (Figure 3). Such an amphipathic chemical structure makes them poorly soluble in water and provides easy transfer through membrane lipid bilayers. The polar end group can exist at several oxidation states, varying from the low oxidation state of retinol to a higher oxidation state in RA (Figure 2A).

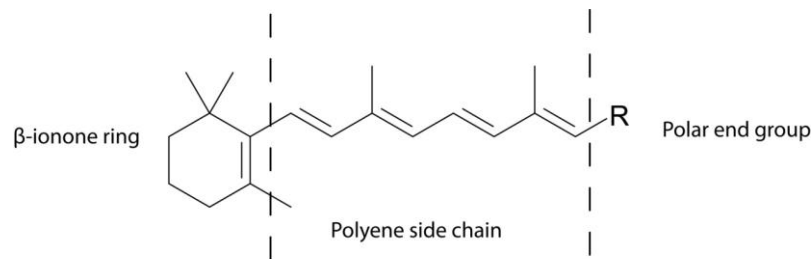


Figure 3: Structure of retinoids. Adapted from (Hong and Lotan, 1993).

- RETINOID METABOLISM

1. Enzymatic Conversion of Proretinoids (Carotenoids) to Retinoids

As early as 1930, it has been reported that β -carotene can be transformed to retinoids within the small intestine (Moore, 1930). Later on, two independent groups (Goodman and Huang, 1965; Olson and Hayaishi, 1965) showed that one molecule of β -carotene yields two molecules of retinal via a central cleavage catalyzed by an enzyme termed $\beta\beta$ -carotene-15, 15'-monooxygenase (BCMO-I) (Figure 4).

Another enzyme, β,β -carotene-9'10'-dioxygenase (BCMO-II) is also able to cleave β -carotene (Kiefer et al., 2001). However, BCMO-II catalyzes an asymmetrical cleavage of β -carotene at non-central double bonds of the polyene chain, yielding apocarotenals like β -apo-8'-, β -apo-10'- and β -apo-12'-carotenals (Figure 4). This alternative pathway is very important as it implies that, in tissues expressing BCMO-II, retinoic acid can be produced in the absence of "classical RA synthesis pathway" enzymes, such as alcohol dehydrogenase (ADH), short-chain dehydrogenase/reductase (SDR), retinaldehyde dehydrogenase (RALDH) (Simoes-Costa et al., 2008) or certain cytochrome P450s (Chen et al., 2000) (see below).

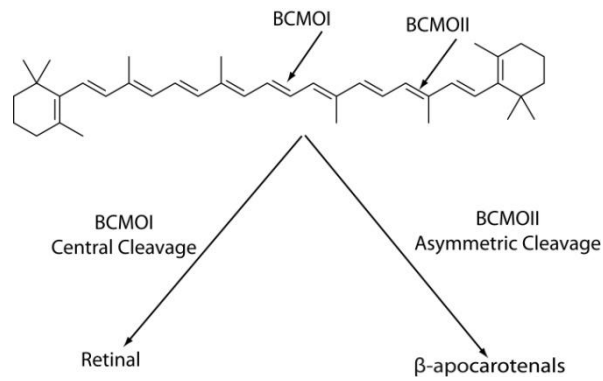


Figure 4: Carotenoids undergo cleavage either symmetrically by BCMOI or asymmetrically by BCMOII. Adapted from (D'Ambrosio et al., 2011).

2. Enterocyte Esterification of Retinol

Retinal obtained by carotenoid cleavage is then reduced to retinol and taken up by enterocytes. Enterocytes also take dietary consumed retinyl esters after hydrolysis into retinol within the intestinal lumen (Blomhoff and Blomhoff, 2006).

In enterocytes, retinol binds to the cellular retinol binding protein II (CRBP_{II}), which is specifically highly expressed in the intestinal mucosa. CRBP_{II} belongs to the greater family of fatty acid binding proteins and its role is to solubilize fat-soluble retinol (Sporn et al., 1994) (Figure 5).

Then, the majority of CRBP_{II}-bound retinol is re-esterified via the enzyme lecithin retinol acyl transferase (LRAT). The remaining esterification activity would be assumed by two other enzymes diacylglycerol acyltransferase 1 (DGAT1) and acyl-CoA:retinol acyltransferase ARAT (D'Ambrosio et al., 2011) (Figure 5).

Afterwards retinyl esters are included into chylomicrons and secreted into general circulation (Blomhoff et al., 1982), where they are taken up by hepatocytes (Blomhoff et al., 1982), bone marrow, peripheral blood cells, spleen, adipose tissue, skeletal muscle and kidney (Paik et al., 2004). In mammals, 50-80% of the body's overall retinoids are collected in hepatic stellate cells as retinyl esters (Blomhoff and Blomhoff, 2006; Fontana and Rishi, 2002) (Figure 5).

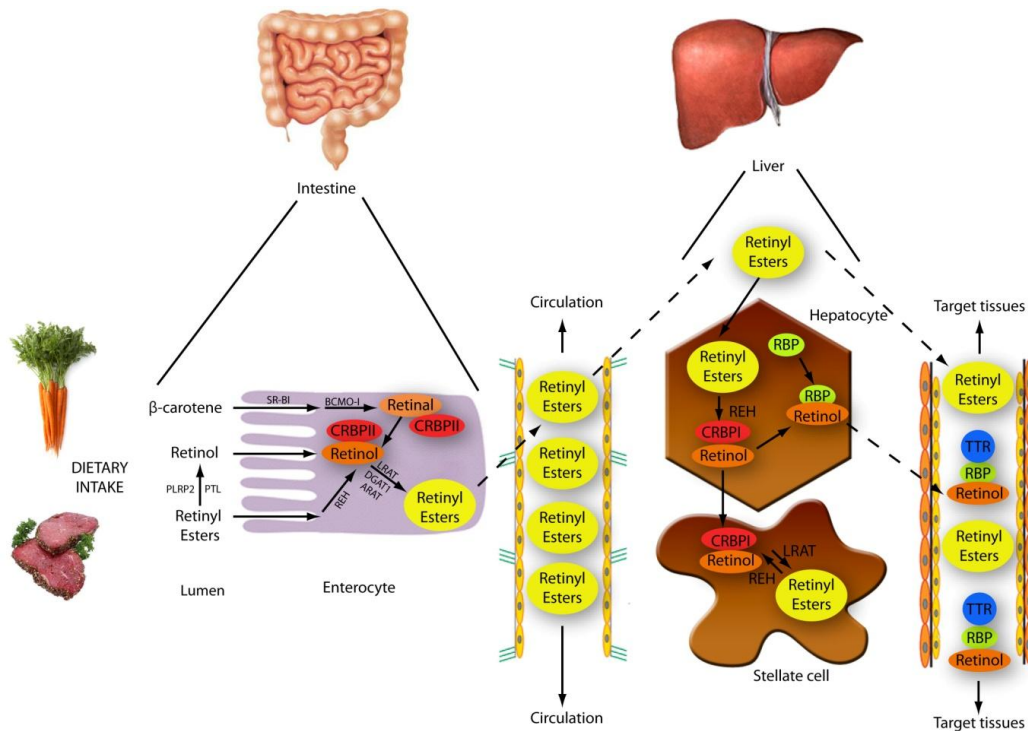


Figure 5: Metabolism of vitamin A. In the intestine, carotenoids are converted to retinol, which binds CRBP. Then retinol is transformed into retinyl esters, exported into the circulation and taken up by the liver. In hepatocytes, retinyl esters are reconverted to retinol and bind RBP for transport to target cells. In stellate cells of the liver, retinol is retransformed to retinyl esters for storage. In the bloodstream, the retinol:RBP complex is bound to TTR to avoid removing by the kidney and for guaranteed delivery to target tissues. Figure adapted from (Theodosiou et al., 2010).

3. Hepatic retinoid metabolism

In hepatocytes, retinyl esters are re-converted to retinol, which then binds retinol binding-protein (RBP) and is secreted into circulation. The majority of the retinol:RBP complexes are associated with transthyretin (TTR), which prevents elimination by the kidney and ensures delivery to target tissues. However, a big part of hepatic retinol is reesterified into retinyl esters and packed within cytoplasmic lipid droplets in stellate cells (Blomhoff and Blomhoff, 2006) (Figure 5).

4. *Retinol processing*

In target tissues, retinol either associates with CRBP or is transformed into active metabolites. Indeed retinol undergoes oxidation to retinaldehyde by enzymes termed retinol dehydrogenases (Figure 6) (Gottesman et al., 2001; Pares et al., 2008). These enzymes are members of the ADH (alcohol dehydrogenase) or SDR (short-chain dehydrogenase/reductase) families, which depict cytosolic and microsomal localizations respectively. Given that the next step, the irreversible oxidation of retinaldehyde to retinoic acid, takes place in cytosol, it has been suggested that ADHs would be more important than microsomal SDRs for RA synthesis (Duester et al., 2003).

Then the oxidation of retinaldehyde to RA is carried out by retinaldehyde dehydrogenases (RALDHs), such as RALDH 1, 2, 3, and 4 depending on tissue types (Niederreither et al., 2002). Finally, newly synthesized RA associates to cellular RA binding proteins types I and II (CRABP-I and CRABP-II), and then either enters nuclei for activation of transcription (autocrine) or is transported to adjacent target cells (paracrine) (Napoli, 1996).

5. *Retinoic acid degradation*

Catabolism is necessary to control RA levels in cells and tissues. It occurs mainly through enzymes of the Cytochrome P450 enzyme family (CYP26). There are several CYP26 enzymes and the first one to be cloned was CYP26A1, which generates several hydroxylated forms of RA, such as 4-hydroxy retinoic acid, 4-oxo retinoic acid, 18-hydroxy retinoic acid, 5,6-epoxy retinoic acid, and 5,8-epoxy retinoic acid (Swindell and Eichele, 1999). Other similar enzymes (CYP26B1 and 26C1) have been identified later and are also able to metabolize RA (Taimi et al., 2004; White et al., 2000). The expression patterns of CYP26A1, CYP26B1, and CYP26C1 normally do not overlap, suggesting specific and distinct roles for each enzyme in the catabolism of RA (Reijntjes et al., 2004).

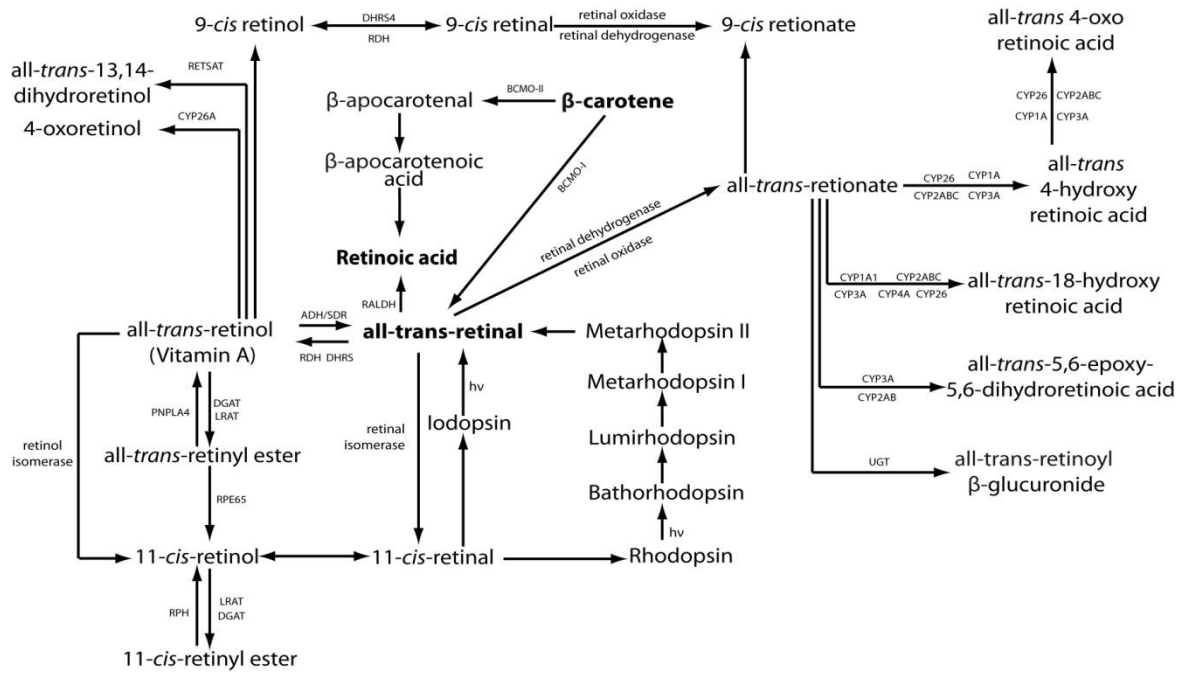


Figure 6: Biochemical pathway of retinoids. The enzymes responsible for conversion of the retinoids: ADH alcohol dehydrogenase, BCMO-I β,β -carotene-15',15'-monooxygenase, BCMO-II β,β -carotene-9',10'-dioxygenase, DGAT diacylglycerol O-acyltransferase, CYP26 cytochrome P450, DHRS dehydrogenase/reductase SDR family member, LRAT phosphatidylcholine-retinol O-acyltransferase, PNPLA4 patatin-like phospholipase domain-containing protein 4, RDH retinol dehydrogenase, RETSAT all-trans-retinol 13,14-reductase, RPE65 retinal pigment epithelium-specific 65 kDa protein, SDR short-chain dehydrogenase/reductase, UGT glucuronosyltransferase. Adapted from (Theodosiou et al., 2010).

CHAPTER 2: NUCLEAR RETINOIC ACID RECEPTORS

The biological effects of RA are mediated through two main families of nuclear receptors, which belong to the nuclear receptor superfamily: the retinoic acid receptors (RAR) and the retinoid x receptors (RXR). For both RARs and RXRs, there are three subtypes - α , β , and γ . They act as ligand-inducible transcription factors and usually form RAR/RXR heterodimers.

Note however that RXRs can also form homodimers and heterodimerize with other nuclear receptors. Indeed, RXRs are promiscuous receptors, which have the capacity to form heterodimers with several different nuclear receptors such as the receptors for fatty acids [peroxisomal proliferator activated receptors (PPAR)], bile acids [farnesoid x receptor (FXR)], oxysterols [liver x receptor (LXR)], xenobiotics [pregnane x receptor (PXR), androstanes [constitutive androstane receptor (CAR)], and vitamin D [vitamin D receptor (VDR)] (Germain et al., 2006b).

- RETINOIC ACID RESPONSE ELEMENTS (RARES)

RARs together with RXRs form asymmetrically oriented heterodimers, which bind to specific DNA sequences, called RA response elements (RAREs), located in the regulatory sequences of target genes.

The classical RAREs are composed of two direct repeats of a core hexameric motif, PuG(G/T)TCA, separated by 1 base pair, 2 base pairs or 5 base pairs and named DR1, DR2 and DR5 respectively (Figure 7) (Germain et al., 2003; Leid et al., 1992; Mangelsdorf and Evans, 1995). Such RAREs have been identified in the promoters of a large number of RA target genes involved in a wide variety of functions. For example, the classical DR5 elements are found in the promoters of the *RAR β 2* gene itself (de The et al., 1990), of the *CYP26A1* gene (cytochrome 450, family 26, subfamily a, polypeptide 1) (Loudig et al., 2000), and of several *Homeobox (Hox)* and *hepatocyte nuclear factor (HNF)* genes (Dupe et al., 1997; Qian et al., 2000). Recently, *in silico* studies revealed new DR5 RARE-associated genes (*Meis2* and *Bhlhe40*) (Lalevee et al. 2011). DR2 elements were identified in the *CRBPI (Cellular retinol binding protein I)* and *CRABPII (Cellular retinoic acid binding protein II)* gene promoters (Durand et al., 1992; Smith et al., 1991). The only natural DR1 element has been found in the rat *CRBPII* gene promoter (Mangelsdorf et al., 1991).

Remarkably, recent ChIP-seq analysis revealed novel natural DR0 and DR8 RAREs, the latter being composed of a DR2 juxtaposed to a DR0 (I. Davidson *et al*, unpublished results).

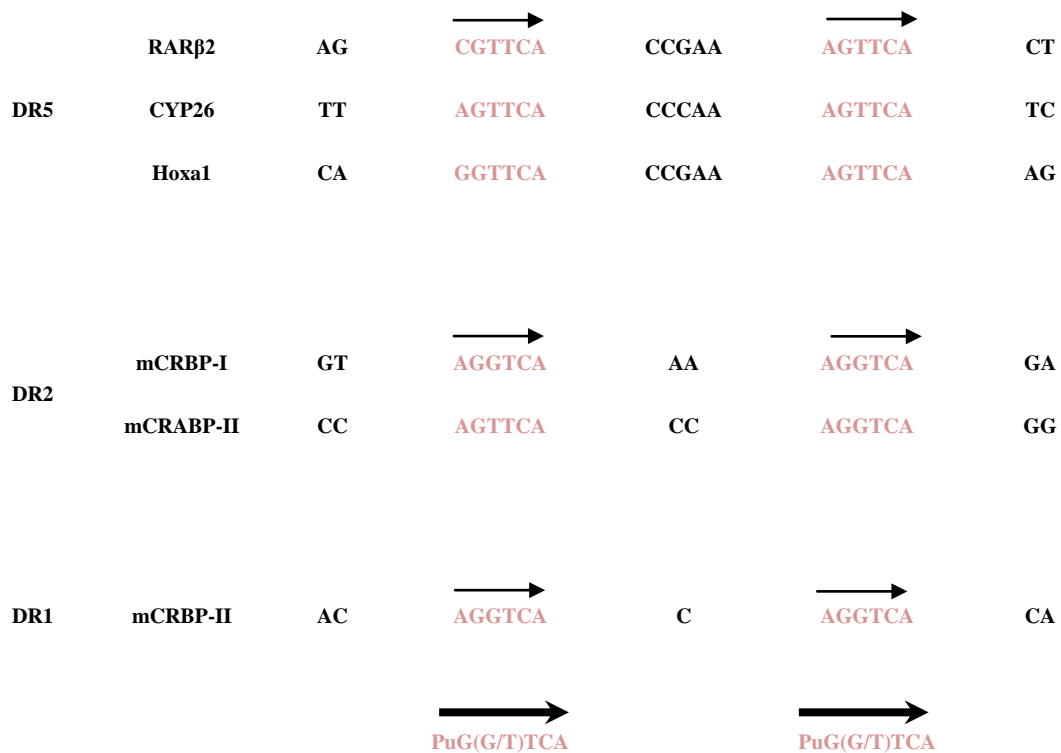


Figure 7: The classical retinoid response elements are composed of two direct repeats of the hexameric, motif 5'-PuG(G/T)TCA spaced by 1 (DR1), 2 (DR2) or 5 (DR5) base pairs. Several examples of natural retinoid response elements from the promoters of RA-target genes are shown. Adapted from (Bastien and Rochette-Egly, 2004).

- STRUCTURE OF RARS

As most nuclear receptors, RARs have a modular structure consisting of 6 regions named A to F, from the N-terminal to the C-terminal end (Figure 8) (Chambon, 1996; Laudet and Gronemeyer, 2002). Some of these regions overlap with functional domains. Indeed, the C and E modules correspond to the DNA binding domain (DBD) and the Ligand Binding Domain (LBD), respectively. These domains are highly conserved between RARs and nuclear receptors and play critical roles in the classical model of RAR transcriptional activity. Oppositely, the A/B, D and F modules are less conserved.



Figure 8: Modular structure of RARs. Adapted from (Rochette-Egly and Germain, 2009).

1. DNA binding domain (DBD)

The DBD, which is responsible for sequence-specific DNA recognition, consists of two zinc-nucleated modules, two α -helices and a COOH-terminal extension (CTE) (Zechel et al., 1994). Functionally, the DBD is divided into 4 boxes: the P box within the first helix and the A box in the CTE, are responsible for discrimination between the half sites, while the D and T boxes are involved in the heterodimerization interface (Figure 9A).

According to nuclear magnetic resonance and crystallographic studies, when the DBD is complexed with DNA, helix 1 and helix 2 cross at right angles and fold into a globular conformation to form the core of the DBD (Lee et al., 1993) (Figure 9B). Indeed, helix 1 fits specifically into the major groove of the DNA through the P box, while helix 2 and the CTE cooperate to create the interface between the heterodimerization partners.

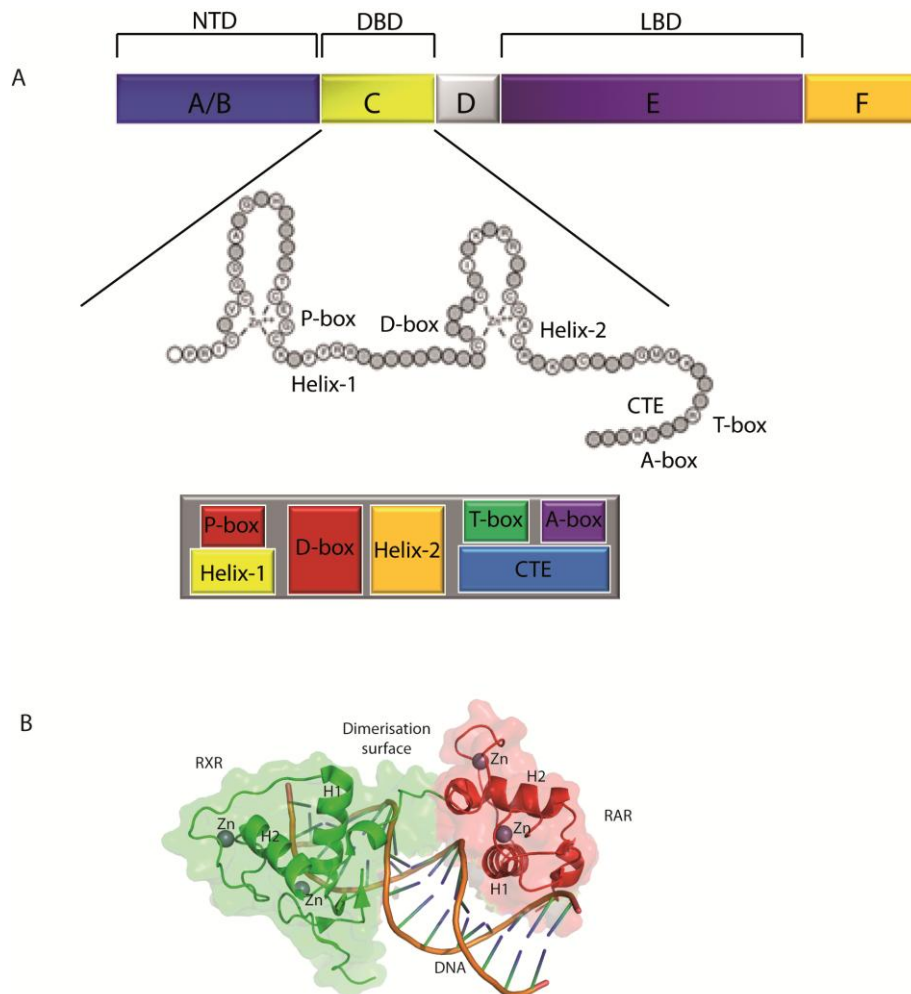


Figure 9: Structure of the DNA binding domain

A. Schematic view of the DBD, showing the relative locations of the P-box, D-box, T-box, A-box, Helix 1, Helix 2, and the C-terminal extension (CTE). Adapted from (Aranda and Pascual, 2001; Bain et al., 2007). B. Structure of a RAR/RXR DBD heterodimer in complex with a DR1 DNA response element. Zn = atoms of zinc, H1 and H2 = helices 1 and 2. Adapted from (Rastinejad et al., 2000) pdb1dsz.

Depending on the RARE, the heterodimers are differently oriented. For example on DR2 and DR5 elements, the RXR partner occupies the 5' hexameric motif and the RAR partner the 3' motif (5'-RXR-RAR-3') (Chambon, 1996; Laudet and Gronemeyer, 2002). However, for DR1 elements, the polarity is opposite, with the RAR in 5' side and the RXR in 3' (5'-RAR-RXR-3') (Figure 10). This variation of orientation depending on the DR type, would explain why the activity of the heterodimer switches from an activator (DR5) to a repressor (DR1).

Moreover, also depending on the DR type, different regions of the DBD of each partner participate in the dimerization interface, in order to achieve the required binding to the response

elements. Indeed, the binding of RXR-RAR heterodimers to DR5 elements requires the D box of the RXR second zinc-finger, and the tip of the RAR first zinc finger. However, binding with reverse polarity to the DR1 elements involves the second zinc finger of RAR and the T box of the RXR CTE (Renaud and Moras, 2000).

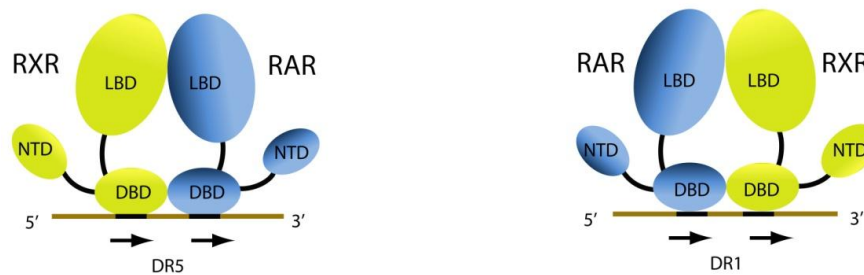


Figure10: Different orientations of RXR/RAR hetodimers depending on the DR type. On DR5 elements, the 5' hexameric motif is occupied by RXR. On DR1 elements, the 5' hexameric motif is occupied by RAR. Adapted from (Bastien and Rochette-Egly, 2004).

2. Ligand- binding domain (LBD)

The structures of the RAR LBDs were demonstrated by crystallographic studies (Moras and Gronemeyer, 1998; Renaud and Moras, 2000; Wurtz et al., 1996). The LBD is composed of 12 conserved α helices and a β -turn (located between H5 and H6) (Figure 11). Helices 1-11 are folded into a three-layered, anti parallel helical sandwich where H4, H5, H8, H9 and H11 are sandwiched between H1, H2 and H3 on one side and H6, H7 and H10 on the other side. In this structure, H12 that encompasses the AF-2 activation domain, points away from the LBD core. Functionally, the LBD is divided into three main functional domains: the ligand-binding pocket (LBP), the major dimerization interface and the ligand-dependent activation function-2 (AF-2).

- Ligand-binding pocket (LBP)

The ligand-binding pocket (LBP) contains hydrophobic residues mainly from helices H3, H5, H11 and the β -sheet, which establish van der Waals interactions with the ligand (Klaholz et al., 2000). Several crystallographic studies revealed the structural basis of ligand recognition (Bourguet et al., 2000a; Li et al., 2003; Renaud et al., 1995). The carboxylic group of the retinoid molecules is buried deep inside the LBP, engaging hydrogen bonds with specific amino acids of H3 and the β -sheet. The rest of the molecule has to adapt to the overall structure of the LBP, which causes the ligand molecule to bend to accommodate the RAR LBP.

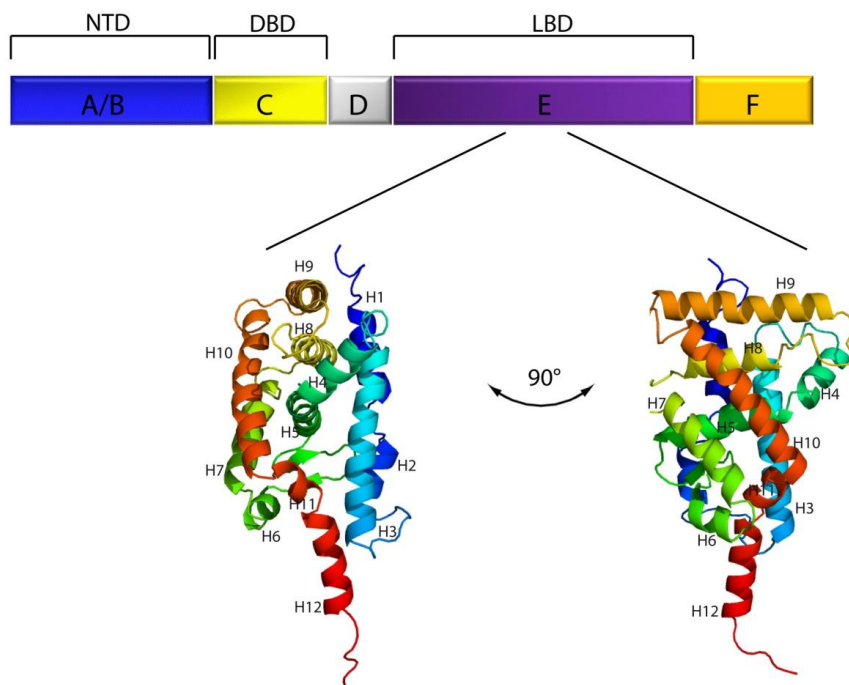


Figure 11: The 3D structure of the LBD. Helices are shown as ribbons and labelled from H1 to H12. The LBD is consisted of 12 α helices which form a three-layered, antiparallel helical sandwich (on the left side of the figure). H4, H5, H8, H9 and H11 are sandwiched between H1, H2 and H3 on one side and H6, H7 and H10 on another side. Adapted from (Bourguet et al., 1995) pdb1lbd.

The precise contacts with ligands involve three divergent residues, which are unique for each subtype receptor-cognate ligand pair and are located in H3, H5 and H11 (Table 1). Therefore, it has been possible to generate subtype-selective ligands (Germain et al., 2004). For example, the unique polar residues S232 and M272 located within LBP of RAR α and RAR γ respectively have been used to develop specific ligands for RAR α (Am580) or RAR γ (BMS270394 or CD666). Via their amino group, these ligands form hydrogen bonds with S232 of RAR α or M27 of RAR γ leading to increased affinity and selectivity for RAR α and RAR γ respectively (Table1).

Receptor	Helices		
	H3	H5	H11
RAR α	Ser232	Ile270	Val395
RAR β	Ala225	Ile263	Val388
RAR γ	Ala234	Met272	Ala397

Table 1. Residues within the α -helices H3, H5 and H11 of the different RAR isotypes involved in ligand binding

- Heterodimerization surface

The main heterodimerization surface between the RAR and RXR partners is located in the LBD. It involves residues from helices H7, H9, H10 and H11, as well as loops L8-9 and L9-10 (Bourguet et al., 2000b; Gampe et al., 2000; Pogenberg et al., 2005). The core of the dimer is formed mostly by helices H9 and H10, which contribute to more than 75% of the total dimerization surface. In contrast to the almost perfect symmetric organization of RXR homodimers (so called butterfly shape), the heterodimer interfaces are asymmetric. Indeed, helix H7 of RXR contacts loop L8-9 of RAR, but loop L8-9 of RXR and helix H7 of RAR are not involved in the interaction (Figure 12).

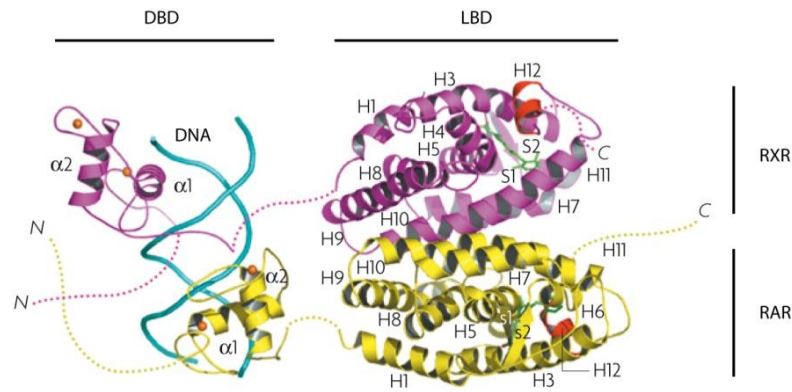


Figure 12: The three-Dimensional structure of RXR–RAR heterodimer with 9-cis-retinoic acid and DNA. Pointed lines indicate domains with unresolved structures. Helices are shown as ribbons and labelled from H1 to H12 (LBD) or $\alpha 1$ and $\alpha 2$ (DBD). Helix H12 (AF-2) is represented in red in each subunit. The short LBD β -strands are labelled S1 and S2. 9-cis-retinoic acid in RAR and RXR LBDs is shown by green sticks lines. The orange spheres in the DBD indicate atoms of zinc. Image modified from (de Lera et al., 2007).

Recently Rochel *et al* revealed new structural features of the RAR-RXR heterodimers architecture on different RAREs. They demonstrated that the RXR–RAR–DR5 complex is elongated and asymmetric, with two separate DBDs and LBDs connected by a narrow segment (Figure 13 B) (Rochel et al., 2011). The RAR–RXR–DR1 complex is similarly elongated but with a larger connecting volume between the DBDs and LBDs (Figure 13 A). Interestingly, in both cases (DR5 or DR1), the LBD dimers are always positioned at the 5' end of the target DNA. The observed asymmetry of the overall architecture and the relative position of the domains point to the essential role played by the hinge domains in establishing and maintaining the integrity of the functional structures.

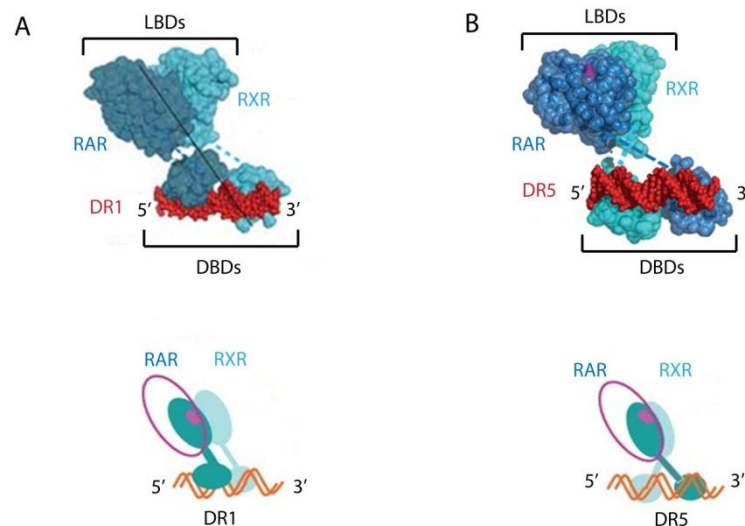


Figure 13: A. RAR-RXR-DR1 complex B. RAR-RXR-DR5 complex. Adapted from (Rochel et al., 2011).

- C-terminal helix 12, named AF-2

The C-terminal helix 12, known as AF-2, regulates the interaction of RARs with coregulators. The analysis of the crystal structures of the unliganded and ligand-bound LBDs of RXR α and RAR α respectively (Bourguet et al., 1995; Renaud et al., 1995), highlighted the conformational flexibility of H12 and how AF-2 becomes transcriptionally active (Figure 14 A) (Egea et al., 2001; Steinmetz et al., 2001).

In the unliganded receptor (so called apo-conformation), H11 is almost perpendicular to H10 and points towards the ligand-binding pocket and some of the hydrophobic residues of H11 partially fill and stabilize the LBP. H12 extends away from the core LBD, pointing away from the dimer axis at an angle of about 45° (Bourguet et al., 1995).

Upon ligand binding, H11 is repositioned in the continuity of H10, causing the concomitant swinging of H12, which moves in a ‘mouse trap’ model and packs tightly against H3 and H4 (Figure 14B). Consequently the lid of the LBD is sealed and ligand binding is stabilized (Moras and Gronemeyer, 1998). Moreover, a new hydrophobic cleft between H3, H4 and H12 is formed, creating a defined surface for the interaction with transcriptional coactivators. This liganded conformation is referred as “holo” or “active” conformation (Figure 14B). Note that in the case of the RAR β and RAR γ subtypes, some biochemical studies proposed that even in the absence of ligand, H12 interacts with H3 and adopts a constitutively closed conformation that approximately corresponds to the conformation of liganded RAR α (Farboud et al., 2003; Farboud and Privalsky, 2004; Hauksdottir et al., 2003).

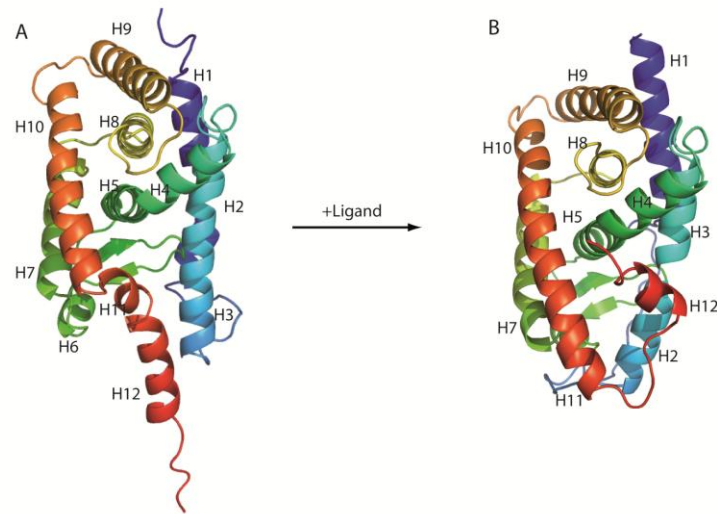


Figure 14: Three-dimensional structure of LBD and structural changes induced by ligand binding. Helices are represented as ribbons and labelled from H1 to H12. A. Structure of the LBD of RXR α in apo conformation. Adapted from (Bourguet et al., 1995) pdb1lbd. B. Structure of the LBD of RAR γ with ligand (holo conformation). Adapted from (Renaud et al., 1995) pdb2lbd.

3. *N-terminal AF-1 domain (NTD)*

The N-terminal domain (NTD) of RARs (activation function AF-1) corresponds to the A and B regions (Nagpal et al., 1993; Nagpal et al., 1992). Within the NTD, the A regions are comparatively variable between the different RAR subtypes and isoforms (Chambon, 1996). In contrast, the B region is well conserved and holds a proline-rich motif containing phosphorylation sites (see below, Figure 26 page 42).

In contrast to the DBD and the LBD, there are still no high-resolution structures available for the NTD of RARs and most nuclear receptors. Even the relatively very short NTD of peroxisome proliferator-activated receptor- γ (PPAR- γ) failed to show any signature of structure (Chandra et al., 2008). According to several studies, the NTDs of the Estrogen Receptor (Warnmark et al., 2001), the Glucocorticoid Receptor (Warnmark et al., 2001), the Progesterone Receptor (Bain et al., 2000) and the Androgen Receptor (Reid et al., 2002) possess an intrinsically disordered (ID) conformation.

Importantly, intrinsically unstructured proteins are functional and the NTD of RARs has been shown to play an important role in the regulation of transcription (Nagpal et al., 1993). Though the mechanism of this functionality has not been elucidated yet, it has been shown that disordered domains provide the flexibility that is necessary for modifications by kinases or ubiquitin ligases (Dyson and Wright, 2005). Such modifications may change structural properties of the domain and

subsequently affect the dynamics of neighboring structural domains (Pufall et al., 2005) and therefore interactions with co-regulators and/or DNA (Dyson and Wright, 2005; Liu et al., 2006). In line with this, it is interesting to note that the NTD of RARs contains phosphorylation sites located in a proline-rich motif (PRM). As PRMs have the capacity to bind proteins with SH3 (Src-homology-3) or WW (tryptophan-tryptophan) domains (Kay et al., 2000b), one can speculate that the NTD of RARs might regulate transcription via the phospho-dependent association or dissociation of coregulators (See below chapter 5).

4. *D-region*

The D domain or hinge region is poorly conserved and serves as a hinge between the DBD and the LBD. It has been proposed that its flexibility would permit the adaptation of the RAR/RXR heterodimers to different types of RAREs (Glass, 1994; Rochel et al., 2011). In RARs, this domain is very small (12 amino acids) and shares 50% of identity between RAR α and RAR β and 33% between RAR α and RAR γ . The hinge region would also harbor a nuclear localization signal (Hamy et al., 1991).

5. *The F-region*

The F region is the most carboxy-terminal region of RARs and is absent in RXRs. It is not conserved between RARs and its three-dimensional structure is not known. So far the precise functions of region F are not well understood. It has been proposed that in the absence of ligand this region might stabilize the H12 of RAR α in open conformation, thus enhancing binding of corepressors (Farboud and Privalsky, 2004). According to recent studies, this region would be able to bind specific mRNA motifs (Poon and Chen, 2008). Interestingly, the F region is phosphorylated at multiple sites and such modifications might change the properties of RARs (Bastien et al., 2000; Rochette-Egly et al., 1997).

CHAPTER 3: THE CLASSICAL MODEL OF RAR-MEDIATED REGULATION OF TRANSCRIPTION

The canonical mechanism of action of RARs involves the activation or repression of target-gene transcription (Figure 15).

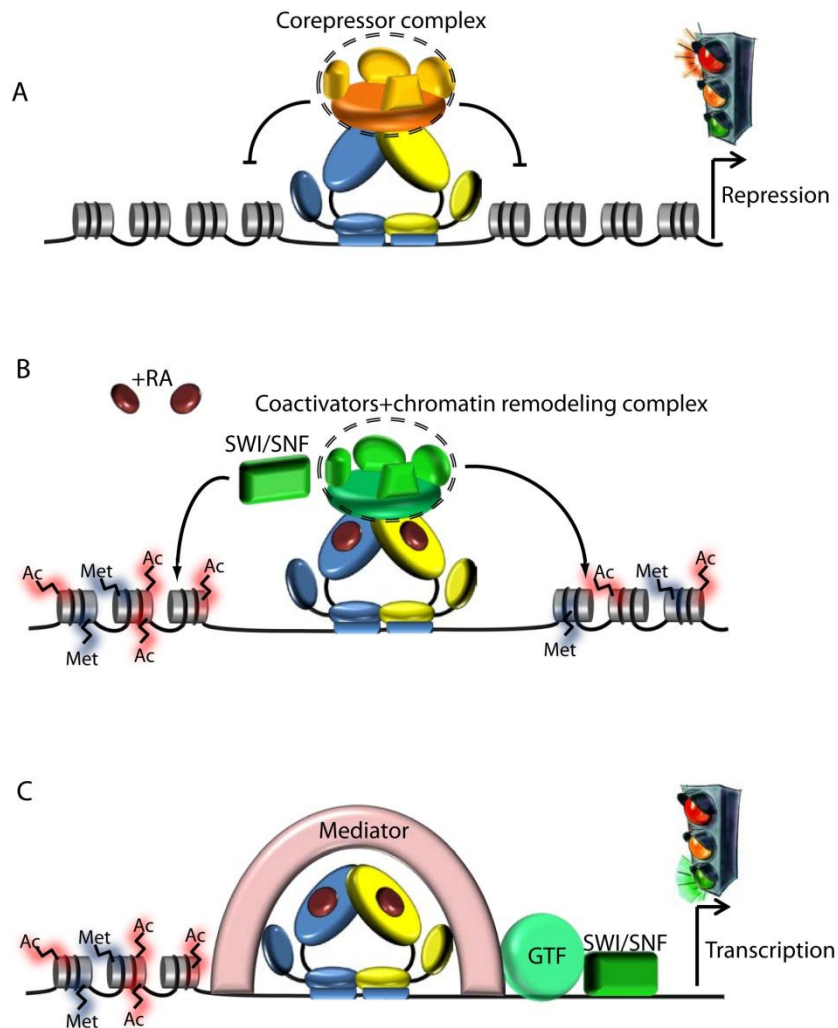


Figure 15: Classical model of activation of RA-target genes.

A. In the absence of ligand, RAR α /RXR heterodimers bind DNA in association with corepressor complexes. B. Ligand binding induces the release of corepressors and the recruitment of coactivator complexes. C. Upon decompaction of chromatin, the transcriptional machinery, which consists of the Mediator, RNA polymerase II and the general transcription factors (GTFs), is recruited to the promoter, resulting in the initiation of transcription. Adapted from (Bour et al., 2007b).

This mechanism is at the basis of the regulation by RARs of gene networks involved in a wide number of functions such as homeostasis, development and reproduction. According to such a model, genes are silenced through the recruitment of corepressor-containing complexes to unliganded (apo) DNA-bound receptors. Conversely, genes are activated subsequent to corepressors release from liganded receptors (holo) and recruitment of coactivator complexes (Figure 15). At the molecular level, the discrimination between coactivators and corepressors relies in the positioning of H12 within the LBD.

- REPRESSION OF TRANSCRIPTION IN THE ABSENCE OF LIGAND

In the absence of ligand, RAR/RXR heterodimers occupy RAREs in association with large multiprotein complexes with several enzymatic activities (histone deacetylases, methylases, ubiquitin ligases etc), which maintain histones and chromatin in a compacted repressed state.

Basically, the corepressor core is composed of NCoR (nuclear receptor co-repressor) or SMRT (silencing mediator for retinoic acid and thyroid hormone receptors). NCoR and SMRT were the first identified corepressors (Chen and Evans, 1995; Lee et al., 1995; Sande and Privalsky, 1996). They bind NRs and serve as platforms for the binding of other proteins such as GPS2 (G-protein pathway suppressor 2), TBL1 (Transducin β -like 1), TBLR1 (TBL1-related protein 1), HDAC3 (Histone deacetylase 3) and Sin3 (Figure 16) (Li et al., 2000; Zhang et al., 2002).

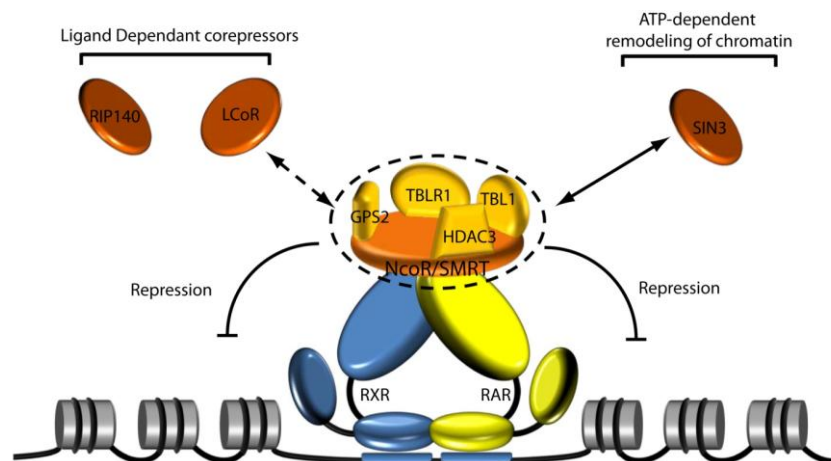


Figure 16: Corepressors and associated complexes. Core of the complex (pointed) and associated complexes. Adapted from (Perissi and Rosenfeld, 2005).

Of note is that SMRT is the preferential corepressor of RARs. It is an ubiquitous 270 kDa protein, which belongs to a variety of multiprotein complexes containing histone deacetylases. These complexes repress transcription by deacetylation of lysine residues located in the N-terminal tails of histones.

NCoR and SMRT are structurally and functionally similar and share about 40% amino-acid identity. Both have been shown to repress the transcriptional activity of several nuclear receptors and of a variety of unrelated transcription factors involved in several cellular processes. For example SMRT represses serum response factor (SRF), activator protein-1 (AP-1), and nuclear factor- κ B (NF κ B), which are all transcription factors involved in stimulation of cell proliferation (Lavinsky et al., 1998; Shibata et al., 1997; Zamir et al., 1996). SMRT as well as NCoR display specific domain structures (Figure 17).

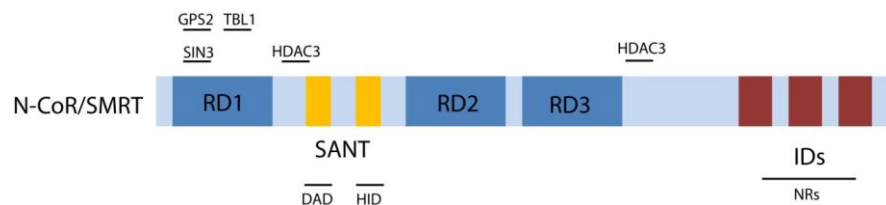


Figure 17: Schematic N-CoR/SMRT domains with the associated proteins. Adapted from (O'Malley and Kumar, 2008).

The C-terminus contains corepressor nuclear receptor (CoRNR) boxes, also called NR interaction domains (IDs), which interact with the LBD of NRs (Hu and Lazar, 1999; Nagy et al., 1999; Perissi et al., 1999). The ID contains the sequence (L/I)XX(I/V)I or LXXX(I/L)XXX(I/L) (where X is any amino acid), and forms an extended α helix that interacts with the hydrophobic groove generated by H3, L3-4 and H4 of RARs, the N-terminal extension of the motif masking the H12 interaction interface (Figure 18). As this surface is topologically related to that involved in coactivator interaction, but without H12; this may explain why the binding of corepressors and coactivators is mutually exclusive (Hu and Lazar, 1999).

In contrast, the amino terminus of N-CoR and SMRT contains the domains responsible for transcriptional repression (Figure 17). Three repressive regions (RD1, RD2, and RD3) were originally described due to their ability to act as autonomous repression domains when associated to DNA binding proteins (Horlein et al., 1995). RD1 interacts with GPS2 but little is known about the role of GPS2 in NR repression (Zhang et al., 2002). RD1 also interacts with TBL1 and TBLR1, which are members of the WD40 family.

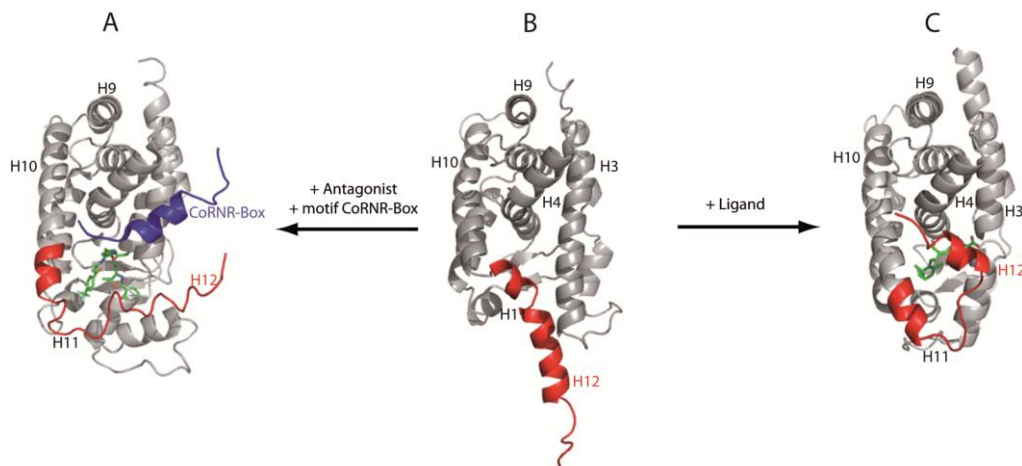


Figure 18: Interaction of NR LBDs with corepressors.

A. Structure of the LBD of PPAR α complexed with an antagonist and a CoRNR box. Adapted from (Xu et al., 2002) pdb1kkq. B. Structure of apo RXR LBD. Adapted from (Bourguet et al., 1995) pdb1lbd. C. Structure of holo RAR γ LBD (with an agonist). Adapted from (Renaud et al., 1995) pdb2lbd

TBL1 and TBLR1 interact simultaneously with deacetylated histone H4 (Yoon et al., 2003), thereby stabilizing the corepressor complex on chromatin and facilitating repression. The other repressive domains interact with HDAC3 and with SIN3, a component of the Sin3A corepressor complex (Alland et al., 1997; Heinzel et al., 1997; Nagy et al., 1997). Remarkably, SIN3 can recruit additional enzymes with repressive activity such as the histone H3K9 methyltransferase ESET/SETDB1 and the ATP-dependent chromatin remodeling complex SWI/SNF (Underhill et al., 2000; Yang et al., 2003).

Between RD1 and RD2 there are two SANT (SWI3, ADA2, N-CoR, and TFIIB) motifs, which are also important for corepressor function. The first SANT motif forms a deacetylase activation domain (DAD), which stably associates with and activates histone deacetylase 3 (HDAC3) (Danielian et al., 1992; Umesono et al., 1991). The second one named histone interaction domain (HID), interacts directly with unacetylated histone H4 N-terminus tails (Yu et al., 2003).

- ACTIVATION OF TRANSCRIPTION UPON LIGAND BINDING

Ligand binding induces conformational changes of RAR α , with reorientation of H12 (Figure 19), resulting in the formation of a charge clamp between a conserved glutamate residue in H12 and a lysine residue in H3. Such a charge clamp can form hydrogen bonds with the LxxLL motif of coactivators. However it does not fit with the extended LxxI/HIxxxI/L motif of corepressors. Thus, it has been proposed that the length difference of the interacting motifs might be at the origin of the alternative interactions of the hydrophobic cleft in the apo or holo conformations, with corepressors and coactivators (Germain et al., 2006b; Perissi et al., 1999).

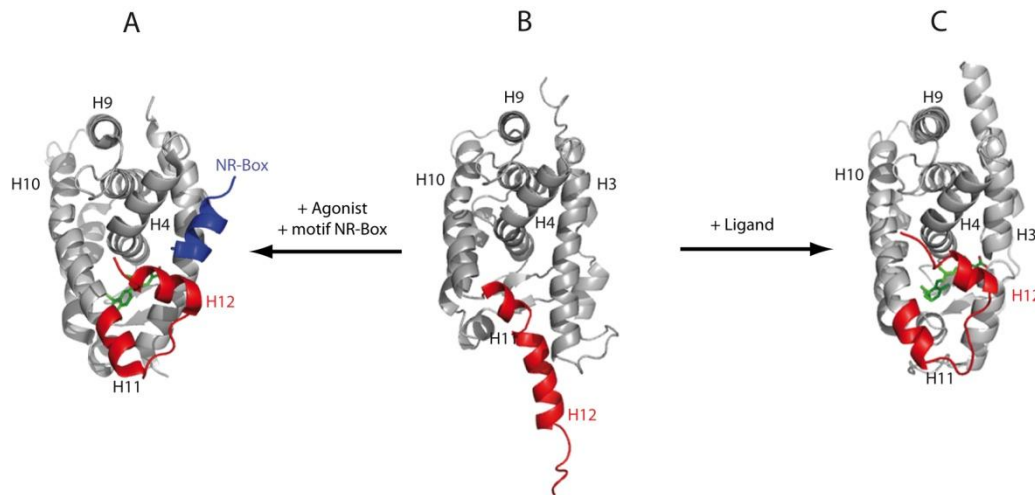


Figure 19: Conformational changes in LBD and interaction with coactivators.

A. Structure of the LBD of RXR bound to an agonist and to the NR box of coactivators. Adapted from (Lippert et al., 2009) pdb2zxx. B. Structure of apo RXR LBD. Adapted from (Bourguet et al., 1995) pdb1lbd. C. Structure of holo RAR γ LBD complexed with a ligand. Adapted from (Renaud et al., 1995) pdb2lbd.

According to the classical model of transcriptional activation, ligand binding releases bound corepressors and promotes the recruitment of coactivators that serve as a platform for larger complexes with chromatin modifying and remodeling activities (Figure 20).

The coactivators of the p160/SRC (Steroid Receptor Coactivators) family have been the most extensively studied among the large spectrum of identified coactivators. This family comprises three members: SRC-1 (also referred to as NCoA-1), SRC-2 [NCoA2, TIF-2 (transcriptional intermediary factor 2), GRIP-1 (glucocorticoid receptor interacting protein 1)] and SRC-3 [pCIP (p300/CBP-interacting protein), ACTR (Acetyltransferase), AIB1 (amplified in breast cancer I), TRAM1 (thyroid

hormone receptor-activator molecule 1), RAC3 (Receptor-Associated Coactivator 3)] (Chatterjee and Kashfi, 2011).

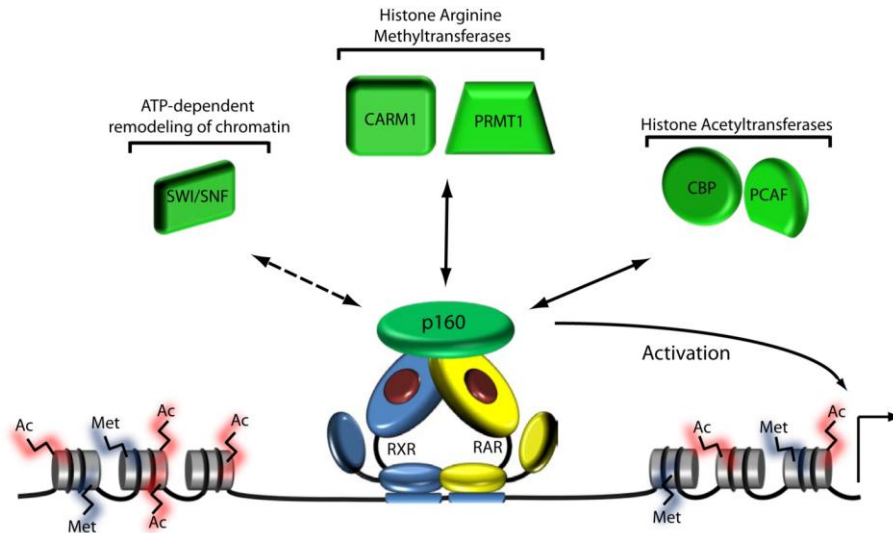


Figure 20: Coactivators and associated complexes. The RAR/RXR heterodimers in holo conformation recruit the p160 coactivators, which serve as a platform for chromatin modifying and remodeling complexes. Adapted from (Perissi and Rosenfeld, 2005).

The p160 SRCs are approximately 160 kDa in size and share an overall of 50-55% sequence similarity and 43-48% of sequence identity. Structurally p160/SRCs are composed of several domains (Figure 21). The central Receptor-Interacting Domain (RID) contains three LXXLL motifs or NR boxes and is responsible for interaction with the hydrophobic cleft of ligand-bound RARs. The C-terminal transcriptional activation domains (AD1 and AD2) recruit proteins that contribute to chromatin remodelling. AD1 is responsible for the recruitment of histone acetyltransferases such as p300/CBP (CREB-binding protein) and PCAF (P300/CBP-associated factor) (Chen et al., 1997; Stallcup et al., 2003; Torchia et al., 1997). AD2 usually recruits histone methyltransferases such as CARM1 (coactivator-associated arginine methyltransferase 1) and PRMT1 (Protein arginine N-methyltransferase 1) (Chen et al., 1999; Lee et al., 2005; Stallcup et al., 2003). Moreover, the C-terminal domain of SRCs itself shows a weak HAT activities (Chen et al., 1997; Spencer et al., 1997).

The N-terminal domain called bHLH/PAS (helix-loop-helix/Per/ARNT/Sim) is highly conserved and functions as a third AD (AD3) domain. It serves as a binding site for DNA-binding transcription factors such as TEF-4, MEF-2C, p53 and myogenin. Additionally, bHLH/PAS can recruit other coactivators including GAC63, CoCoA, FliI, G9a,BAF57 and ANCO1 (Kim et al., 2003; Lee et al., 2006).

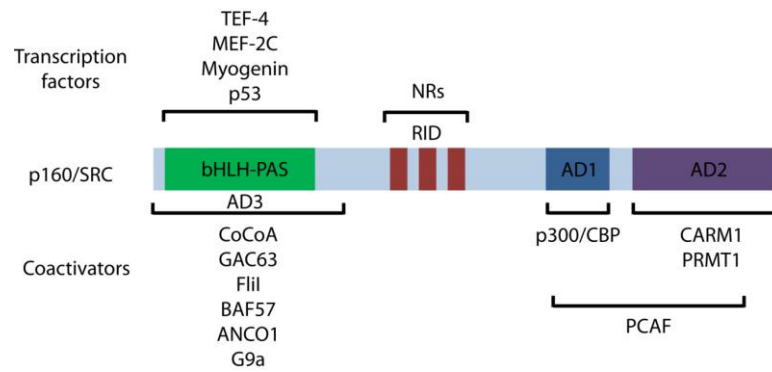


Figure 21: Schematic representation of functional domains and interacting proteins of p160/SRC family. Adapted from (O'Malley and Kumar, 2008).

The complexes with enzymatic activities associated to coactivators alter the chromatin structure around the promoter of target genes and create modifications of histone tails according to a “histone code”. Indeed these modifications create new sites for the recruitment of other complexes such as SWI/SNF (SWItch/Sucrose NonFermentable) that also contribute to chromatin remodeling using the energy of ATP hydrolysis (Huang et al., 2003; Sims and Reinberg, 2008).

Finally, chromatin remodeling and modifications pave the way for the recruitment of the transcriptional machinery that includes the multisubunit Mediator complex DRIP205/TRAP220, RNA polymerase II and the general transcription factors (Bastien and Rochette-Egly, 2004; Dilworth and Chambon, 2001; Rochette-Egly, 2005; Rosenfeld et al., 2006). Note that the recruitment of the transcription machinery involves interaction of RARs with a specific subunit of the Mediator complex, DRIP205/TRAP220, which contains two LxxLL motifs (Lefebvre et al., 2005).

It must be noted that depending on the target gene's promoter context, RARs can carry out different programs for gene activation. Indeed, recent chromatin immunoprecipitation experiments showed that even in the absence of RA, RAR α can occupy the promoters of some genes in association with the Mediator complex and RNA PolII (Flajollet et al., 2006; Mendoza-Parra et al., 2011; Pavri et al., 2005; Perissi et al., 2004). In this case, initiation of transcription relies on the dissociation of cdk8 (cyclin-dependent kinase 8 inhibitory subunit) from the Mediator complex (Andrau et al., 2006; Elmlund et al., 2006) and on the subsequent recruitment of the general transcription factors such as TFIID.

- UNCONVENTIONAL COREGULATORS OF RARS

In addition to the above classical corepressors and coactivators several other unconventional coregulators have been characterized and divided in two groups: (i) corepressors with LXXLL motifs and (ii) coregulators devoid of LXXLL motifs.

1. Corepressors with LXXLL motifs

This group includes LCoR (Ligand-dependent CoRepressor), RIP140/NRIP1 (receptor interacting protein of 140kDa), PRAME (preferentially expressed antigen in melanoma) and TIF1 α /Trim24 (transcription intermediary factor-1 α) (Augereau et al., 2006; Epping et al., 2005; Fernandes et al., 2003; Hu et al., 2004; Le Douarin et al., 1995). These proteins interact with liganded RARs via LXXLL motifs (one in TIF1 α , seven in PRAME and nine plus a modified LxxML motif in RIP140), but in contrast to the classical coactivators, they attenuate the activity of RARs (Farooqui et al., 2003; Heery et al., 1997) via the recruitment of complexes with repressive activity.

2. Coregulators devoid of LXXLL motifs

This group includes:

SUG-1 (Suppressor of Gal 1) interacts with RARs and participates to chromatin remodeling via its ATPases activity. It is also a subunit of the 19S regulatory complex of the 26S proteasome and as such it promotes the degradation of RARs and SRC-3 (Ferry et al., 2009; Gianni et al., 2002).

CRABP II (Cellular Retinoic Acid Binding Protein II) together with cyclin D3 interacts with RAR α (Bastie et al., 2001; Delva et al., 1999; Despouy et al., 2003), and serves for channeling of RA to the receptor (Budhu and Noy, 2002; Dong et al., 1999).

Cyclin H binds RAR α at a specific docking site located in loop L8–9 of the LBD and allows the well-positioning of its-associated kinase cdk7 which then can phosphorylate the NTD of the receptor (Bour et al., 2005a) (see chapter 4).

TACC1 (transforming acidic coiled coil 1) serves as a scaffold protein and builds up a transcriptional complex around RAR α (Guyot et al., 2010).

Actin and actin-binding proteins (ABP). In recent years, more and more attention has focused on the role of actin and ABPs in transcriptional regulation (Zheng et al., 2009a). Recently, the group of Dr. Rochette-Egly identified vinexin β as a new partner of the RAR γ subtype (Bour et al., 2005b). In fact

vinexin β , which contains an SH3 domain, interacts with the NTD of RAR γ and functions as a repressor via sequestering RAR γ out of chromatin (Lalevee et al., 2010a) (see chapter 4, pages 43-44).

CHAPTER 4: NEW PICTURES OF RARS: RARS HAVE NON-GENOMIC EFFECTS AND ARE PHOSPHOPROTEINS

- THE NON-GENOMIC EFFECTS OF RARS: ACTIVATION OF KINASE PATHWAYS

Today, it is becoming increasingly evident that, in addition to their genomic effects, RARs also have a number of non-genomic effects. Indeed, recent studies from several laboratories, including ours, demonstrated that RA activates rapidly and transiently several kinase cascades.

RA has been shown to activate Protein Kinase C (PKC) (Kambhampati et al., 2003) and the PI3K/Akt pathway (Álvarez et al., 2007; Bastien et al., 2006) in several cell lines. RA also activates the MAPK/ERK signaling pathways in several neuronal cell lines such as neuroblastoma cell lines (Miloso et al., 2004), hippocampal cells (Chen and Napoli, 2008) and mouse embryonic stem cells committed to differentiate into neurons by RA (Stavridis et al., 2010). RA also induces this pathway in embryocarcinoma cells (Gupta et al., 2008).

RA was also found to activate p38MAPK and the downstream mitogen and stress-activated kinase MSK1 in various cell lines such as rat cardiac myoblasts, mouse embryonic fibroblasts, mouse embryocarcinoma cells, mammary breast tumor cells and leukemic cells (Alsayed et al., 2001; Bruck et al., 2009; Ren et al., 2007).

According to recent results from the laboratory of C. Rochette-Egly, these effects of retinoic acid are transcriptionally independent but involve RARs and more precisely the RAR α subtype. Indeed no p38MAPK activation was observed in cells knockout for RAR α (Bruck et al., 2009). However the molecular mechanism of p38MAPK activation by RARs was still unknown at the time of my arrival to the laboratory.

Remarkably, the other nuclear receptors and their cognate hormones are also able to activate the MAPK pathways (Piskunov and Roch  tte-Egly 2012) (Figure 22). Indeed, most of the steroid hormones, estrogens, progestins, and androgens activate the ERK pathway while glucocorticoids and vitamin D activate p38MAPK like RA. The interesting point is that the non-genomic effects of these hormones were recently found to be mediated by a subpopulation of their cognate receptor present in specialized plasma membrane structures such as caveolae and lipid rafts (Marquez et al., 2006; Matthews et al., 2008; Norman et al., 2004), that contain lipids, structural proteins like flotillin and caveolin, and several proteins involved in signal transduction including heterodimeric G proteins, c-Src, Rho and RAC GTPases and Phosphoinositide 3-kinase (PI3K) (de Laurentiis et al., 2007; Luoma et al., 2008).

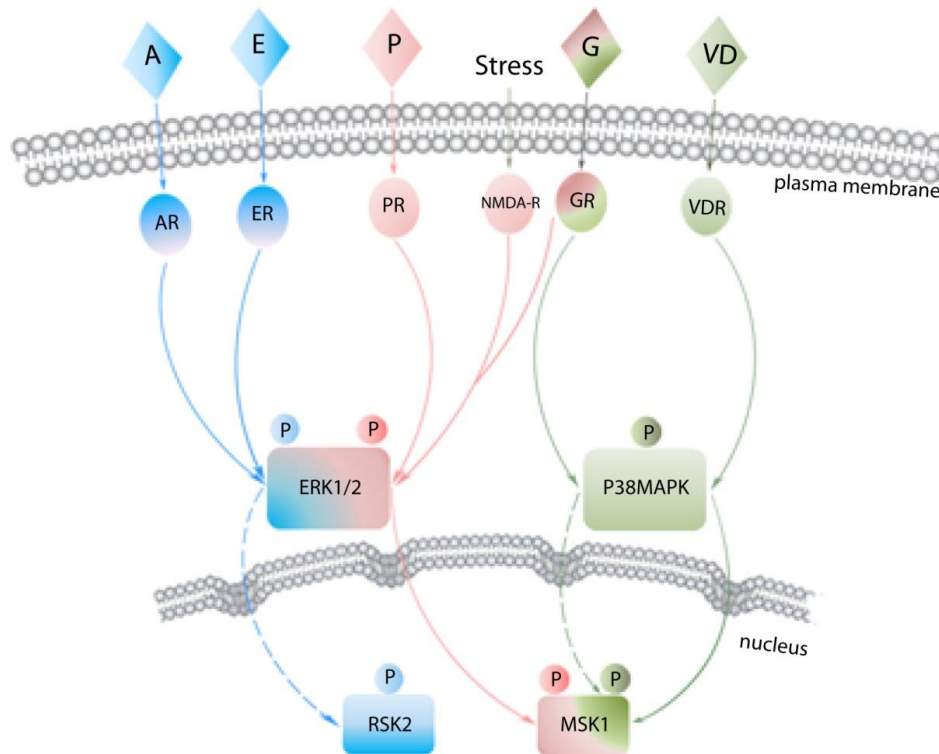


Figure 22: Non-genomic effects of nuclear receptors. A subpopulation of the classical steroid receptors (ER, PR, GR, AR) and non-steroid receptors VDR is associated to cell membranes and initiates cascades of kinase activations upon binding of their cognate ligands. Accordingly, liganded non-steroid receptor VDR activates p38MAPK and the downstream MSK1 kinase. Among the steroid receptors, GR bound to glucocorticoids also activates p38MAPK but there is no data indicating whether MSK1 is activated or not. However, upon the concomitant activation of NMDA-R under stress conditions, liganded GR activates MSK1 but through Erks. The other steroid receptors PR, ER and AR also activate Erks but only PR was found to activate the downstream MSK1. In the case of ER and AR another downstream effector of Erks, RSK2 would be an interesting candidate. Adapted from (Piskunov and Rochette-Egly, 2011b).

In these rafts, steroid NRs are part of protein complexes and activate MAPK signaling through interaction with specific signaling proteins. As an example, in response to the hormone, ER α rapidly activates the Src/p21ras/Erk pathway via direct interaction with the SH2 domain of c-Src. Progestins and androgens also activate this signaling cascade via direct interaction of the cognate receptor with the SH3 domain of c-Src or with ER α which itself activates c-Src (Castoria et al., 2003; Hagan et al., 2009; Migliaccio et al., 2000; Migliaccio et al., 1998) (Figure 22).

- RARS ARE PHOSPHOPROTEINS

A number of studies demonstrated that RARs, like most nuclear receptors, are targets for phosphorylation processes (Rochette-Egly, 2003; Rochette-Egly, 2005). Several phosphorylation sites and associated kinases have been identified for RARs and RXRs (Table 2).

Receptor	Domain/Region	Sesidue	Kinase	Referense
RAR α	NTD	S77	cdk7/cycH(TFIIH)	(Rochette-Egly et al., 1997)
	DBD	S96	Akt	(Srinivas et al., 2006)
		S115	PKC	(Sun et al., 2007)
		S157	PKC	(Delmotte et al., 1999)
		T181	JNK	(Srinivas et al., 2005)
	Hinge		CAMKII γ	(Si et al., 2007)
	LBD	S369	PKA/MSK1	(Bruck et al., 2009; Rochette-Egly et al., 1995)
F region	S445, S461	JNK,cdk7	(Rochette-Egly et al., 1997; Srinivas et al., 2005)	
RAR β 2	NTD			(Rochette-Egly and Germain, 2009)
RAR γ 2	NTD	S66	p38MAPK	(Bastien et al., 2000)
		S68	cdk7/cycH(TFIIH)	(Gianni et al., 2002)
	LBD	S360	PKA/MSK1	(Rochette-Egly et al., 1995)
RXR α 1	NTD	S22	cdk/cyc	(Bastien et al., 2002)
		S32	JNK	(Mann et al., 2005)
		S61, S75, T87	JNK	(Adam-Stitah et al., 1999; Bruck et al., 2005)
	DBD	T162	PKC	(Sun et al., 2007)
	LBD	S265	JNK	(Adam-Stitah et al., 1999; Bruck et al., 2005; Li et al., 2002)

Table 2: RAR and RXR phosphorylation sites and associated kinases.

However the most important and functional phosphorylated residues lie within the LBD and the N-terminal domain (NTD) (Figure 23). The LBD of RARs depicts one main phosphorylation site, serine 369 in RAR α , which is located in the loop between helices 9 and 10 and belongs to an arginine-lysine-rich motif. This motif corresponds to a consensus phosphorylation motif for several kinases such as cyclic AMP-dependent protein kinase (PKA) and MSK1 and thus may integrate several signaling pathways (Gaillard et al., 2006).

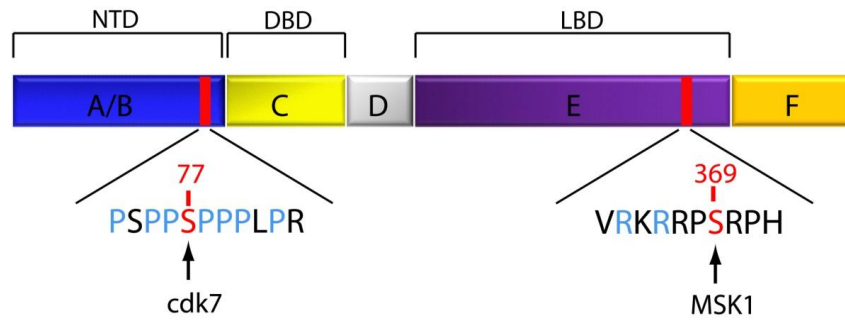


Figure 23: Main phosphorylation sites of RAR α . The LBD contains a phosphorylation site for the MSK1 kinase. The N-terminal domain contains a proline-rich motif with a phosphorylation site for Cdk7. Adapted from (Rochette-Egly and Germain, 2009).

The NTD also contains a phosphorylation site, serine 77 in RAR α , which is located at the C-terminal end of the NTD, in proximity of the DBD. This serine belongs to a proline-rich motif (PRM) and therefore corresponds to a consensus site for cyclin-dependent protein kinases (cdks) and Mitogen-Activated Protein Kinases (MAPKs). The kinase involved in the phosphorylation of this residue has been identified in the laboratory (Rochette-Egly et al., 1997). It is the cdk7 kinase, which belongs to the cyclin-dependent kinase (CDK)-activating kinase (CAK) subcomplex of TFIIF (general transcription factor composed of 10 subunits). Interestingly, the activity of cdk7 depends on the association of the kinase with other components of the CAK complex, cyclin H and MAT1 (Gigliamari et al., 2004). Recently, it has been shown in the laboratory that the accurate positioning of the cdk7 kinase and thus the phosphorylation of the NTD by cdk7 depends on the docking of cyclin H at a specific domain of the LBD, encompassing loop L8-9 and the N-terminal part of H9 (Bour et al., 2005a; Gaillard et al., 2006).

Remarkably, the two phosphorylation sites are conserved between the different RAR subtypes in mammals (Samarut et al., 2012). However the phosphorylation site located in the LBD is not conserved in the other nuclear receptors (Rochette-Egly, 2003). The phosphorylation site of the NTD is not conserved either as none of them depict a stretch of proline residues around the serine residue similar to that of RARs. Nevertheless all nuclear receptors (except VDR due to its very short NTD), contain other phosphorylation sites that are substrates for several types of kinases such as cdks, p42/p44MAPK, p38MAPK, and c-Jun N-terminal kinases (JNKs) (Chen et al., 2008b; Lannigan, 2003; Rochette-Egly, 2003; Wang et al., 2007; Weigel and Moore, 2007a; Weigel and Moore, 2007b; Weigel and Moore, 2007c).

- RARS PHOSPHORYLATION INVOLVES A CASCADE OF KINASES

Remarkably, the two main serine residues of RARs are rapidly phosphorylated in response to RA (Bruck et al., 2009). Recent studies demonstrated that this RA-induced phosphorylation of RAR α results from a coordinated phosphorylation cascade starting with the phosphorylation of serine 369 by MSK1 (Bruck et al., 2009). Interestingly, phosphorylation of this serine increases the flexibility of loop L8–9 (Samarut et al., 2012), which is in close proximity and corresponds to the cyclin H binding domain (Figure 24). Consequently, the binding of cyclin H and the associated cdk7 to this domain is facilitated and the serine located in the NTD can be phosphorylated by cdk7 (Gaillard et al., 2006).

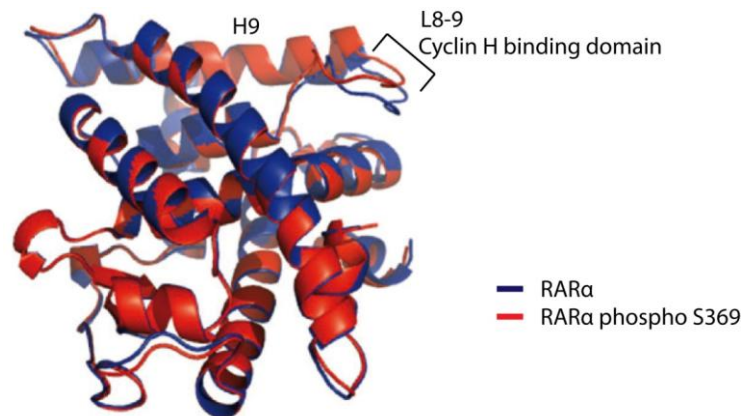


Figure 24: Superposition of the average structures of the RAR α LBD unphosphorylated (blue) and phosphorylated (red). Adapted from (Samarut et al., 2012).

This is a unique example of cooperation between the N- and C-terminal domains of RARs through a kinase complex. The docking site of cyclin H and the two phosphorylation sites are conserved between RARs, but whether the above cascade is common for all RARs needs to be further investigated.

Remarkably, the cyclin H docking site as well as the serine located in loop L9-10 are not conserved in other nuclear receptors and other cdk7 targets, suggesting that the cascade and the phosphorylation by cdk7 might be specific for RARs.

- CONSEQUENCES OF PHOSPHORYLATION ON RARS ACTIVITY

1. *RAR phosphorylation and the transcription of RA target genes*

Recently, Bruck *et al.* highlighted a new paradigm in which, *in vivo*, the RA-induced phosphorylation cascade, starting with the rapid activation of p38MAPK and ending with the phosphorylation of RAR α , is crucial for RAR α -mediated transcription (Bruck *et al.*, 2009) (Figure 25). Indeed, they demonstrated that the expression of several RA target genes is abolished upon silencing of p38MAPK or MSK1 and upon mutation of RAR phosphorylation sites. At the molecular level, the MSK1-dependent phosphorylation of S369 located in the LBD of RAR α is critical for the binding of TFIID. Moreover, phosphorylation of S77, which is a consequence of S369 phosphorylation and the last step of all phosphorylation cascades, promotes the recruitment of RAR α to the target genes promoters. These results corroborate previous observations in fibroblasts from patients suffering from Xeroderma pigmentosum (Keriel *et al.*, 2002). In these cells, which are characterized by mutations of a TFIID subunit, RAR α is hypophosphorylated at serine 77 and the RA response is deficient.

In parallel, activated MSK1 is also recruited to RAR α target promoters where it phosphorylates histones H3 at serine 10 (Bruck *et al.*, 2009). This phosphorylation process, which is coupled to the acetylation of nearby lysine residues (K9 or K14) (Cheung *et al.*, 2000; Clayton *et al.*, 2000; Lo *et al.*, 2000), and to the recruitment of the chromatin remodeling complex SWI/SNF (Vicent *et al.*, 2006) paves the way for the recruitment of RARs and the transcriptional machinery.

Altogether, these data highlight that there is cooperation between the phosphorylation of RAR α and that of histones for the recruitment of RAR α to RAREs and the initiation of transcription of the target genes (Figure 25).

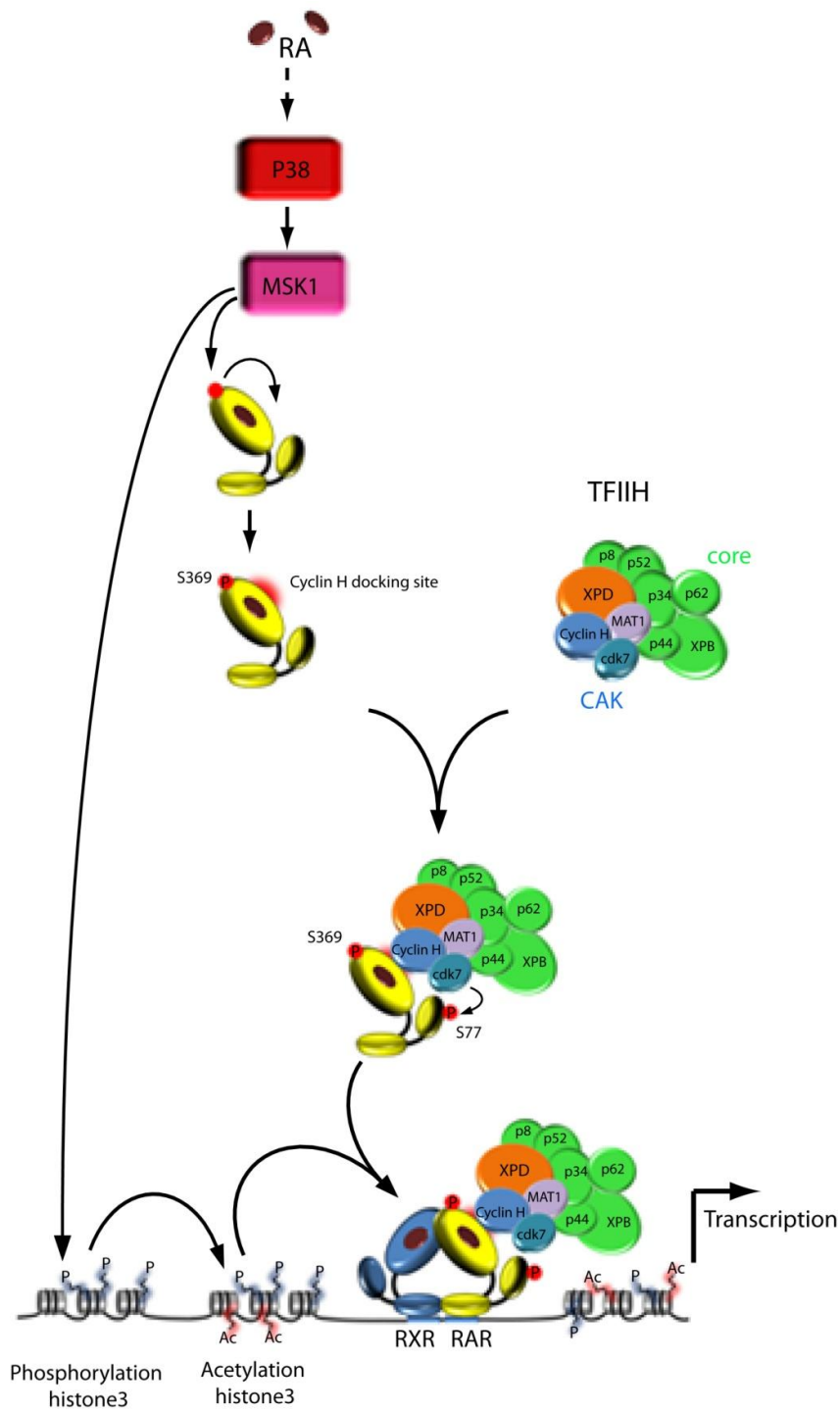


Figure 25: Cooperation of genomic and non-genomic effects in the initiation of transcription of RAR α target genes in response to RA. Adapted from (Bruck et al., 2009).

2. RARs phosphorylation and their subcellular localization

Generally, nuclear receptors display a nuclear localization. However, some of them such as AR, GR, and MR are cytoplasmic and translocate to a nuclei upon ligand induction.

Several processes control the nuclear localization of nuclear receptors among which phosphorylation processes. Indeed, recent results indicated that phosphorylation of specific sites enhances nuclear localization while phosphorylation of others increases nuclear export (Lombardi et al., 2008; Sun et al., 2007; Weigel and Moore, 2007a). Han *et al.* recently demonstrated that phosphorylation of the RAR γ NTD by p38MAPK induces the cytoplasmic localization of receptor (Han et al., 2009).

3. RARs phosphorylation and binding proteins with WW or SH3 domains

The phosphorylation site located in the NTD of RARs belongs to a proline-rich motif (PRM) (Figure 26).

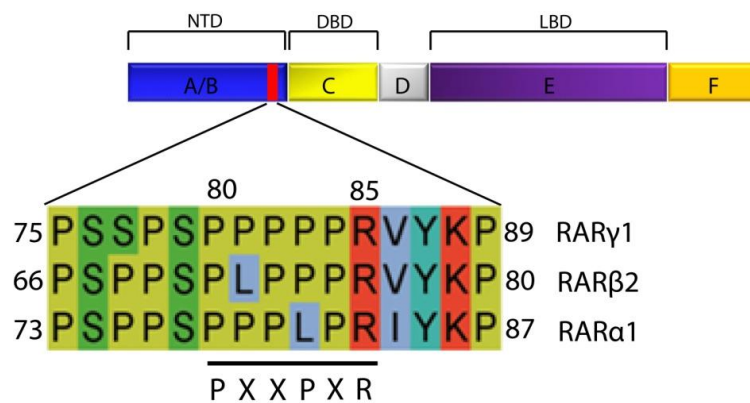


Figure 26: Amino acid sequence of the PRM of RAR γ 1, RAR β 2 and RAR α 1. Adapted from (Lalevee et al., 2010a).

Such motifs are well known to bind proteins with SH3 or WW domains. Moreover, phosphorylation of a serine residue located in PRMs has been shown to prevent or favorize interactions (Kay et al., 2000b; Macias et al., 2002; Sudol et al., 2001; Zarrinpar and Lim, 2000). Indeed, phosphorylation may involve cis-trans isomerization of the proline residues surrounding the phosphorylated serines, creating new specific recognition sites for interacting factors (Bao et al.,

2004). In this context the peptidyl-prolylisomerase Pin1, an important enzyme with a WW domain and involved in the regulation of signaling pathways, transcription and cell cycle progression (Nelson et al., 2006) has been shown to interact with the phosphorylated form of the NTD of RAR α (Brondani et al., 2005).

Recently, the group of Dr. Rochette-Egly identified and characterized vinexin β as a novel co-regulator interacting directly with the PRM of RAR γ (Bour et al., 2005b). Vinexin β is an actin-binding protein which plays a role in cytoskeleton organization, cell spreading and intracellular signaling. It is an adaptor composed of three SH3 domains without any enzymatic activity (Kioka, 2002). Only the third C-terminal domain of vinexin β (SH3-3) interacts with a consensus PxxPxR motif located in the PRM of RAR γ (Lalevee et al., 2010a) (Figure 26). Most interestingly, substitution of the second proline of the motif with a leucine, as in RAR α , abolishes the interaction and explains why vinexin β interacts specifically with the RAR γ subtype.

Vinexin β is present not only in the cytosol but also in the nucleus where it interacts with the non-phosphorylated form of RAR γ (Bour et al., 2005b). Then in response to RA, phosphorylation of serine 79 (the equivalent of S77 in RAR α), which is in the vicinity of the PxxPxR motif, induces the dissociation of vinexin β . According to recent unpublished results from the laboratory, phosphorylation of this residue would induce subtle changes in the conformation of the polyproline helix, decreasing its propensity to interact with the SH3 domain of vinexin β .

In fact, vinexin β is a repressor of RAR γ -mediated transcription. As vinexin β is undetectable in chromatin, Lalevée *et al.* proposed that it would sequester the non-phosphorylated RAR γ in an inactive state out of chromatin. The dissociation of vinexin β subsequent to the phosphorylation of the PRM would allow the recruitment of RAR γ to chromatin and thereby the activation of the target genes (Lalevee et al., 2010a).

Knowing that vinexin β is a scaffolding protein with three SH3 domains, which can interact with several proteins at the same time, the following model was proposed. Vinexin β and RAR γ belong to a multiprotein complex in which vinexin β interacts directly with the NTD of RAR γ via its third SH3 domain and indirectly with the LBD of RAR γ through two other SH3 domains and intermediary proteins (Lalevee et al., 2010a) (Figure 27).

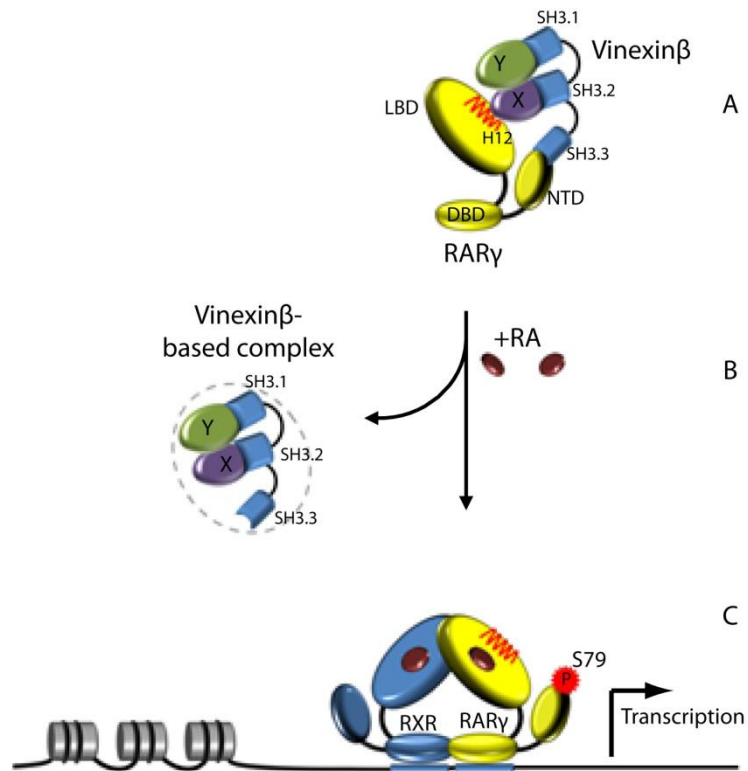


Figure 27: Model for the role of vinexin β in the control of RAR γ transcriptional activity.

A. In the absence of RA, the third SH3 domain of vinexin β (SH3.3) interacts with the non-phosphorylated N-terminal PRM of RAR γ . Through other two SH3 domains, vinexin β might also act as a scaffold linking the NTD to the LBD of RAR γ *via* protein complexes (exemplified as X and Y). Such a complex sequesters RAR γ out of chromatin, thereby impeding transcription. B. Upon RA addition, phosphorylation of the RAR γ PRM and the conformational changes of the LBD cooperate to induce the dissociation of the vinexin β -based complex. C. Once separated from vinexin β -based complex, phosphorylated RAR γ can dimerize with RXR and occupy the promoters of the target genes to initiate the transcription of RA-target genes. Adapted from (Lalevee et al., 2010a).

CHAPTER 5: IMPORTANCE OF ACTIN-BINDING PROTEINS WITH SH3 DOMAINS

The discovery that RARs can interact with actin-binding proteins such as vinexin β was new and rather unexpected. In fact, it is not so surprising as other proteins of the same vinexin family, and several other actin-binding proteins such as gelsolin have been shown recently to interact with several activators of transcription including nuclear receptors (Table 3) (Zheng et al., 2009a). Moreover, there is a growing evidence that actin and actin-binding proteins (ABPs) are present in nuclei and play an important role in key nuclear processes: chromatin remodeling, transcription, DNA repair, DNA replication and formation and maintenance of nuclear structure (Figure 28) (For review see (Castano et al., 2010)).

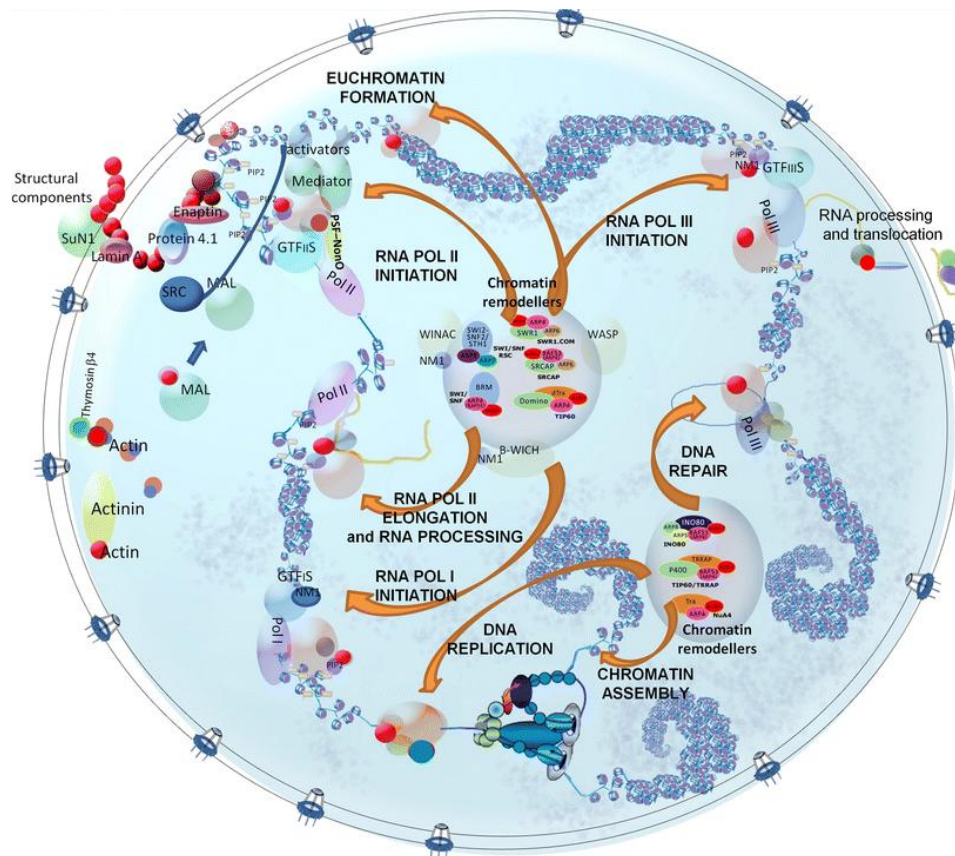


Figure 28: Model showing the actin, actin-binding proteins and actin complexes involved in chromatin remodeling, transcription initiation and elongation, DNA repair and replication. Actin and actin-binding proteins may function as key proteins bringing together various factors to form a network that can be used in several processes in the nucleus. Adapted from (Castano et al., 2010).

How ABPs regulate nuclear processes is not fully understood but they may function as adaptors recruiting actin, which is now known to have a structural and/or regulatory role with chromatin-remodeling complexes and the RNA polymerase machinery.

Actin-binding protein	Classes	Role in the cytoplasm	NR type association	NR effect	Direct/indirect association with the AR	Region
Gelsolin	Actin filament severing and capping protein	Involved in gel-to-sol transformations; severs and caps polymeric actin filaments; acts in the actin-scavenging system; inhibits actin polymerization	AR	Co-activator	Direct	LBD
Flightless I	Actin-remodeling proteins	Possess F-actin-severing activity	AR	Co-activator	Direct	
α-actinin 2	Bundling proteins	Functions as scaffolds for signaling intermediates that stimulate actin elongation; binding partners for ICAM-1	AR	Co-activator	Indirect	
α-actinin 4	Bundling proteins	Functions as scaffolds for signaling intermediates that stimulate actin elongation; binding partners for ICAM-1	ER VDR	Co-activator	Direct	
Vinexin α	adaptor protein	Promotes up-regulation of actin stress fiber formation	AR, ER α , ER β , GR	Co-activator		
Vinexin β	adaptor protein	Regulates cell spreading	RAR γ	Co-repressor	Direct	NH2-terminal
Supervillin	F-actin- and membrane-associated scaffolding protein	Regulates cell-substrate adhesion; organization of muscle co-stameres; stimulus-mediated contractility of smooth muscle and myogenic differentiation	AR	Co-activator	Direct	NH2- and COOH-terminal
Filamin	Cross-linking proteins	Cytoplasmic transport; membrane integrity; cellular adhesion	AR	Co-activator	Direct	Hinge
Filamin A	Cross-linking proteins	Cross-links actin filaments; recruits F-actin into extended networks	AR	Co-repressor	Direct	Hinge
Transgelin	Cross-linking proteins	Organizes actin filaments into dense meshworks	AR	Co-repressor	Indirect	LBD

Table 3: Actin-binding proteins interacting with Nuclear Receptors.

Adapted from (Zheng et al., 2009a).

According to recent studies NRs also interact with cytoskeleton proteins out of the nucleus and participate to their non-genomic effects. For example the androgen receptor has been shown to interact with filamin out of nuclei. As such, AR belongs to a multiprotein complex which is involved in regulation of cell migration (Castoria et al., 2011).

As all RARs contain a PRM in their NTD, the team speculated that they might interact not only with vinexin β but also with other actin-binding proteins with SH3 domains. As such proteins are generally adaptors, they might link RARs either to big nuclear complexes controlling transcription or to extranuclear signaling complexes.

Recently, the group identified in a yeast two-hybrid screening, a new binding partner of the NTD of RAR α , profilin IIA, which is also an actin-binding protein with an SH3-like domain. Therefore another aspect of my work was to focus on this new unconventional partner.

- PROFILIN

Profilin is a small (MW = 12-16 kDa) ubiquitous actin-binding protein, which was originally identified in calf spleen. Its principle role is to form a complex with actin monomers and to inhibit their polymerization (Carlsson et al., 1977). Up to date, profilins have been found in all studied eukaryotes and their cells, indicating that it is a fundamental actin-binding protein (Witke, 2004).

1. *Profilin Isoforms*

In mammals, five isoforms of profilin are known: profilin I, IIA, IIB, III and IV (Table 4) (Carlsson et al., 1977; Di Nardo et al., 2000; Honore et al., 1993; Hu et al., 2001; Obermann et al., 2005). While all isoforms of profilin are conserved in terms of function, overall fold and crystallized structures, their sequence identity is variable. For example, profilin I shares only 37 and 30% amino acid homology with profilins III and IV, respectively (Obermann et al., 2005; Witke, 2004).

However, there are several examples showing that in some species, profilin-deficiency can be rescued by reintroducing profilins from another species. Indeed, Rothkegel et al. (Rothkegel et al., 1996) demonstrated that plants profilin, which share only 22% sequence identity with bovine thymus profilin, can functionally substitute the endogenous mammalian profilin. Another study demonstrated that defects in cell shape, cytokinesis, and development of *Dictyostelium discoideum* profilin-deficient cells can be rescued by profilins I or II from maize (Karakesisoglou et al., 1996). However, isoforms within the same organism differ sufficiently and cannot complement each other. As an example, deletion of profilin II isoforms in mice, cause severe neurological abnormalities, despite the presence of profilin I (Witke, 2004).

Profilin I is expressed in various tissues except skeletal muscle (Witke et al., 1998). It shows diffuse cytoplasmic distribution and dot-like nuclear localization (Gieseemann et al., 1999). Profilin I is actively involved in the regulation and re/organization of the cytoskeleton and has been involved in the regulation of nonmuscle cell motility.

Profilin II is almost exclusively expressed in the central nervous system, but mRNAs encoding this isoform has been detected in kidney and muscle (Lappalainen, 2007). Profilin II can be alternatively spliced in two isoforms: profilin IIA and IIB. They share the first 107 amino acids but have different C-terminal domains. It was shown in mice that profilin IIA is dominantly expressed during embryogenesis at stages of rapid brain development (Di Nardo et al., 2000; Lambrechts et al., 2000), and mice deficient for this isoform have neurological defects (Witke et al., 2001). The minor IIB-isoform, similarly to the profilin encoded by Vaccinia virus (Machesky et al., 1994), is unique among profilins because it does not show any binding affinity to poly-L-proline. Interestingly, this particular profilin also has low affinity for actin, but exceptionally appears to bind tubulin (Di Nardo et al., 2000).

Profilins III and IV are both testis-specific (Braun et al., 2002; Hu et al., 2001; Obermann et al., 2005). They are expressed at various stages of spermatogenesis and are differentially regulated during postnatal testicular development. They interact with the actin cytoskeleton of developing male germ cells at distinct point locations. Their deficiency causes morphological abnormalities in the head of sperm and functional defects of acrosome in infertile male (Obermann et al., 2005).

2. Profilin structure

The structure of profilins has been solved by x-ray crystallography either complexed with β -actin (Schutt et al., 1993) or separately (Cedergren-Zeppezauer et al., 1994). It consists of a central seven-stranded anti-parallel β -pleated sheet and of 4 alpha helices: the N- and C-terminal α -helices (named helix 1 and helix 4, respectively) are closely packed on one side while the two short α -helices (helix 2 and helix 3) are on the opposite side (Cedergren-Zeppezauer et al., 1994; Schutt et al., 1993) (Figure 29).

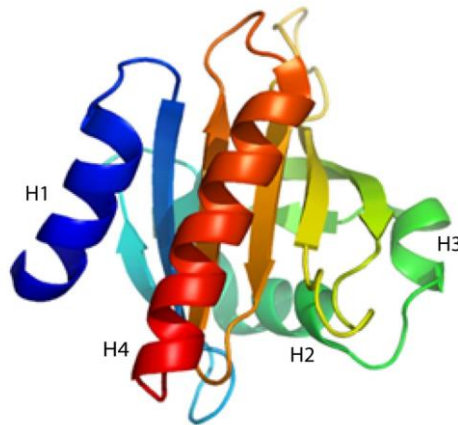


Figure 29: The three-dimensional structure of mouse profilin IIA. Helices are shown as ribbons and labelled from H1 to H4. Adapted from (Kursula et al., 2008) pdb 2v8c.

In mammalian profilin, strands 5 and 6 (K90-T97) are connected with a loop, which protrudes from the surface of the protein (Schutt et al., 1993) and is positioned close to an actin-binding site. Remarkably, profilins also depict an SH3-like domain, which is composed of the N- and C-terminal α -helices.

3. Profilin interaction domains

In general, profilins were found to interact with three classes of ligands: (i) actins (Schutt et al., 1993) including actin-related proteins (ARPs) (Machesky et al., 1994), (ii) poly-L-proline (PLP) stretches (Mahoney et al., 1997) and (iii) phosphatidylinositol lipids (Lassing and Lindberg, 1988) (Figure 30).

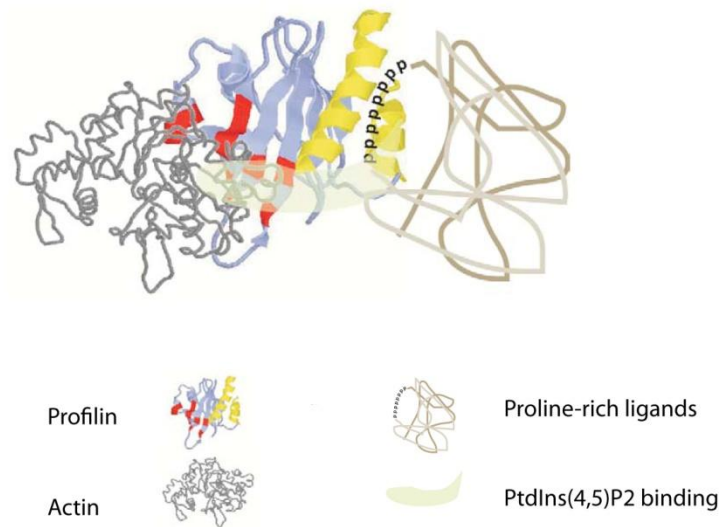


Figure 30: Structure of profilin complexes. Profilins form complexes with actin, proline-rich ligands and phosphatidylinositol (4,5)-bisphosphate [PtdIns(4,5)P₂]. The actin-binding sites (red) and poly-L-proline (yellow) are distinct, while the PtdIns(4,5)P₂-binding surface (light green) is more spread out over the surface of the molecule and overlaps with both actin-binding and poly-L-proline binding. Adapted from (Witke, 2004).

- Actin-binding site

The actin-binding site of profilin consists of amino acid residues located in α -helices 3 and 4, β -strands 4, 5, 6 (Figure 31). It also consists of the extended loop regions between β -strands 5 and 6, as a double-deletion of two residues (P96 and T97) within this loop, lowers the interaction with actin (the K_d value changed from 0.37 μ M to 1.15 μ M (Hajkova et al., 1997)).

All these residues make contacts with residues in subdomains 1 and 3 at the barbed end of actin monomers (Cedergren-Zeppezauer et al., 1994; Schutt et al., 1993). However they can also bind

the most distal subunit of the fast-growing end of filamentous actin (Gutsche-Perelroizen et al., 1999) as well as actin related proteins (ARPs) (Mullins et al., 1998) and postsynaptic scaffolding protein gephyrin (Giesemann et al., 2003).

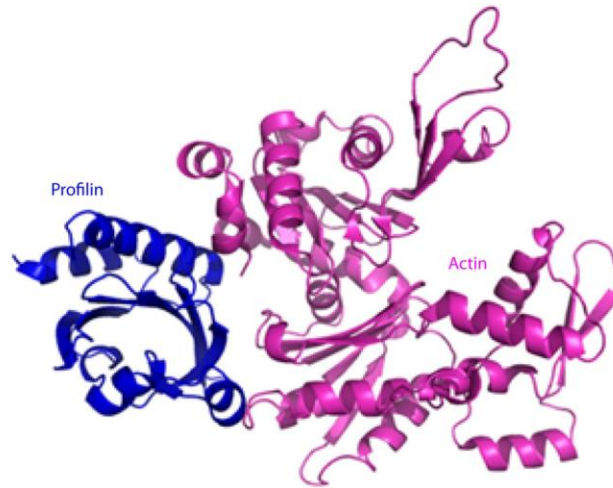


Figure 31: Structure of bovine beta-actin(pink)-profilin(blue) complex. Adapted from (Chik et al., 1996) pdb 1hlu.

- Polyphosphoinositide lipid binding site and association with plasma membrane

Profilin has two phosphatidylinositol-4,5-bisphosphate (PIP₂) interaction sites: one partially overlapping with the poly-L-proline binding surface and the other one with the actin-binding surface (Jockusch et al., 2007; Lambrechts et al., 2002; Lappalainen et al., 2007; Skare and Karlsson, 2002) (Figure 30). The affinity for PIP₂ is variable between the profilin isoforms, with profilin I displaying a higher affinity than profilins IIA and IIB (Lambrechts et al., 2000).

The interaction of profilin with PIP₂ mediates its association to the plasma membrane. Indeed, depletion of membrane PIP₂ levels results in a translocation of profilin from the membrane to the cytosol. Remarkably, upon restoration of PIP₂ plasma membrane levels, profilin translocates back to the membrane fraction, suggesting that phosphoinositide metabolism plays a role in the localization of profilin (Ostrander et al., 1995).

- Poly-L-Proline binding site

Binding of poly-L-proline involves the N- and C-terminal α -helices of profilins (Figure 32), which form a hydrophobic and aromatic core (SH3-like domain). In profilin I, this domain consists of the side chains of residues W3, Y6, W31, H133, L134 and Y139 (Bjorkegren et al., 1993; Cedergren-Zeppezauer et al., 1994; Mahoney et al., 1997; Mahoney et al., 1999; Schutt et al., 1993). In profilin IIA it consists of residues Y7, N10, Y134 and F140 (Haikarainen et al., 2009). It has been suggested that this difference in amino acid composition would be at the basis of the higher affinity of profilin IIA for poly-L-proline ligands (Lambrechts et al., 1995; Lambrechts et al., 1997).

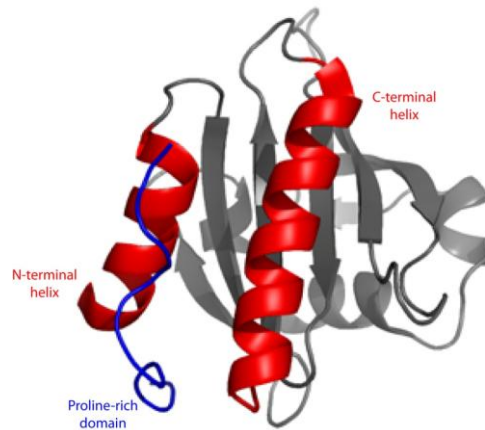


Figure 32: Mouse profilin IIA in complex with proline-rich domain (blue). Binding to proline-rich domain involves the N- and C-terminal α -helices (red) of profilins. Adapted from (Kursula et al., 2008) pdb 2v8c.

Initially, the ability of profilin to binds poly-L-proline was widely used for the purification of profilin and profilin:actin-complex by affinity chromatography on poly-L-proline (Celis, 2006; Lindberg et al., 1988). Now, the poly-L-proline binding activity is considered as an important feature of profilin and several proline-rich ligands have been identified. The first one to be identified was the vasodilator-stimulated phosphoprotein (VASP) (Reinhard et al., 1995), which is a component of focal adhesions and is thought to regulate actin polymerization (Krause et al., 2003; Walders-Harbeck et al., 2002). Several other proline-rich ligands have been identified (Jockusch et al., 2007; Witke, 2004), with a variety of proline-rich sequence-motifs with eight to ten prolines, either in continuous sequence or interrupted by single glycines (Schlüter et al., 1997). It is also worth to note that the binding of

poly-L-proline by profilin might occur in either polypeptide backbone orientation (Mahoney et al., 1997; Mahoney et al., 1999).

4. Cellular localization of profilin

Basically, profilins are enriched in cellular areas characterized by high actin dynamics such as ruffles, lamellipodia, stress fibers and focal adhesions. Profilins were also found at the surface of *Listeria monocytogenes* after infection of host cells cytoplasm (Buss et al., 1992; Geese et al., 2000; Grenklo et al., 2004; Mayboroda et al., 1997; Skare et al., 2003).

Because of their ability to interact with membrane-bound phospholipids, profilins have also been observed in close association with a variety of membrane organelles such as Golgi-derived vesicles (Dong et al., 2000; Finger and Novick, 1997) and endocytotic machinery (Gareus et al., 2006).

Surprisingly, profilins have been reported to be also present in the nucleus. Indeed, profilin I has been detected in nuclei of human fibroblasts (Skare et al., 2003), rat kidney epithelial cells (Lederer et al., 2005a), bovine oocyte germinal vesicles and early embryos (Rawe et al., 2006). In addition, Birbach *et al* showed that profilin II accumulates in the nucleus of hippocampal neurons in response to NMDA receptor signaling (Birbach et al., 2006). Finally, the testis-specific profilin III was found in the nucleus of testicular germ cells, complexed with ArpM1 (actin-related protein M1).

5. Profilin functions

- Role in actin dynamics and cell signaling

The main function of profilins is to regulate the dynamics of actin assembly and organization. Indeed, they are key factors for actin filaments treadmilling, which is a dynamic process of actin turn over *in vivo*, primarily by monomer addition and growth at the fast-growing (barbed) ends and by monomer loss and shortening from the slow-growing (pointed) ends (Littlefield et al., 2001).

Profilins sequester actin monomers in the absence of free actin filament barbed ends and promote the assembly of ATP-actin monomers to filaments when barbed ends are available (Pantaloni and Carlier, 1993) (Figure 33). Then via interactions with polyproline-rich proteins (formins, Ena/VASP, WASP/WAVE), profilins localize monomers of ATP-actin to the sites of rapid actin filament assembly in cells (Reinhard et al., 1995; Evangelista et al., 1997).

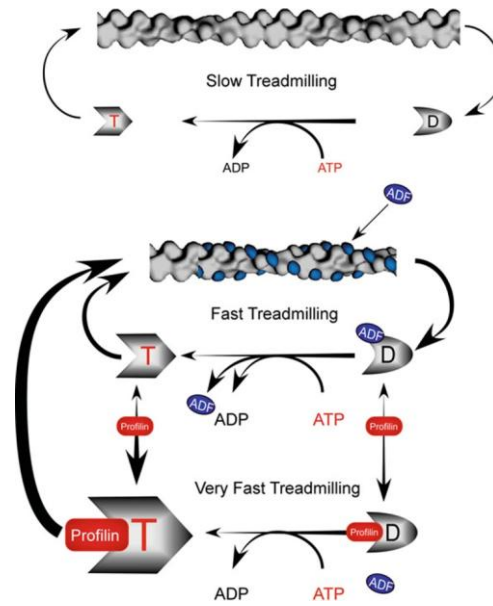


Figure 33: Regulation of actin filament treadmilling by ADF and profilin. *Top panel:* basic slow treadmilling of pure actin assembled at a steady state in ATP. Monomer-polymer exchange occurs at both ends of the filament (ADP-actin and ATP-actin labeled as D and T respectively); nucleotide exchange takes place on monomeric actin only. *Bottom panel:* enhancement of treadmilling by a synergistic action of ADF/cofilin and profilin. ADF (shown in *blue*) binds to ADP-F-actin and causes a structural destabilization of the actin-actin interactions in the filament, which results, at steady state, in a large increase in the rate of dissociation of ADP-actin from the pointed ends. Profilin binds preferentially to ATP-G-actin, accelerates nucleotide exchange on G-actin and forms a complex with ATP-G-actin that associates to barbed ends. Addition of profilin to F-actin at steady state in the presence of ADF thus shifts all binding equilibrium toward the predominant profilin-ATP-G-actin, thus facilitating the vectorial turnover of actin filaments. Adapted from (Carrier, 2010).

In addition, through their ability to bind PIP₂, profilins are coupled to ligand-induced transmembrane-receptor signaling (Lindberg et al., 2008; Sohn and Goldschmidtclermont, 1994) and thus connect closely signaling pathways and actin organization (Ridley et al., 2003). Indeed, activation of transmembrane receptors cause dramatic remodeling of cytoskeleton with rapid formation of actin filaments (Chinkers et al., 1979). It has been proposed that fluctuations in the concentration of PIP₂ at the membrane might cause profilin shuttling between membranes and cytosol (Figure 34). Therefore, profilin could be a potent mediator of external signals to microfilaments (Machesky and Poland, 1993; van Rheenen et al., 2007). Thus, through its participation to the formation of actin filaments, profilin is involved in membrane associated processes such as lamellipodial protrusion during locomotion, cell adhesion and spreading cytokinesis and morphogenesis (Jockusch et al., 2007).

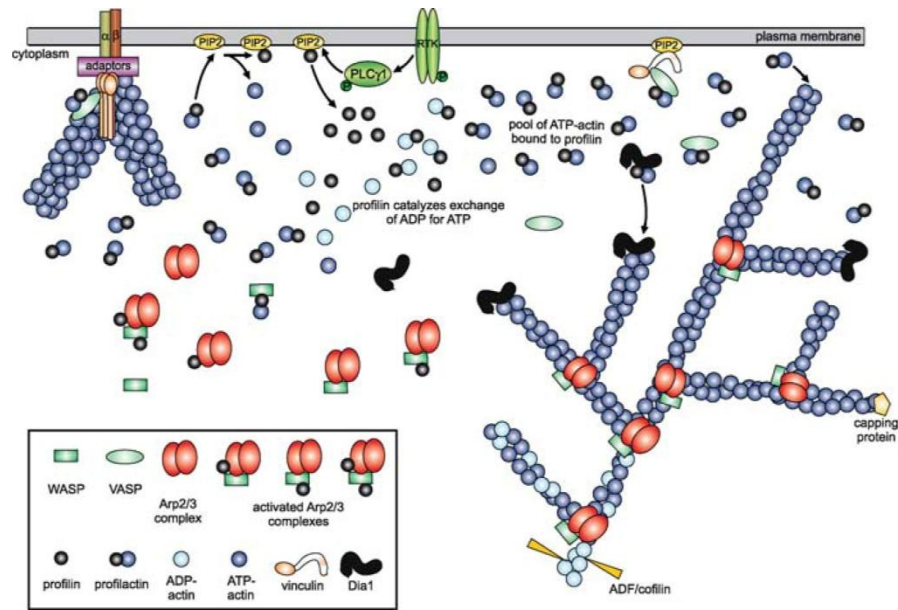


Figure 34: Multiple functional connections of plasma membrane associated and cytoplasmic profilin. The release of profilin from membrane is regulated by the level of PIP₂ and determines the formation of profilin-G-actin complex. Released from the membrane, profilin (*center*) bind ATP-G-actin and adds G-actin to nascent actin filaments and participates in the generation of actin filaments as needed for adhesion complexes (*left*) and lamellipodial actin networks (*right*). Adapted from (Jockusch et al., 2007).

Finally, several molecular genetic studies demonstrated that profilin is important for proper cell function and viability in unicellular and multicellular eukaryotes. Indeed, knockout of profilin drastically impaired cell growth in *Saccharomyces cerevisiae* (Haarer et al., 1990) and led to cell death in *Schizosaccharomyces pombe*, *Dictyostelium discoideum* and *Drosophila melanogaster* (Balasubramanian et al., 1994; Haugwitz et al., 1994; Verheyen and Cooley, 1994). Profilin is also crucial for embryonic development as mouse embryos homozygous for profilin I disrupted gene (profilin (-/-)) die even before the development of the blastula at the two-cell stage. Concerning heterozygous embryos, (profilin (-/+)), they survive but display a reduced viability (Witke et al., 2001).

- Profilin in the nucleus

In addition to its well established cytoplasmic localization, profilin has been found in the nucleus and reported to be involved in regulation of transcription (Lederer et al., 2005a). Indeed profilin reduces repressive transcription activity of p42POP-Myb-related transcription factor.

Moreover, profilin was found to accumulate in subnuclear structures such as gems, Cajal bodies and Speckles (Birbach et al., 2006; Giesemann et al., 1999; Rawe et al., 2006; Skare et al., 2003). This localization of profilin in pre-mRNA processing components, in addition to its interaction with the survival of motor neuron (SMN) protein, which is important in the formation of small nuclear ribonucleoproteins (snRNPs), suggests a role for profilin in the maturation of mRNA.

OBJECTIVES

The main focus of the group of Dr. Cécile Rochette-Egly over the last several years is to understand the role of post translational modifications, mainly phosphorylations, on the activity of nuclear retinoic acid receptors. In that context, the group

- highlighted that RARs become rapidly phosphorylated in response to RA
- identified the phosphorylated residue
- demonstrated that the RA-induced phosphorylation of RARs involves the p38MAPK pathway
- Evidenced that phosphorylation is crucial for RAR transcriptional activity (see Figure 35)

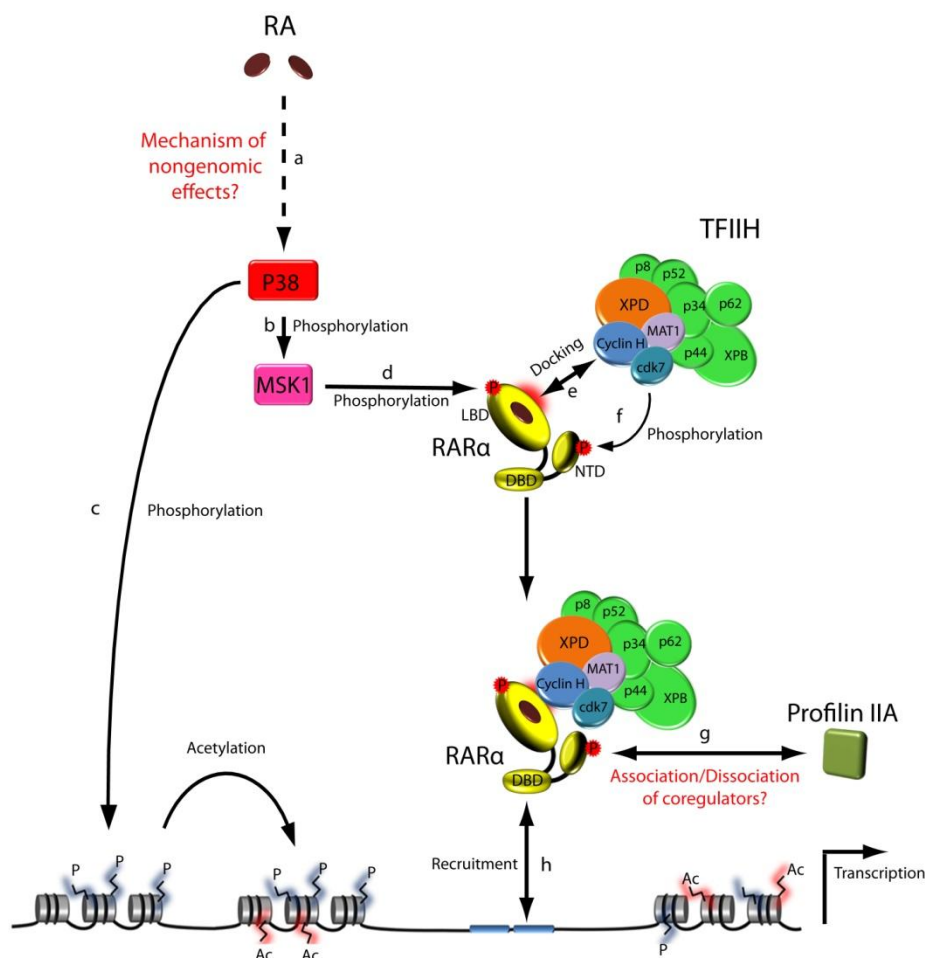


Figure 35: In response to RA, p38MAPK (a) and MSK1 (b) are activated. MSK1 phosphorylates histones at H3S10 (c) and RAR α at a serine located in the LBD (d). Subsequently, the cyclin H subunit of the CAK subcomplex of TFIID is recruited to an adjacent domain (e), allowing the formation of a RAR α /TFIID complex and the phosphorylation of the NTD by the cdk7 kinase (f). Phosphorylation of NTD might promote association/dissociation of coregulators (g). Finally, RAR α phosphorylated and associated with TFIID and is recruited to response elements located in the promoter of target genes (h).

Such results raised several questions:

- **How RA activates the p38MAPK pathway?** As the RA-induced activation of p38MAPK is rapid and transcriptionnally independent, the hypothesis was that this effect is non-genomic, as already described for other nuclear receptors (Marquez et al., 2006; Matthews et al., 2008; Norman et al., 2004)

- **How phosphorylation controls RAR-mediated transcription?** As the last phosphorylation event of the cascade concerns a serine residue located in a proline rich motif of the NTD, one could speculate that phosphorylation of this residue controls the association/dissociation of coregulators with SH3 domains.

Recently, the group identified in a yeast two-hybrid screening, profilin IIA as a new binding partner of the NTD of RAR α . Profilin IIA is an actin-binding protein, which as several other proteins with SH3 domains, interacts with proline-rich motifs (PRMs) of a huge variety of proteins (Gareus et al., 2006; Mahoney et al., 1999). Most importantly, profilin IIA has been identified in the nucleus of several cell types and shown to interact with transcription factors (Lederer et al., 2005a). The precise mechanism by which profilin IIA regulates transcription is still ill-defined. However, one can suggest that, similarly to vinexin β (Lalevee et al., 2010a), profilin IIA functions as an adaptor, recruiting actin and/or other nuclear proteins with a structural and/or regulatory role within chromatin and/or the transcriptional machinery (Bettinger et al., 2004; Wang et al., 2006).

In this context, the objectives of my thesis have been to attempt to answer these two questions, i.e. decipher at the molecular level:

- **How RARs activates the p38MAPK pathway through non-genomic effects**
- **How profilin IIA interacts with RAR α and controls its transcriptional properties**

RESULTS

1. NOVEL NON-GENOMIC EFFECTS OF RA: ACTIVATION OF THE P38MAPK PATHWAY VIA A MEMBRANE-ASSOCIATED POOL OF RAR α (PUBLICATION 1)

Recent results from the group demonstrated that RA rapidly and transiently activates the p38MAPK pathway in several cell lines such as MCF7, HeLa, MEF and F9 cells (Bruck et al., 2009). By analogy with other nuclear receptors we hypothesized that it occurs through a non-genomic effect.

- RA ACTIVATES P38MAPK VIA G α Q PROTEINS AND A POOL OF RAR α PRESENT IN MEMBRANE LIPID RAFTS

The first question was what is upstream of p38MAPK. First of all, we found that Rho-GTPases such as Rac and Rho, which are upstream of p38MAPK, were also activated in response to RA (Publication1, Figures 1e and 1f). Then, as Rho-GTPases activation involves upstream G proteins alpha Q (G α q) that interact with scaffolding proteins in membranes (Mizuno and Itoh, 2009; Sugawara et al., 2007), we analyzed whether G α q proteins are involved in the rapid RA-induced activation of the p38MAPK pathway by using the siRNA strategy. No activation of p38MAPK was observed after knockdown of G α q (Publication 1, Figures 2a and 2c), indicating that the rapid activation of the p38MAPK pathway by RA involves G α q.

Then we asked whether the RA-induced activation of p38MAPK is RAR-dependent. Taking advantage of different cell lines invalidated or knockdown for one specific RAR subtype we demonstrated that the activation of p38MAPK in response to RA, involves specifically the RAR α subtype (Publication1, Figures 1b, 2b and 2c). Moreover, in MEFs knockout for the three RARs, p38MAPK was restored only upon re-expression of RAR α WT (Publication1 Figures 1c and 1d). Thus the rapid activation of p38MAPK by RA appears to involve RAR α , in addition to G α q.

Remarkably, G α q proteins as well as most signal components are concentrated in specific highly ordered membrane micro domains termed “lipid rafts” (Pike, 2003; Simons and Toomre, 2000), which orchestrate intracellular signaling pathways and thus are considered as signaling centers. Therefore, we investigated whether these membrane domains contain RAR α . We isolated lipid rafts from MCF-7 cells and found that they do contain RAR α (but not RAR γ or RAR β) in addition to flotillin-2, a marker of lipid rafts, and signaling proteins such as Rock-2, PKC σ and G α q (Publication 1 Figure 3b). However, the amount of RAR α present in lipid rafts was very low compared with the amount of RAR α present in nuclei as assessed in immunofluorescence experiments, (Publication 1, Figure 3d). Indeed, only low amounts of RAR α were found to colocalize with Flotillin-2 out of nuclei

(Publication 1, Figure 3f and 3g). Collectively, these results converge to a novelty in the field, i.e. a small population of RAR α is present out of nuclei in membrane lipid rafts.

Then, the next question was which domain/region/sequence is responsible for targeting RAR α to membranes. Given that the three RAR subtypes differ essentially in their NTD, one can speculate that this domain might specifically target RAR α at the membrane. To verify this hypothesis we took advantage of F9 cells reexpressing RAR α WT or deleted of the NTD (RAR α Δ NTD) in a RAR α null background (Rochette-Egly et al., 2000). Remarkably, RAR α Δ NTD could not be detected in lipid rafts, indicating that the NTD would be involved in targeting RAR α to membranes (Publication 1, Figure 3h).

- RAR α INTERACTS WITH G α Q *IN VITRO* AND *IN VIVO*

Given that G α q proteins colocalize with RAR α in lipid rafts, we investigated whether the two proteins can interact with each other. We found that, *in vitro*, recombinant RAR α and G α q interact with each other in GST pull down and coimmunoprecipitation experiments. Remarkably, the interaction was increased in response to RA. Endogenous RAR α and G α q also interacted *in vivo* in immunoprecipitation experiments performed with lipid rafts (Publication1, Figures 3a-c).

However, due to the low amounts of RAR α in lipid rafts, the RAR α /G α q complexes were rather difficult to detect. Therefore we set up a “Proximity Ligation Assay” (PLA), which can reveal transient interactions between endogenous proteins even when present at very low levels (Soderberg et al., 2006). Rabbit anti-RAR α and mouse anti-G α q antibodies were used, followed by species-specific secondary antibodies, called PLA probes, each attached with a unique short DNA strand. When the PLA probes are in close proximity, the DNA strands can be joined through the addition of a circle-forming DNA oligonucleotide that can be amplified using a polymerase. Then the amplified products are revealed with labeled complementary oligonucleotide probes and are easily visible as bright red spots under a fluorescence microscope. This technique allowed us to visualize *in situ* a rapid and transient increase (10-15 min after RA addition) in the number of RAR α /G α q complexes. Remarkably, the complexes were found out of the nuclei, confirming that the non-genomic effects of RA involve a pool of extra nuclear RAR α (Publication1, Figure 5). It is important to note that the increased interaction between RAR α and G α q occurred specifically in response to RA. Indeed, in response to EGF, which also activates p38MAPK through G α q, no interaction between RAR α and G α q could be detected (Publication1, Figure 7a-g).

- RAR α INTERACTS WITH G α Q ONLY IN CELLS THAT RESPOND TO RA VIA THE ACTIVATION OF P38MAPK

Then the question was whether the RA-induced interaction between RAR α and G α q was a general phenomenon.

In fact, the formation of RAR α -G α q complexes was observed in epithelial and fibroblastic cells, which respond to RA by the activation of p38MAPK. However, in other cells, such as neuronal cells (human neuroblastoma SH-SY5Y cell line), RAR α , though present in lipid rafts, doesn't interact with G α q in response to RA and p38MAPK is not activated (Figure 36). Of note is that in neuronal cells RA rather activates the Erk pathway through Src and PI3K (Chen and Napoli, 2008; Dey et al., 2007; Masia et al., 2007; Pan et al., 2005; Zanotto-Filho et al., 2008). Thus, depending on the cell type, it appears that RA can activate various MAPK pathways via different membrane-associated complexes.

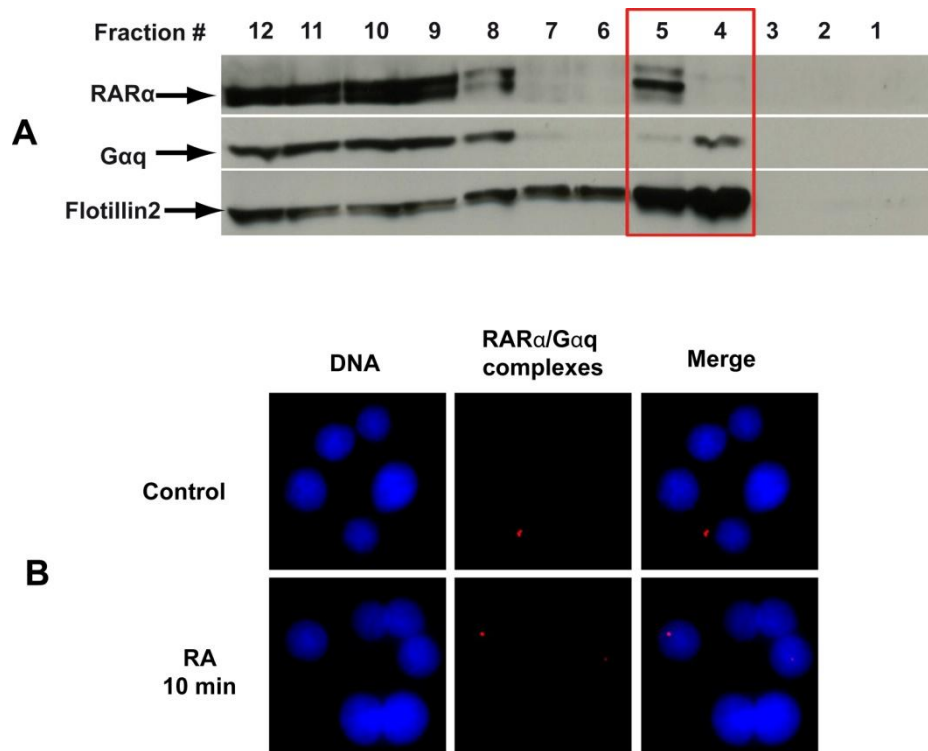


Figure 36: A. Immunoblotting analysis of the different gradient fractions from SH-SY5Y cells, showing that RAR α is present with Flotillin-2 and G α q in lipid rafts. B. Analysis of RAR α /G α q complexes in SH-SY5Y cells by immunofluorescence microscopy in combination with in situ proximity ligation assay (PLA).

2. THE NON-GENOMIC EFFECTS OF RA CONTROL THE GENOMIC ONES (Publication 1)

Given that RARs are basically ligand-dependent regulators of gene transcription, we asked whether the actors of the non-genomic effects, i.e. *Gαq* and the downstream p38MAPK/MSK1 pathway, cross-talk with the genomic ones.

Remarkably, knockdown of *Gαq*, p38MAPK and MSK1 decreased the RA-induced expression of several RA-target genes, as well as the antiproliferative action of RA (Publication1, Figure 9). Such results highlight the importance of the *Gαq*/p38MAPK/MSK1 pathway and thus of the non-genomic effects of RA for the genomic effects, i.e., RAR-target genes expression and growth arrest. Corroborating this conclusion, we found that in cells that are resistant to the antiproliferative effect of RA and exemplified by the human *erbB-2* positive breast cancer cells, BT474, SKBR3, MDA-MB453 and MDA-MB361 cells no interaction could be detected between RAR α and *Gαq* either in the absence or presence of RA and p38MAPK was not activated (Publication1, Figure 8).

Conclusion

We highlighted a novel unconventional localization of RAR α in membrane lipid rafts. We also demonstrated that this membrane pool interacts with *Gαq* proteins in response to RA and is responsible for the non-genomic effects of RA, i.e. the activation of the p38MAPK pathway. The other novelty is that these non-genomic effects are required for genomic ones.

3. PROFILIN IIA, A NOVEL COREGULATOR OF RAR α (publication 2)

The main consequence of the non-genomic effects of RA, i.e. the activation of the p38MAPK/MSK1 pathway, is a phosphorylation cascade targeting RARs. This cascade starts with the phosphorylation of the LBD by MSK1 (downstream of p38MAPK), and ends with the phosphorylation by cdk7/cyclin H of another serine residue, located in a proline-rich motif (PRM) of the NTD. Phosphorylation of this second residue proved to be crucial for the transcriptional activity of RARs, but the question is how.

Now it is increasingly evident that phosphorylations induce subtle conformation changes of adjacent domains (Bao et al., 2004) or the cis-trans isomerization of adjacent proline residues. The result is the creation of new recognition sites for interacting factors (Bao et al., 2004). Thus a significant effort in the laboratory has been made to identify and characterize co-regulators that interact directly with the PRM of RARs in a phosphorylation-dependent manner. Such an effort led to the discovery, in yeast two-hybrid screenings, of new coregulators with SH3 domains: Vinexin β for the RAR γ subtype (Lalevee et al., 2010a), and profilin IIA for RAR α . During my thesis I deciphered the mechanism and the relevance of the RAR α /profilin IIA interaction.

- PROFILIN IIA INTERACTS WITH THE N-TERMINAL PRM OF RAR α BUT INDEPENDENTLY OF ITS PHOSPHORYLATION

In a first step, the data obtained by yeast two-hybrid screening were corroborated in GST pull down and coimmunoprecipitation experiments using recombinant WT or mutated proteins (Publication 2, Figure 2A). These experiments confirmed that profilin IIA interacts specifically with the RAR α subtype and not with RAR β or RAR γ . We also deciphered further the mechanism of the interaction and demonstrated that it involves the PRM of RAR α located in the NTD and the SH3-like domain of profilin IIA (Publication 2, Figure 2B-D).

The PRM of RAR α involved in the interaction with profilin IIA contains a serine residue (S77), which can be phosphorylated *in vitro* and *in vivo*. Therefore we aimed at investigating whether phosphorylation of this residue modulates the interaction as previously described for RAR γ /vinexin β . In fact, coimmunoprecipitation experiments revealed that profilin IIA interacts as efficiently with RAR α , whatever S77 is substituted with a glutamic acid (RAR α S77E) or an alanine (RAR α S77A), which mimic the phosphorylated and non-phosphorylated forms respectively (Publication 2, Figure

3A). Moreover, the interaction was not affected upon RA addition, which induces RAR α phosphorylation (Publication 2, Figure 3B-C).

Then by using Surface Plasmon Resonance (SPR) we measured the equilibrium affinity of the interaction, using GST-profilin IIA and synthetic peptides corresponding to the proline-rich motif of RAR α . The use of peptides in which S77 is phosphorylated confirmed that phosphorylation does not affect the affinity (Publication 2, Table1).

- PROFILIN IIA INTERACTS WITH RAR α IN NUCLEI

Profilin IIA is an actin-binding protein, which is not expressed in all cell types. Indeed, profilin IIA is well known to be expressed mainly in brain and neuronal cells (Birbach, 2008; Michaelsen et al., 2010). Accordingly, in immunoblotting experiments, we detected significant levels of profilin IIA in human neuroblastoma cells (SH-SY5Y cell line) and mouse hippocampus cells (HT22 cell line) (Publication 2, Figure 4A). Interestingly, significant levels of profilin IIA were also detected in mouse embryonic fibroblasts and human breast cancer cell lines (MCF7 and SKBR3 cell lines) (Publication 2, Figure 4A). In contrast, profilin IIA was hardly detected in mouse embryocarcinoma cells (F9 and P19 cell lines) and no profilin IIA was found in human acute promyelocytic cells (NB4 cell line), (Publication 2, Figure 4A).

In immunofluorescence experiments, profilin IIA was detected mainly in the nucleus (Publication 2, Figure 4B) where it colocalized with RAR α (Figure 5A). Therefore we investigated whether endogenous profilin IIA and RAR α interact with each other in nuclei, using the proximity ligation assays (PLA) described above, which allows the detection *in situ* of interacting endogenous proteins. RAR α /profilin IIA complexes were seen in the nuclei of MCF7 cells and MEFs (Publication 2, Figure 5B). The number of these complexes did not change after RA addition up to 1 hour, in line with the absence of regulation of the interaction upon RAR α phosphorylation.

Altogether these results indicate that profilin IIA interacts with RAR α in nuclei, independently of RAR α phosphorylation.

- PROFILIN IIA AND RAR α : ROLE IN THE TRANSCRIPTION OF RAR α TARGET GENES

Given that profilin IIA interacts with RAR α in the nuclei of MCF7 cells and MEFs, one could speculate that this actin-binding protein is involved in the transcription of RA target genes. Corroborating this hypothesis, we found that knockdown of profilin IIA decreases the RA-induced

expression of several genes as assessed by qRTR-PCR (Publication 2, Figure 6). Moreover, in ChIP experiments, profilin IIA was recruited with RAR α to the promoter of these genes. Finally, ChIP western experiments revealed that profilin IIA coimmunoprecipitates with RAR α in chromatin (Publication 2, Figure 7).

Conclusion

We characterized a new coregulator of RAR α , profilin IIA, which is an actin-binding protein. Profilin IIA interacts with the N-terminal proline-rich motif of RAR α but independently of its phosphorylation. The interesting point is that profilin IIA is present in chromatin and is involved in the transcription of some RA-target genes. However the *in vivo* relevance of the RAR α /profilin IIA interaction (in cell differentiation/proliferation) remains to be investigated.

4. NEW UNCONVENTIONAL ROLE OF RAR α IN CELL ADHESION (UNPUBLISHED RESULTS)

- RAR α KNOCKOUT CELLS ARE DEFICIENT IN ADHESION

Then the challenge was to investigate the role of RAR α (with profilin IIA) in the RA response. As mammal models are quite complex, we selected mouse embryonic stem (ES) cells, which differentiate into neurons after RA addition, recapitulating early stages of mouse embryogenesis (Bibel et al., 2004b). These cells are an experimental paradigm and are extensively used as a model to investigate RA signaling *in vitro*. ES cells express the different RAR subtypes and ES cells either WT or invalidated for the different RARs are available in the laboratory (Al Tanoury *et al*, manuscript in preparation). Most interestingly, disruption of the whole RAR α gene (RAR α ^{-/-} cells) did not affect the ability of ES cells to commit into neuronal lineages after RA treatment. Indeed, RAR α ^{-/-} cells have kept their ability to become neural progenitors characterized by β -tubulinIII (Figure 37f). They have also kept their ability to develop a dense neuritic network within 2-3 days after dissociation and plating of embryonic bodies (Figure 37 c and f). This is in contrast to the targeted disruption of the whole RAR γ gene (RAR γ ^{-/-} cells) that severely blunted the RA response so that neurons with fine and long processes were almost absent (Figure 37b,e) (Al Tanoury *et al*, manuscript in preparation).

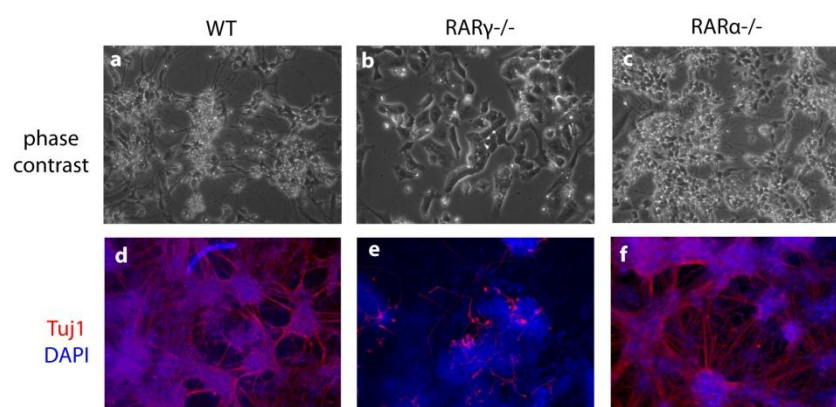


Figure 37: WT, RAR γ ^{-/-} and RAR α ^{-/-} mouse ES cells were compared for their ability to differentiate into neuronal cells in response to RA as assessed by immunofluorescence analysis of β tubulin III (TuJ1).

However we found that $RAR\alpha^{-/-}$ cells (and not $RAR\gamma^{-/-}$ cells) were severely impaired in adhesion. Indeed differentiated neurons were elongated but did not adhere efficiently to the substrate. Moreover, the undifferentiated cells did not adhere and did not spread on laminin-coated coverslips as assessed by spreading-adhesion assay (Figure 38). Indeed, while WT ES cells are fast well-spreading cells, $RAR\alpha^{-/-}$ cells remain compact and round, without substantial spreading.

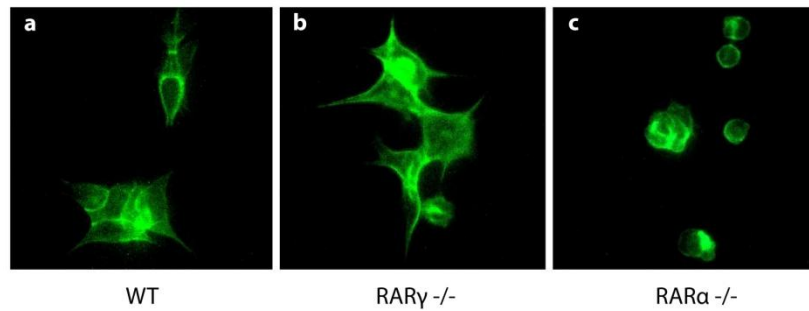


Figure 38. Spreading-adhesion assay. Mouse ES cells (WT, $RAR\alpha^{-/-}$ or $RAR\gamma^{-/-}$) were allowed to adhere for 3 hours onto laminin-coated coverslips and then fixed and stained for F-actin.

- A NOVEL UNCONVENTIONAL LOCALIZATION OF RAR α IN THE CYTOSOL OF NEURONAL AND FIBROBLASTIC CELLS

Unexpectedly, in immunofluorescence experiments performed with our highly specific purified rabbit polyclonal antibodies (Buchanan et al., 2011), we observed that RAR α is present in the cytosol of ES cells either pluripotent (Figure 39a-c) or differentiated into neurons (Figure 39d-f).

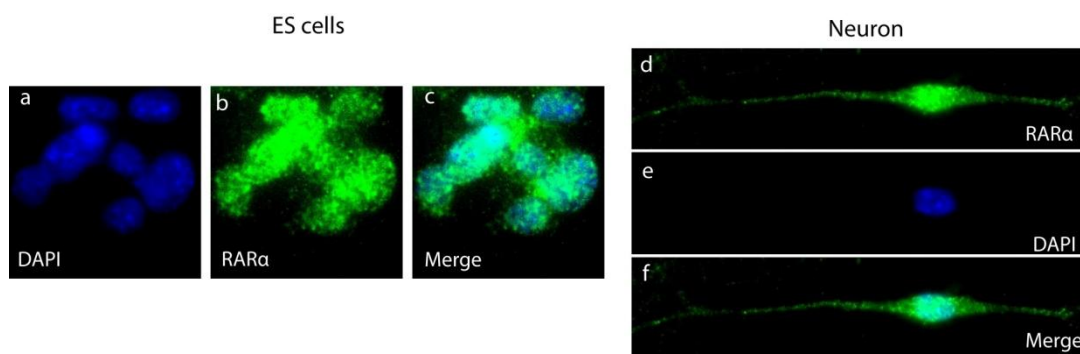


Figure 39: Nuclear and cytosolic localization of RAR α . Immunofluorescence experiments showing that RAR α is present in nuclei and also in the cytosol of mouse ES cells either undifferentiated or differentiated into neurons.

Remarkably, RAR α was also detected in the cytosol of other neuronal cells such as neuroblastoma cells (SH-SY5Y cell line) and hippocampus cells (HT22 cell line) (Figure 40 a-h). Moreover RAR α was also detected in the cytosol of MEFs (Figure 40 i-l). In contrast, in these cells, RAR γ was strictly nuclear (Figure 40 compare pannels l and t). The specificity of our antibodies was confirmed by using MEF RAR ($\alpha\beta\gamma$) $-/-$ (Figure 40 m-p and u-x). Note that these KO cells were more round than the WT ones, corroborating the role of RARs in cell adhesion and spreading.

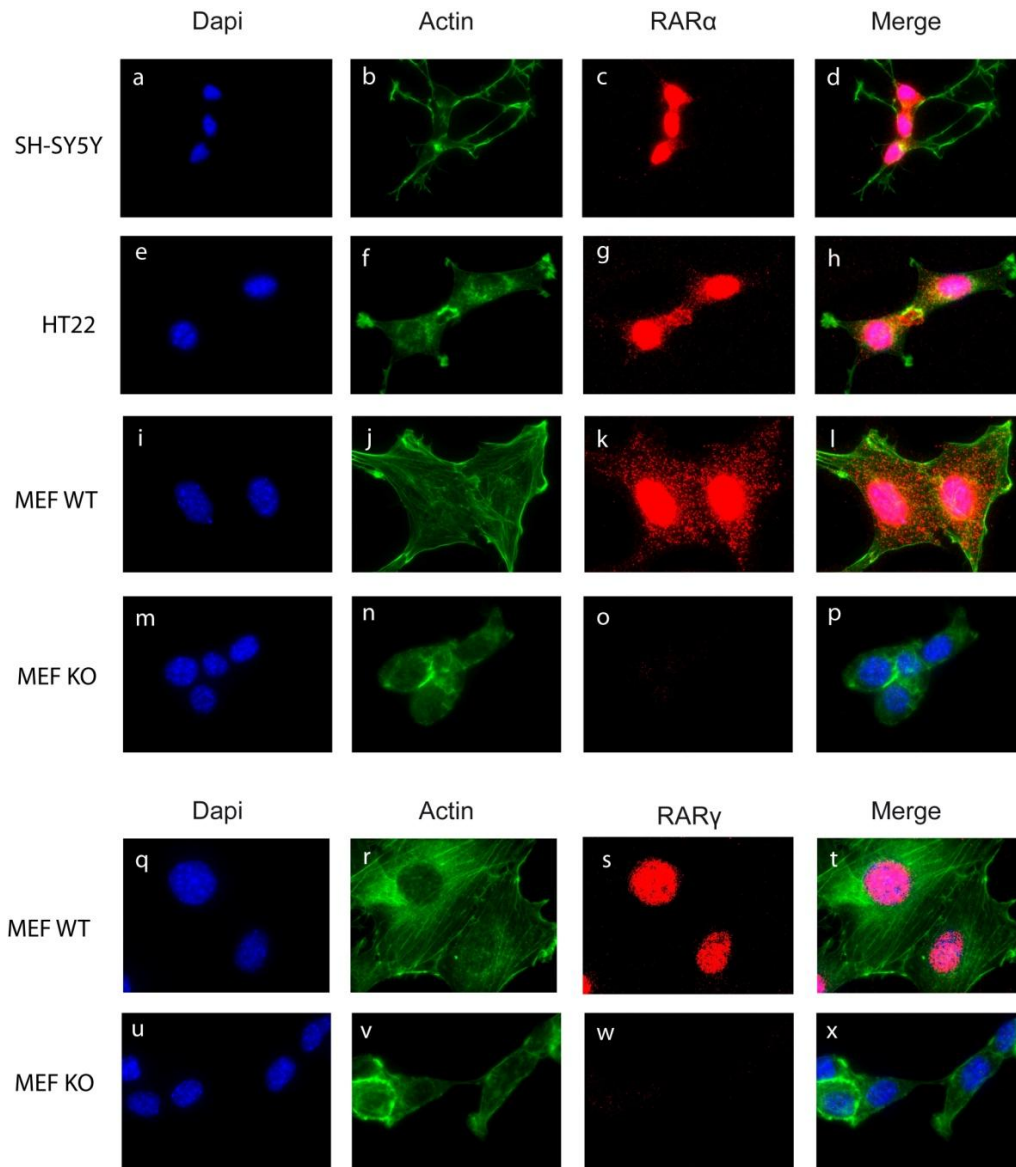


Figure 40: Nuclear and cytosolic localization of RAR α . Immunofluorescence experiments showing mainly nuclear and additional cytosolic RAR α in MEFWT, HT-22 and SH-SY5Y cells. In contrast RAR γ in MEFWT cells is strictly nuclear. Negative MEFKO cells are depleted in all RARs.

- THE POOL OF CYTOSOLIC RAR α IS INCREASED IN CARCINOMA-ASSOCIATED FIBROBLASTS (CAFS)

In the context of the study of the consequences of aberrant kinases activity on RARs phosphorylation in tumors, the laboratory succeeded to generate primary cultures of carcinoma-associated fibroblasts (CAFs) from erbB-2 positive breast cancer surgery sections (obtained in collaboration with the hospital) and to keep these cells viable after several passages. The interesting point is that these CAFs express higher amounts of cytosolic RAR α than normal fibroblasts (Figure 41). Moreover the localization of RAR α in CAFs was rather speckled than diffused.

As CAFs play a key role in tumor invasion and metastasis, one can be suggested that increased amounts of cytosolic RAR α might be linked to these processes.

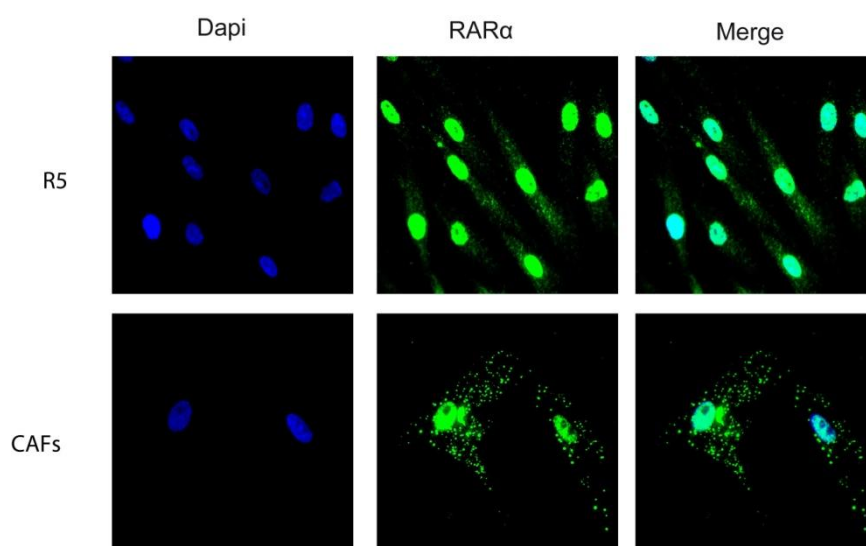


Figure 41: Nuclear and cytosolic localization of RAR α . Immunofluorescence experiments showing mainly nuclear and additional cytosolic RAR α in normal human fibroblasts (R5) and carcinoma-associated fibroblasts (CAFs) isolated from the stroma of highly invasive erbB-2 positive breast cancer tumors.

Conclusion

Here, we highlighted a novelty in the field of RAR α , i.e. an unconventional localization in the cytosol and a role in cell adhesion.

- MATERIALS AND METHODS (UNPUBLISHED)

Antibodies and reagents

Mouse monoclonal antibodies recognizing neuronal class III β -tubulin (Tuj1) were from Covance (Eurogentec France). Purified rabbit polyclonal antibodies raised against the F region of RAR α (RP α (F)) are described in publication 2. Purified rabbit polyclonal antibodies against RAR γ were described earlier (Lalevee et al., 2010a). Fluorescent green 488 phalloidin was from Biotium, Inc. Hayward USA.

Mouse embryonic stem cells

Wild type mouse ES cells were derived from the 129 sub-strain. RAR α ^{-/-} and RAR γ ^{-/-} knockout ES cell lines were previously described (Lohnes et al., 1993; Lufkin et al., 1993).

ES cell lines were cultivated and differentiated as described (Bibel et al., 2007; Bibel et al., 2004a). Briefly, they were kept undifferentiated by repeated splitting on feeders (inactivated mouse embryonic fibroblasts) in ES cell culture medium (DMEM supplemented with GLUTAMAX-I, 15% FCS, 700 U leukemia Inhibitory Factor (LIF), gentamicin and β -mercaptoethanol at 37 °C and 5.5 % CO₂). Then after deprivation of feeders, embryoid bodies (EB) were formed by plating 4x10⁶ cells onto non adherent bacteriological petri dishes (Greiner, cat.no. 633102) in 15 ml EB medium (DMEM supplemented with GLUTAMAX-I, 10% FCS, non essential amino acids, gentamicin and β -mercaptoethanol). Medium was changed every 2 days and RA (2-5 μ M) was added after 4 days. Then after another 4 days, EB were dissociated and plated into laminin-precoated culture dishes in N2 medium [DMEM/ Ham-F12 (1:1), supplemented with N2 (Fisher Scientific), BSA (50 mg/ml) and penicillin/streptomycin]. N2 medium was changed after 1 day and replaced by neurobasal medium supplemented with B27 (Fisher Scientific) after 2 additional days.

MEFs were cultured as described before (Piskunov and Rochette-Egly, 2011a). HT22 and SH-SY5Y cells were cultured according to standard procedures (Ha et al., 2010).

Immunofluorescence experiments were performed as described earlier (Piskunov and Rochette-Egly, 2011a)

Spreading and motility assays

Adhesion and spreading of mouse ES cells were analyzed by plating cells onto laminin-coated coverslips. Cells were allowed to adhere for 3 hours and washed three times in PBS. Then cells were fixed in 4% paraformaldehyde, permeabilized in 0,5% Triton X-100 and stained with 488 phalloidin (Biotium, Inc. Hayward USA).

DISCUSSION
AND
PERSPECTIVES

My work revealed three novelties in the field of the RAR α subtype:

- A pool of RAR α is present in membrane lipid rafts. This membrane fraction of RAR α is involved in non-genomic effects, i.e. the activation of the p38MAPK pathway, which cross talk with the genomic ones.

- Profilin IIA an actin-binding protein, has been identified as a new partner of nuclear RAR α . It positively modulates the genomic effects of RAR α .

- RAR α plays a novel unconventional role in cell adhesion. The function of another unconventional pool of RAR α in the cytosol is proposed.

- A POOL OF RAR α IS PRESENT IN LIPID RAFTS FOR NON-GENOMIC EFFECTS

In this study we discovered a novel unconventional localization of RAR α in membrane lipid rafts, which are signaling centers. This was new in the field of RARs and added a new element to the cohort of nuclear receptors (ER, GR, PR, AR, VDR), which were already shown to be localized in lipid rafts (Figure 42) (Huhtakangas et al., 2004; Luoma et al., 2008; Marquez et al., 2006; Matthews et al., 2008; Pedram et al., 2007; Piskunov and Rochette-Egly, 2011b) .

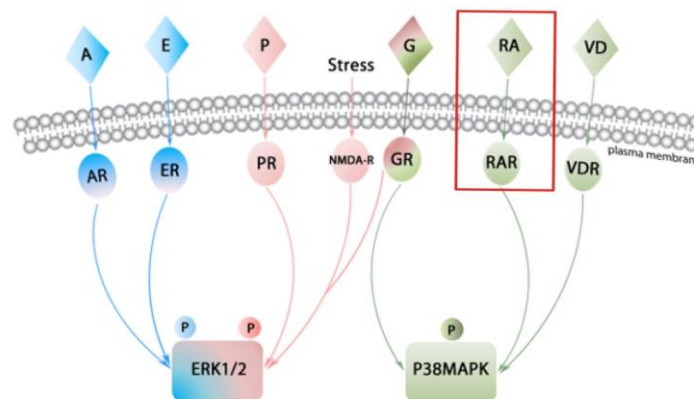


Figure 42: Non-genomic effects of nuclear receptors. A subpopulation RAR α as well as the other nuclear receptors (ER, PR, GR, AR, VDR) is associated to cell membranes and initiates cascades of kinases upon binding of their cognate ligands. Adapted from (Piskunov and Rochette-Egly, 2011b).

The important point is that RAR α is recruited to the plasma membrane via its NTD, but the mechanism of this recruitment is still undefined and would require further investigation.

One possibility might be that membrane anchoring involves posttranslational modifications of the NTD, such as palmitoylation and myristoylation, a covalent attachment of fatty acids, such as palmitic acid or a myristoyl group (derived from myristic acid) (Krauss, 2008), as described for the steroid receptors (Pedram et al., 2007). Unfortunately the NTD of RAR α does not depict any motif for these modifications (Pedram et al., 2007), eliminating such a mechanism.

Another possibility would be that membrane recruitment involves the interaction of the N-terminal PRM of RAR α with profilin IIA, which belongs to the actin cytoskeleton associated to membranes and which also interacts with phosphatidylinositol lipids (see introduction). However, according to our results, no profilin IIA could be detected in lipid rafts.

The last possibility might be that RAR α , like the other nuclear receptors, is targeted to membranes via the binding of its proline-rich motif to other SH3-domain containing membrane-associated proteins such as c-Src tyrosine kinase (Le Romancer et al., 2011; Migliaccio et al., 2000; Migliaccio et al., 1998). The other interesting point is that in response to its ligand, RAR α localized in lipid rafts interacts with G α q proteins and then activate Rho-GTPases and the p38MAPK pathway (Figure 43).

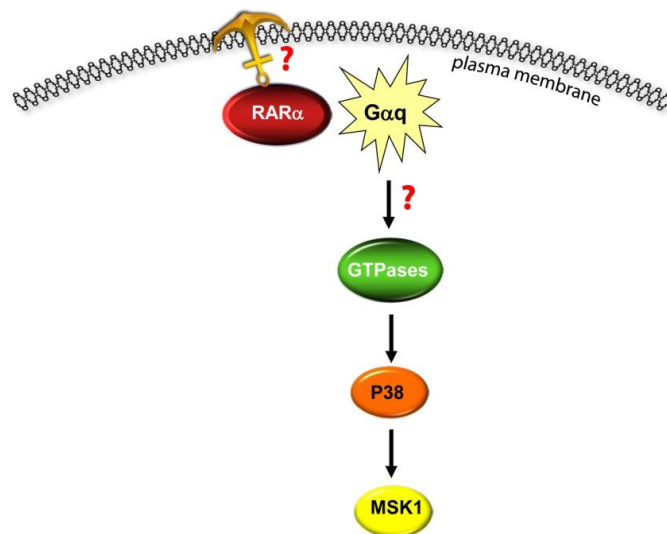


Figure 43: Model of the activation of the p38MAPK pathway through RAR α and G α q located in membranes. Question marks show that it is still unclear how RAR α is anchored to the plasma membrane and what is the mechanism of GTPases activation via G α q. Adapted from (Piskunov and Rochette-Egly, 2011a).

However, the steps between $G\alpha_q$ and Rho-GTPases have not been elucidated yet. Further investigations should be required to determine whether, similarly to the steroid receptors, there is a rapid increase in intracellular calcium concentration $[Ca^{2+}]$ and the activation of effector molecules such as PKC, PKA, PI3K/AKT, Phospholipase C, c-Src, Raf etc (Mizuno and Itoh, 2009).

Nevertheless, according to our results, the integrity of lipid rafts composition is required for the RA-induced interaction between $RAR\alpha$ and $G\alpha_q$, and thus for the activation of p38MAPK. As an example, no interaction was observed in erbB-2 positive cells (Figure 44). One can suggest that high levels of erbB-2 in membranes alter the organization of rafts and therefore affect the formation of the multiprotein complexes which include $RAR\alpha$ and $G\alpha_q$. In line with such a hypothesis, the EGF pathway, which also involves $G\alpha_q$ proteins, was also affected. Note that in these cells, caveolin-1, a component of lipid rafts is frequently down regulated (Park et al., 2005) corroborating that the integrity of the rafts is required for the activation of signaling pathways.

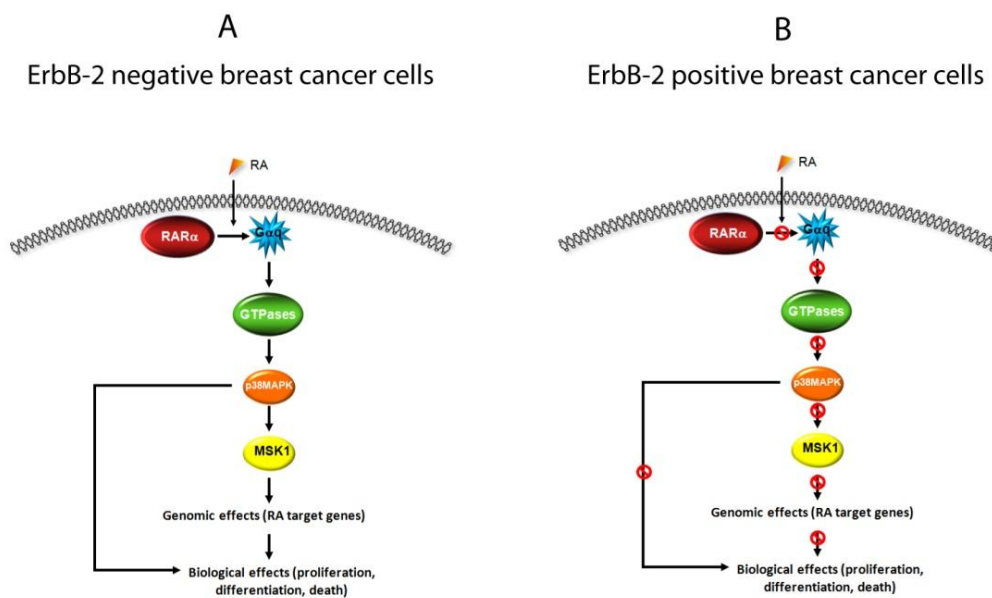


Figure 44: Models of RA signaling in erbB2 positive and negative breast cancer cells. A. In erbB2 negative cells, RA induces formation of $RAR\alpha/G\alpha_q$ complexes and subsequently p38MAPK/MSK1 pathway which is resulting in various biological activities. B. In erbB2 positive cells, RA does not induce formation of $RAR\alpha/G\alpha_q$ complexes therefore p38MAPK/MSK1 pathway is blocked.

Remarkably, the RA-induced activation of p38MAPK via RAR α and G α q protein was observed only in epithelial and fibroblastic cells and not in neuronal cells where RA activates erks (Chen and Napoli, 2008; Dey et al., 2007; Masia et al., 2007; Pan et al., 2005; Zanotto-Filho et al., 2008). This raises the hypothesis that as for the other nuclear receptors, different kinases can be activated by a same ligand via different membrane molecular complexes, depending on their functional significance (Losel and Wehling, 2003; Norman et al., 2004). As an example, in breast cancer cells and in response to its cognate ligand, the estrogen receptor ER α , activates the Erk pathway through complexes containing c-Src and the regulatory subunit of PI3K (p85 α) (Le Romancer et al., 2008; Migliaccio et al., 1998). In contrast, in neuronal cells, ER rather activates Protein Kinase C through G α q and phospholipase C (Qiu et al., 2003). In the same line of idea, depending on the cell type, VDR activates either the RhoA-Rock-p38MAPK pathway (Ordonez-Moran et al., 2008) or the Raf/Erk pathway (Losel and Wehling, 2003; Norman et al., 2001).

- RELEVANCE OF THE NON-GENOMIC EFFECTS OF RAR α : CROSS TALK WITH THE GENOMIC EFFECTS

According to our data, G α q and the downstream effectors, p38MAPK and MSK1 have an important role in the transcription of RA-target genes and in the antiproliferative effects of RA. This is in line with a general concept that G α q proteins as well as several components of lipid rafts control not only the signaling pathways but also transcription and cell growth (Lai et al., 2008; Staubach and Hanisch, 2011; White et al., 2008). Moreover MAPKs are now considered as integrators dispensing decisions to the downstream cellular and transcriptional machineries that coordinately manage major cellular fates, including cell proliferation (or inappropriate proliferation/malignant transformation), differentiation, or death (Figure 45). In line with this concept and according to other work from the laboratory, RA-activated p38MAPK targets several transcriptional actors. Indeed p38MAPK phosphorylates RARs coactivators such as SRC-3 and influences the dynamics of their association/dissociation (Ferry et al., 2011). Moreover, p38MAPK also activates MSK1, which initiates coordinated phosphorylation cascades that target RARs and histones (Bruck et al., 2009). *In fine* these phosphorylations cooperate for RARs recruitment to DNA via modifications of the chromatin environment according to the histone code and via changes in the affinity of RARs for their response elements (Figure 46). According to these data, it is tempting to speculate that, in erbB-2 positive cells, the absence of activation of the p38MAPK pathway might be one of the reasons among several others, of the resistance of these cells to RA.

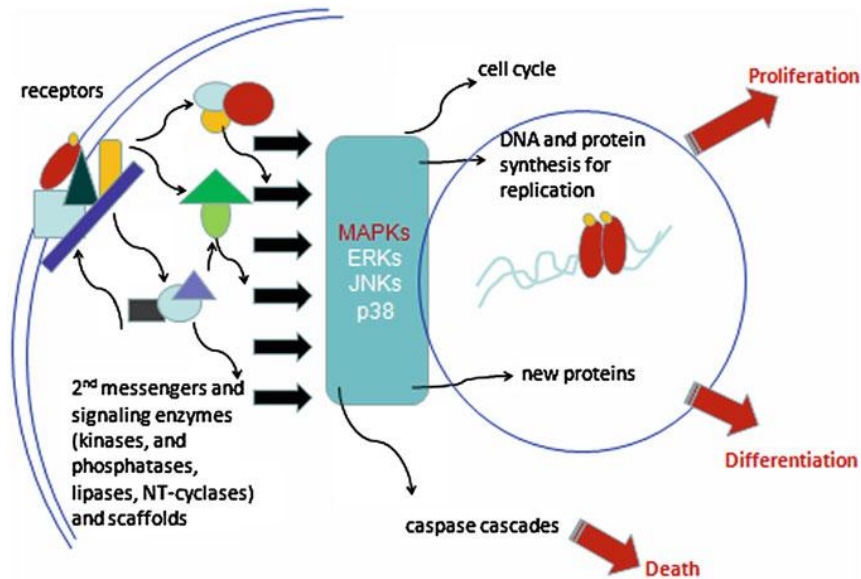


Figure 45: Biological relevance on non-genomic effects of NRs. Nuclear receptors (yellow liganded red oval at the membrane) interact with a variety of signaling proteins (various colored shapes) resulting in activation of MAPKs, which then can regulate cell proliferation (altering activation of cell cycle proteins and causing production of new DNA and proteins), differentiation (the production of new proteins for an altered function), or cell death (by initiating caspase cascades or other forms of active cell death mechanisms). Adapted from

Of note is that other nuclear receptors such as ER, AR, GR and PR, are also phosphorylated by MAPKs, in response to steroid hormones (Chen et al., 2008a; Faus and Haendler, 2006; Lannigan, 2003) and that MSK1 also contributes to histone phosphorylation and chromatin remodeling (Vicent et al., 2006; Vicent et al., 2010; Vicent et al., 2009) with characteristic downstream consequences on target genes expression (Weigel and Moore, 2007a) (Figure 46).

Altogether these data corroborate our results and converge towards the concept that the non-genomic effects of RARs are required for the genomic ones.

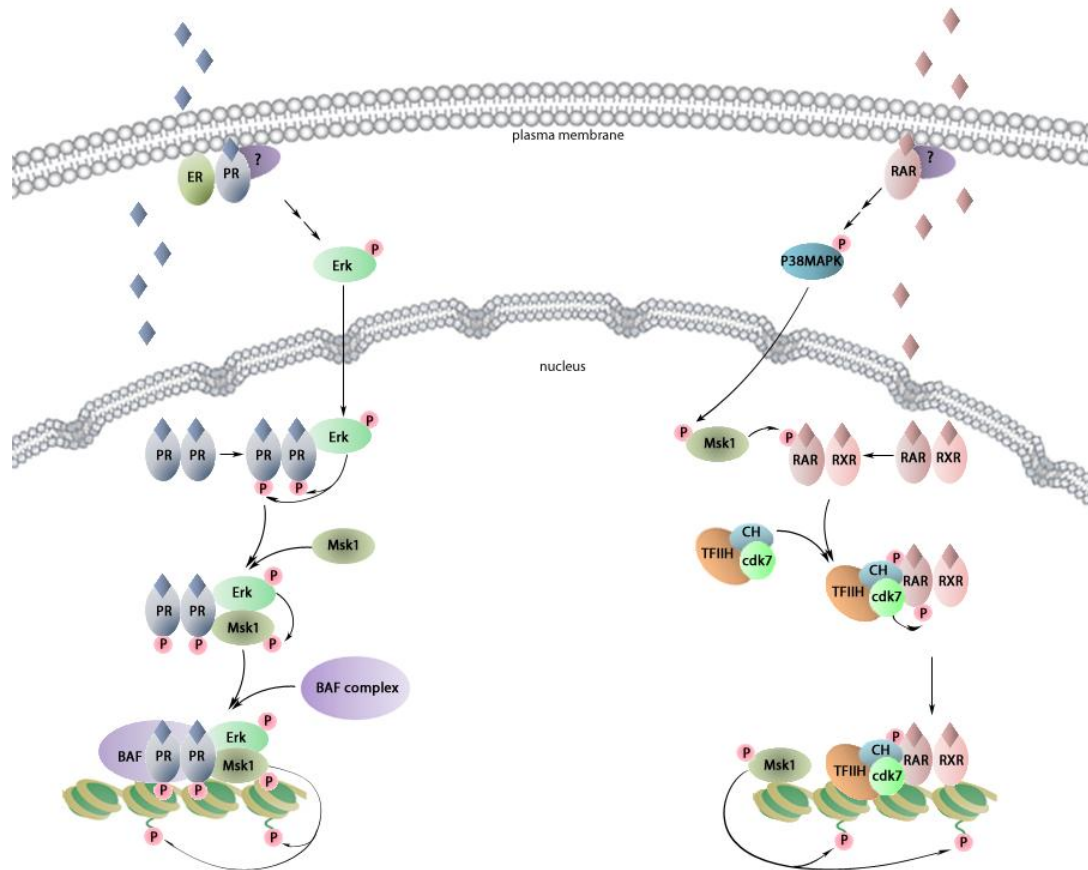


Figure 46: Convergence of genomic and non-genomic effects of nuclear receptors. Progestins activate the Src/Ras/Erk pathway via membrane associated PR, leading to accumulation of activated Erk in the nucleus. Then a nuclear population of PR becomes phosphorylated by activated pErk, which also phosphorylates MSK1. A “PR-activated complex” composed of pPR, pErk and pMSK1 is recruited to the promoter, followed by histone H3 phosphorylation and acetylation. The BAF complex is also recruited through direct interaction with PR and is anchored to chromatin through the histone marks. Due to a lack of kinetic experiments, a precise order of events cannot be proposed. Right). Upon RA binding, a subpopulation of membrane RAR activates the p38MAPK/MSK1 pathway. Activated MSK1 phosphorylates RARα at S369 located in the LBD, subsequently facilitating the docking of cyclin H, which forms with cdk7 and MAT1 the CAK subcomplex of the general transcription factor TFIIH. Within the RARα-TFIIH complex, cdk7 phosphorylates RARα at S77 located in the N-terminal domain. Finally, the phosphorylated RARα/TFIIH complex is recruited to response elements located in the promoter of target genes. MSK1 is also recruited, but separately of the RARα-TFIIH complex, and phosphorylates histones H3.

- NUCLEAR RAR α INTERACTS WITH AN ACTIN-BINDING PROTEIN, PROFILIN IIA

The fact that phosphorylation of the NTD is crucial for the transcriptional activity of RAR α led us to find phospho-dependent partners of this domain. Up to now, only a few proteins have been reported to interact with the N-terminal domain of nuclear receptors including RARs (Boonyaratanakornkit et al., 2001; Bour et al., 2007a; Bour et al., 2005; Zhao et al., 2009).

With that aim, we isolated profilin IIA, an actin-binding protein with an SH3-like domain. However, we found that the interaction of profilin IIA with RAR α is not affected by the phosphorylation of the serine residue flanking the proline motif. This is in contrast to the traditional model in which phosphorylation of serine residues flanking the proline motifs have the ability to positively or negatively regulate the binding of SH3 domains (Kay et al., 2000a; Lalevee et al., 2010b). It is also in contrast to our previous report where we demonstrated that phosphorylation of the serine residue flanking the proline stretch of RAR γ induces the dissociation of vinexin β .

- PROFILIN IIA MODULATES THE TRANSCRIPTIONAL ACTIVITY OF RAR α

In fact, our results challenged the hypothesis that profilin IIA would control the activity of RAR α via a mechanism different from that which was described for vinexin β and RAR γ . Indeed, we found that, in contrast to vinexin β , profilin IIA participates positively to the transcription of RAR α target genes. Such results are in line with another study showing that nuclear profilin also modulates the activity of other transcription factors (Lederer et al., 2005b). Moreover, profilin IIA is present in chromatin and is recruited with RAR α to the promoters of target genes in response to RA.

Most importantly, our results also corroborate the evergrowing evidence that actin, actin-related proteins and actin-binding proteins are constituents of nuclear protein complexes and play a role in transcription (Bettinger et al., 2004; Jockusch et al., 2006; Zheng et al., 2009b). Indeed, a number of actin-binding proteins have been shown to regulate the activity of several transcription factors including nuclear receptors through the recruitment of multiple components of transcription complexes such as chromatin-remodelling, histone acetyl transferase complexes (Archer et al., 2005; Blessing et al., 2004; Gettemans et al., 2005). Such a role of actin-binding proteins in transcription complexes emerged only recently but up to now there are no data showing that profilin IIA belongs to nuclear complexes.

However, one can propose that, profilin IIA might have a role in regulating the properties of nuclear actin through its ability to promote ADP to ATP exchange in G-actin (Fenn et al., 2011; Kast and Dominguez, 2011). Such a role might explain why nuclear forms of actin are prominently found in monomeric states within transcription complexes. Nevertheless, it will require further experiments to test whether profilin IIA has such a role in maintaining the pool of monomeric actin in the nucleus,

when complexed with RAR α at RA-target genes promoters. Moreover, it would be interesting to address whether profilin IIA also modulates the activity of the coregulatory complexes of RAR α through nucleotide-dependent conformational transitions. Finally, whether the interaction of RAR α with profilin IIA can be modulated by other processes than RA signaling or RAR α phosphorylation would provide important insights into the role of this adaptor in RA signaling.

In conclusion this study opened new concepts and avenues in the regulation of RA-target genes transcription via an actin-binding protein interacting with the NTD of the RAR α subtype. However the biological relevance of profilin IIA remains unclear and requires further investigations.

- NOVEL UNCONVENTIONAL ROLE OF RAR α IN CELL ADHESION

Then in order to find out the *in vivo* biological relevance of the RAR α interaction with profilinIIA, we looked for a biological model. As mammal biological models are rather complex, we selected mouse ES cells, which are well known to undergo neuronal differentiation in response to RA. WT ES cells are available at the IGBMC and express RAR α . However, according to recent studies from the laboratory, RAR α is not involved in RA-induced neuronal differentiation of ES cells. Indeed, invalidation of RAR α did not affect the ability of these cells to form neurons (Al Tanoury *et al*, manuscript in preparation). Surprisingly, we found that these RAR α ^{-/-} ES cells were severely impaired in adhesion and spreading. This result brought us to the conclusion that RAR α may have a role in cell adhesion and spreading. Two main molecular mechanisms can be proposed for this RAR α -dependent process:

- RAR α might control the expression of proteins involved in adhesion via genomic effects. Therefore, recently we launched RNA-seq experiments using WT and RAR α ^{-/-} cells that will give some indications soon. Whether profilin IIA is involved in such genomic process as a coregulator of RAR α is still unknown and will require further profilin IIA gain and loss of function experiments.

- By analogy with the androgen receptor, which was shown to be involved in cell migration via its association with filamin A (Castoria *et al.*, 2011), RAR α might also be involved in adhesion and cell spreading through non-genomic effects via its interaction with cytoskeleton actin-binding proteins. One candidate could be profilin IIA, which is known to be involved in cell adhesion (Murk *et al.*, 2009). In this line of idea, we found that a pool of RAR α is present outside of nuclei, in the cytosol of ES cells as well as of several neuronal cells and fibroblasts. Unfortunately, profilin IIA was hardly detectable in the cytosol of these cells with our antibodies in immunofluorescence experiments. RAR α /profilin IIA complexes were also hardly detectable in the cytosol, eliminating such a possibility. Nevertheless, one cannot exclude that RAR α interacts with other actin-binding proteins and/or proteins involved in matrix adhesion (integrin, talin, α -actinin, filamin, vinculin *etc.*) through

adaptors with SH3 or WW domains. Such a hypothesis will require further experiments.

Finally, the striking point of this study is that CAFs depict higher amounts of cytosolic RAR α than normal fibroblasts. As these cells are highly invasive, it strengthens our hypothesis concerning a role for RAR α in cell adhesion and migration.

Now the challenge will be to investigate how RAR α controls cell adhesion and to discriminate between the genomic and/or non-genomic effects. This will implicate the identification of potential adhesion genes by RNA-seq and or new partners in the cytosol. Finally, it opens new avenues in tumor invasion with RAR α as a novel potential marker for prognosis.

LIST OF REFERENCES

- Achkar, C.C., F. Derguini, B. Blumberg, A. Langston, A.A. Levin, J. Speck, R.M. Evans, J. Bolado, Jr., K. Nakanishi, J. Buck, and L.J. Gudas.** 1996. 4-Oxoretinol, a new natural ligand and transactivator of the retinoic acid receptors. *Proc Natl Acad Sci U S A.* 93:4879-84.
- Adam-Stitah, S., L. Penna, P. Chambon, and C. Rochette-Egly.** 1999. Hyperphosphorylation of the retinoid X receptor alpha by activated c-Jun NH2-terminal kinases. *J Biol Chem.* 274:18932-41.
- Alland, L., R. Muhle, H. Hou, J. Potes, L. Chin, N. SchreiberAgus, and R.A. DePinho.** 1997. Role for N-CoR and histone deacetylase in Sin3-mediated transcriptional repression. *Nature.* 387:49-55.
- Alsayed, Y., S. Uddin, N. Mahmud, F. Lekmine, D.V. Kalvakolanu, S. Minucci, G. Bokoch, and L.C. Plataniias.** 2001. Activation of Rac1 and the p38 mitogen-activated protein kinase pathway in response to all-trans-retinoic acid. *J Biol Chem.* 276:4012-9.
- Álvarez, S., D. Baretino, Á.R.d. Lera, and S. Masiá.** 2007. Rapid, non-genomic actions of Retinoic Acid on Phosphatidylinositol-3-Kinase. *Molecular Endocrinology.* 21:2391-2402.
- Andrau, J.C., L. van de Pasch, P. Lijnzaad, T. Bijma, M.G. Koerkamp, J. van de Peppel, M. Werner, and F.C. Holstege.** 2006. Genome-wide location of the coactivator mediator: Binding without activation and transient Cdk8 interaction on DNA. *Mol Cell.* 22:179-92.
- Aranda, A., and A. Pascual.** 2001. Nuclear hormone receptors and gene expression. *Physiol Rev.* 81:1269-304.
- Archer, S.K., C. Claudianos, and H.D. Campbell.** 2005. Evolution of the gelsolin family of actin-binding proteins as novel transcriptional coactivators. *Bioessays.* 27:388-96.
- Augereau, P., E. Badia, S. Carascossa, A. Castet, S. Fritsch, P.O. Harmand, S. Jalaguier, and V. Cavailles.** 2006. The nuclear receptor transcriptional coregulator RIP140. *Nucl Recept Signal.* 4:e024.
- Bain, D.L., M.A. Franden, J.L. McManaman, G.S. Takimoto, and K.B. Horwitz.** 2000. The N-terminal region of the human progesterone A-receptor. Structural analysis and the influence of the DNA binding domain. *J Biol Chem.* 275:7313-20.
- Bain, D.L., A.F. Heneghan, K.D. Connaghan-Jones, and M.T. Miura.** 2007. Nuclear receptor structure: implications for function. *Annu Rev Physiol.* 69:201-20.
- Balasubramanian, M.K., B.R. Hirani, J.D. Burke, and K.L. Gould.** 1994. The Schizosaccharomyces-Pombe Cdc3+ Gene Encodes a Profilin Essential for Cytokinesis. *Journal of Cell Biology.* 125:1289-1301.
- Bao, L., A. Kimzey, G. Sauter, J.M. Sowadski, K.P. Lu, and D.G. Wang.** 2004. Prevalent overexpression of prolyl isomerase Pin1 in human cancers. *Am J Pathol.* 164:1727-37.

- Bastie, J.N., G. Despouy, N. Balitrand, C. Rochette-Egly, C. Chomienne, and L. Delva.** 2001. The novel co-activator CRABP II binds to RAR alpha and RXR alpha via two nuclear receptor interacting domains and does not require the AF-2 'core'. *FEBS Letters*. 507:67-73.
- Bastien, J., S. Adam-Stitah, J.L. Plassat, P. Chambon, and C. Rochette-Egly.** 2002. The phosphorylation site located in the A region of retinoic X receptor alpha is required for the antiproliferative effect of retinoic acid (RA) and the activation of RA target genes in F9 cells. *J Biol Chem*. 277:28683-9.
- Bastien, J., S. Adam-Stitah, T. Riedl, J.M. Egly, P. Chambon, and C. Rochette-Egly.** 2000. TFIID interacts with the retinoic acid receptor gamma and phosphorylates its AF-1-activating domain through cdk7. *J Biol Chem*. 275:21896-904.
- Bastien, J., J.L. Plassat, B. Payraastre, and C. Rochette-Egly.** 2006. The phosphoinositide 3-kinase/Akt pathway is essential for the retinoic acid-induced differentiation of F9 cells. *Oncogene*. 25:2040-7.
- Bastien, J., and C. Rochette-Egly.** 2004. Nuclear retinoid receptors and the transcription of retinoid-target genes. *Gene*. 328:1-16.
- Bettinger, B.T., D.M. Gilbert, and D.C. Amberg.** 2004. Actin up in the nucleus. *Nat Rev Mol Cell Biol*. 5:410-5.
- Bibel, M., J. Richter, E. Lacroix, and Y.A. Barde.** 2007. Generation of a defined and uniform population of CNS progenitors and neurons from mouse embryonic stem cells. *Nat Protoc*. 2:1034-43.
- Bibel, M., J. Richter, K. Schrenk, K.L. Tucker, V. Staiger, M. Korte, M. Goetz, and Y.A. Barde.** 2004a. Differentiation of mouse embryonic stem cells into a defined neuronal lineage. *Nat Neurosci*. 7:1003-9.
- Bibel, M., J. Richter, K. Schrenk, K.L. Tucker, V. Staiger, M. Korte, M. Goetz, and Y.A. Barde.** 2004b. Differentiation of mouse embryonic stem cells into a defined neuronal lineage. *Nature Neuroscience*. 7:1003-1009.
- Birbach, A.** 2008. Profilin, a multi-modal regulator of neuronal plasticity. *Bioessays*. 30:994-1002.
- Birbach, A., J.M. Verkuyl, and A. Matus.** 2006. Reversible, activity-dependent targeting of profilin to neuronal nuclei. *Exp Cell Res*. 312:2279-87.
- Bjorkegren, C., M. Rozycki, C.E. Schutt, U. Lindberg, and R. Karlsson.** 1993. Mutagenesis of human profilin locates its poly(L-proline)-binding site to a hydrophobic patch of aromatic amino acids. *FEBS Lett*. 333:123-6.
- Blessing, C.A., G.T. Ugrinova, and H.V. Goodson.** 2004. Actin and ARPs: action in the nucleus. *Trends Cell Biol*. 14:435-42.
- Blomhoff, R., and H.K. Blomhoff.** 2006. Overview of retinoid metabolism and function. *J Neurobiol*. 66:606-30.

- Blomhoff, R., P. Helgerud, M. Rasmussen, T. Berg, and K.R. Norum.** 1982. In vivo uptake of chylomicron [3H]retinyl ester by rat liver: evidence for retinol transfer from parenchymal to nonparenchymal cells. *Proc Natl Acad Sci U S A.* 79:7326-30.
- Boonyaratanakornkit, V., M.P. Scott, V. Ribon, L. Sherman, S.M. Anderson, J.L. Maller, W.T. Miller, and D.P. Edwards.** 2001. Progesterone receptor contains a proline-rich motif that directly interacts with SH3 domains and activates c-Src family tyrosine kinases. *Mol Cell.* 8:269-80.
- Bour, G., E. Gaillard, N. Bruck, S. Lalevee, J.L. Plassat, D. Busso, J.P. Samama, and C. Rochette-Egly.** 2005a. Cyclin H binding to the RARalpha activation function (AF)-2 domain directs phosphorylation of the AF-1 domain by cyclin-dependent kinase 7. *Proc Natl Acad Sci U S A.* 102:16608-13.
- Bour, G., S. Lalevee, and C. Rochette-Egly.** 2007a. Protein kinases and the proteasome join in the combinatorial control of transcription by nuclear retinoic acid receptors. *Trends Cell Biol.* 17:302-9.
- Bour, G., S. Lalevee, and C. Rochette-Egly.** 2007b. Protein kinases and the proteasome join in the combinatorial control of transcription by nuclear retinoic acid receptors. *Trends in Cell Biology.* 17:302-309.
- Bour, G., J.L. Plassat, A. Bauer, S. Lalevee, and C. Rochette-Egly.** 2005. Vinexin {beta} Interacts with the Non-phosphorylated AF-1 Domain of Retinoid Receptor {gamma} (RAR{gamma}) and Represses RAR{gamma}-mediated Transcription. *J Biol Chem.* 280:17027-37.
- Bour, G., J.L. Plassat, A. Bauer, S. Lalevee, and C. Rochette-Egly.** 2005b. Vinexin beta interacts with the non-phosphorylated AF-1 domain of retinoid receptor gamma (RARgamma) and represses RARgamma-mediated transcription. *J Biol Chem.* 280:17027-37.
- Bourguet, W., P. Germain, and H. Gronemeyer.** 2000a. Nuclear receptor ligand-binding domains: three-dimensional structures, molecular interactions and pharmacological implications. *Trends Pharmacol Sci.* 21:381-8.
- Bourguet, W., M. Ruff, P. Chambon, H. Gronemeyer, and D. Moras.** 1995. Crystal structure of the ligand-binding domain of the human nuclear receptor RXR-alpha. *Nature.* 375:377-82.
- Bourguet, W., V. Vivat, J.M. Wurtz, P. Chambon, H. Gronemeyer, and D. Moras.** 2000b. Crystal structure of a heterodimeric complex of RAR and RXR ligand-binding domains. *Mol Cell.* 5:289-98.
- Braun, A., A. Aszodi, H. Hellebrand, A. Berna, R. Fassler, and O. Brandau.** 2002. Genomic organization of profilin-III and evidence for a transcript expressed exclusively in testis. *Gene.* 283:219-25.
- Brondani, V., Q. Schefer, F. Hamy, and T. Klimkait.** 2005. The peptidyl-prolyl isomerase Pin1 regulates phospho-Ser77 retinoic acid receptor alpha stability. *Biochem Biophys Res Commun.* 328:6-13.

- Bruck, N., J. Bastien, G. Bour, A. Tarrade, J.L. Plassat, A. Bauer, S. Adam-Stitah, and C. Rochette-Egly.** 2005. Phosphorylation of the retinoid x receptor at the omega loop, modulates the expression of retinoic-acid-target genes with a promoter context specificity. *Cell Signal.* 17:1229-39.
- Bruck, N., D. Vitoux, C. Ferry, V. Duong, A. Bauer, H. de The, and C. Rochette-Egly.** 2009. A coordinated phosphorylation cascade initiated by p38MAPK/MSK1 directs RARalpha to target promoters. *EMBO J.* 28:34-47.
- Buchanan, F.Q., C. Rochette-Egly, and M.A. Asson-Batres.** 2011. Detection of variable levels of RARalpha and RARgamma proteins in pluripotent and differentiating mouse embryonal carcinoma and mouse embryonic stem cells. *Cell Tissue Res.* 346:43-51.
- Buck, J., F. Derguini, E. Levi, K. Nakanishi, and U. Hammerling.** 1991. Intracellular signaling by 14-hydroxy-4,14-retro-retinol. *Science.* 254:1654-6.
- Budhu, A.S., and N. Noy.** 2002. Direct channeling of retinoic acid between cellular retinoic acid-binding protein II and retinoic acid receptor sensitizes mammary carcinoma cells to retinoic acid-induced growth arrest. *Molecular and Cellular Biology.* 22:2632-2641.
- Buss, F., C. Temm-Grove, S. Henning, and B.M. Jockusch.** 1992. Distribution of profilin in fibroblasts correlates with the presence of highly dynamic actin filaments. *Cell Motil Cytoskeleton.* 22:51-61.
- Carrier, M.F.** 2010. Actin-based Motility: Cellular, Molecular and Physical Aspects. Springer.
- Carlsson, L., L.E. Nystrom, I. Sundkvist, F. Markey, and U. Lindberg.** 1977. Actin polymerizability is influenced by profilin, a low molecular weight protein in non-muscle cells. *J Mol Biol.* 115:465-83.
- Castano, E., V.V. Philimonenko, M. Kahle, J. Fukalova, A. Kalendova, S. Yildirim, R. Dzijak, H. Dingova-Krasna, and P. Hozak.** 2010. Actin complexes in the cell nucleus: new stones in an old field. *Histochem Cell Biol.* 133:607-26.
- Castoria, G., L. D'Amato, A. Ciociola, P. Giovannelli, T. Giraldi, L. Sepe, G. Paoletta, M.V. Barone, A. Migliaccio, and F. Auricchio.** 2011. Androgen-induced cell migration: role of androgen receptor/filamin A association. *PLoS One.* 6:e17218.
- Castoria, G., M. Lombardi, M.V. Barone, A. Bilancio, M. Di Domenico, D. Bottero, F. Vitale, A. Migliaccio, and F. Auricchio.** 2003. Androgen-stimulated DNA synthesis and cytoskeletal changes in fibroblasts by a nontranscriptional receptor action. *J Cell Biol.* 161:547-56.
- Cedergren-Zeppezauer, E.S., N.C. Goonesekere, M.D. Rozycki, J.C. Myslik, Z. Dauter, U. Lindberg, and C.E. Schutt.** 1994. Crystallization and structure determination of bovine profilin at 2.0 Å resolution. *J Mol Biol.* 240:459-75.
- Celis, J.E.** 2006. Cell biology: a laboratory handbook. Elsevier Academic.
- Chambon, P.** 1996. A decade of molecular biology of retinoic acid receptors. *FASEB J.* 10:940-54.

- Chandra, V., P. Huang, Y. Hamuro, S. Raghuram, Y. Wang, T.P. Burris, and F. Rastinejad.** 2008. Structure of the intact PPAR-gamma-RXR- nuclear receptor complex on DNA. *Nature*. 456:350-6.
- Chatterjee, M., and K. Kashfi.** 2011. *Cell Signaling & Molecular Targets in Cancer*. Springer.
- Chen, D., H. Ma, H. Hong, S.S. Koh, S.M. Huang, B.T. Schurter, D.W. Aswad, and M.R. Stallcup.** 1999. Regulation of transcription by a protein methyltransferase. *Science*. 284:2174-7.
- Chen, H., W.N. Howald, and M.R. Juchau.** 2000. Biosynthesis of all-trans-retinoic acid from all-trans-retinol: catalysis of all-trans-retinol oxidation by human P-450 cytochromes. *Drug Metab Dispos*. 28:315-22.
- Chen, H., R.J. Lin, R.L. Schiltz, D. Chakravarti, A. Nash, L. Nagy, M.L. Privalsky, Y. Nakatani, and R.M. Evans.** 1997. Nuclear receptor coactivator ACTR is a novel histone acetyltransferase and forms a multimeric activation complex with P/CAF and CBP/p300. *Cell*. 90:569-80.
- Chen, J.D., and R.M. Evans.** 1995. A Transcriptional Co-Repressor That Interacts with Nuclear Hormone Receptors. *Nature*. 377:454-457.
- Chen, N., and J.L. Napoli.** 2008. All-trans-retinoic acid stimulates translation and induces spine formation in hippocampal neurons through a membrane-associated RARalpha. *FASEB J*. 22:236-45.
- Chen, W., T. Dang, R.D. Blind, Z. Wang, C.N. Civasotto, A.B. Hittelman, I. Rogatsky, S.K. Logan, and M.J. Garabedian.** 2008a. Glucocorticoid receptor phosphorylation differentially affects target gene expression. *Mol Endocrinol*. 22:1754-66.
- Chen, W.W., T. Dang, R.D. Blind, Z. Wang, C.N. Civasotto, A.B. Hittelman, I. Rogatsky, S.K. Logan, and M.J. Garabedian.** 2008b. Glucocorticoid receptor phosphorylation differentially affects target gene expression. *Molecular Endocrinology*. 22:1754-1766.
- Cheung, P., K.G. Tanner, W.L. Cheung, P. Sassone-Corsi, J.M. Denu, and C.D. Allis.** 2000. Synergistic coupling of histone H3 phosphorylation and acetylation in response to epidermal growth factor stimulation. *Mol Cell*. 5:905-15.
- Chik, J.K., U. Lindberg, and C.E. Schutt.** 1996. The structure of an open state of beta-actin at 2.65 angstrom resolution. *Journal of Molecular Biology*. 263:607-623.
- Chinkers, M., J.A. Mckanna, and S. Cohen.** 1979. Rapid Induction of Morphological-Changes in Human Carcinoma-Cells a-431 by Epidermal Growth-Factor. *Journal of Cell Biology*. 83:260-265.
- Clayton, A.L., S. Rose, M.J. Barratt, and L.C. Mahadevan.** 2000. Phosphoacetylation of histone H3 on c-fos- and c-jun-associated nucleosomes upon gene activation. *EMBO J*. 19:3714-26.
- D'Ambrosio, D.N., R.D. Clugston, and W.S. Blaner.** 2011. Vitamin a metabolism: an update. *Nutrients*. 3:63-103.

- Danielian, P.S., R. White, J.A. Lees, and M.G. Parker.** 1992. Identification of a Conserved Region Required for Hormone Dependent Transcriptional Activation by Steroid-Hormone Receptors. *Embo Journal*. 11:1025-1033.
- de Laurentiis, A., L. Donovan, and A. Arcaro.** 2007. Lipid rafts and caveolae in signaling by growth factor receptors. *Open Biochem J*. 1:12-32.
- de Lera, A.R., W. Bourguet, L. Altucci, and H. Gronemeyer.** 2007. Design of selective nuclear receptor modulators: RAR and RXR as a case study. *Nat Rev Drug Discov*. 6:811-20.
- de The, H., M.M. Vivanco-Ruiz, P. Tiollais, H. Stunnenberg, and A. Dejean.** 1990. Identification of a retinoic acid responsive element in the retinoic acid receptor beta gene. *Nature*. 343:177-80.
- Delmotte, M.H., A. Tahayato, P. Formstecher, and P. Lefebvre.** 1999. Serine 157, a retinoic acid receptor alpha residue phosphorylated by protein kinase C in vitro, is involved in RXR.RARalpha heterodimerization and transcriptional activity. *J Biol Chem*. 274:38225-31.
- Delva, L., J.N. Bastie, C. Rochette-Egly, R. Kraiba, N. Balitrand, G. Despouy, P. Chambon, and C. Chomienne.** 1999. Physical and functional interactions between cellular retinoic acid binding protein II and the retinoic acid-dependent nuclear complex. *Molecular and Cellular Biology*. 19:7158-7167.
- Despouy, G., J.N. Bastie, S. Deshaies, N. Balitrand, A. Mazharian, C. Rochette-Egly, C. Chomienne, and L. Delva.** 2003. Cyclin D3 is a cofactor of retinoic acid receptors, modulating their activity in the presence of cellular retinoic acid-binding protein II. *Journal of Biological Chemistry*. 278:6355-6362.
- Dey, N., P.K. De, M. Wang, H. Zhang, E.A. Dobrota, K.A. Robertson, and D.L. Durden.** 2007. CSK controls retinoic acid receptor (RAR) signaling: a RAR-c-SRC signaling axis is required for neurogenic differentiation. *Mol Cell Biol*. 27:4179-97.
- Di Nardo, A., R. Gareus, D. Kwiatkowski, and W. Witke.** 2000. Alternative splicing of the mouse profilin II gene generates functionally different profilin isoforms. *Journal of Cell Science*. 113:3795-3803.
- Dilworth, F.J., and P. Chambon.** 2001. Nuclear receptors coordinate the activities of chromatin remodeling complexes and coactivators to facilitate initiation of transcription. *Oncogene*. 20:3047-54.
- Dong, D., S.E. Ruuska, D.J. Levinthal, and N. Noy.** 1999. Distinct roles for cellular retinoic acid-binding proteins I and II in regulating signaling by retinoic acid. *Journal of Biological Chemistry*. 274:23695-23698.
- Dong, J.X., B. Radau, A. Otto, E.C. Muller, C. Lindschau, and P. Westermann.** 2000. Profilin I attached to the Golgi is required for the formation of constitutive transport vesicles at the trans-Golgi network. *Biochimica Et Biophysica Acta-Molecular Cell Research*. 1497:253-260.

- Duester, G., F.A. Mic, and A. Molotkov.** 2003. Cytosolic retinoid dehydrogenases govern ubiquitous metabolism of retinol to retinaldehyde followed by tissue-specific metabolism to retinoic acid. *Chem Biol Interact.* 143-144:201-10.
- Dupe, V., M. Davenne, J. Brocard, P. Dolle, M. Mark, A. Dierich, P. Chambon, and F.M. Rijli.** 1997. In vivo functional analysis of the Hoxa-1 3' retinoic acid response element (3'RARE). *Development.* 124:399-410.
- Durand, B., M. Saunders, P. Leroy, M. Leid, and P. Chambon.** 1992. All-trans and 9-cis retinoic acid induction of CRABP II transcription is mediated by RAR-RXR heterodimers bound to DR1 and DR2 repeated motifs. *Cell.* 71:73-85.
- Dyson, H.J., and P.E. Wright.** 2005. Intrinsically unstructured proteins and their functions. *Nat Rev Mol Cell Biol.* 6:197-208.
- Egea, P.F., N. Rochel, C. Birck, P. Vachette, P.A. Timmins, and D. Moras.** 2001. Effects of ligand binding on the association properties and conformation in solution of retinoic acid receptors RXR and RAR. *J Mol Biol.* 307:557-76.
- Elmlund, H., V. Baraznenok, M. Lindahl, C.O. Samuelson, P.J. Koeck, S. Holmberg, H. Hebert, and C.M. Gustafsson.** 2006. The cyclin-dependent kinase 8 module sterically blocks Mediator interactions with RNA polymerase II. *Proc Natl Acad Sci U S A.* 103:15788-93.
- Epping, M.T., L. Wang, M.J. Edel, L. Carlee, M. Hernandez, and R. Bernards.** 2005. The human tumor antigen PRAME is a dominant repressor of retinoic acid receptor signaling. *Cell.* 122:835-47.
- Farboud, B., H. Hauksdottir, Y. Wu, and M.L. Privalsky.** 2003. Isotype-restricted corepressor recruitment: a constitutively closed helix 12 conformation in retinoic acid receptors beta and gamma interferes with corepressor recruitment and prevents transcriptional repression. *Mol Cell Biol.* 23:2844-58.
- Farboud, B., and M.L. Privalsky.** 2004. Retinoic acid receptor-alpha is stabilized in a repressive state by its C-terminal, isotype-specific F domain. *Molecular Endocrinology.* 18:2839-2853.
- Farooqui, M., P.J. Franco, J. Thompson, H. Kagechika, R.A. Chandraratna, L. Banaszak, and L.N. Wei.** 2003. Effects of retinoid ligands on RIP140: molecular interaction with retinoid receptors and biological activity. *Biochemistry.* 42:971-9.
- Faus, H., and B. Haendler.** 2006. Post-translational modifications of steroid receptors. *Biomed Pharmacother.* 60:520-8.
- Fenn, S., D. Breitsprecher, C.B. Gerhold, G. Witte, J. Faix, and K.P. Hopfner.** 2011. Structural biochemistry of nuclear actin-related proteins 4 and 8 reveals their interaction with actin. *Embo J.* 30:2153-66.
- Fernandes, I., Y. Bastien, T. Wai, K. Nygard, R. Lin, O. Cormier, H.S. Lee, F. Eng, N.R. Bertos, N. Pelletier, S. Mader, V.K. Han, X.J. Yang, and J.H. White.** 2003. Ligand-dependent nuclear receptor corepressor LCoR functions by histone deacetylase-dependent and -independent mechanisms. *Mol Cell.* 11:139-50.

- Ferry, C., S. Gaouar, B. Fischer, M. Boeglin, N. Paul, E. Samarut, A. Piskunov, G. Pankotai-Bodo, L. Brino, and C. Rochette-Egly.** 2011. Cullin 3 mediates SRC-3 ubiquitination and degradation to control the retinoic acid response. *Proc Natl Acad Sci U S A.* 108:20603-8.
- Ferry, C., M. Gianni, S. Lalevee, N. Bruck, J.L. Plassat, I. Raska, Jr., E. Garattini, and C. Rochette-Egly.** 2009. SUG-1 plays proteolytic and non-proteolytic roles in the control of retinoic acid target genes via its interaction with SRC-3. *J Biol Chem.* 284:8127-35.
- Finger, F.P., and P. Novick.** 1997. Sec3p is involved in secretion and morphogenesis in *Saccharomyces cerevisiae*. *Molecular Biology of the Cell.* 8:647-662.
- Flajollet, S., B. Lefebvre, C. Rachez, and P. Lefebvre.** 2006. Distinct roles of the steroid receptor coactivator 1 and of MED1 in retinoid-induced transcription and cellular differentiation. *J Biol Chem.* 281:20338-48.
- Fontana, J.A., and A.K. Rishi.** 2002. Classical and novel retinoids: their targets in cancer therapy. *Leukemia.* 16:463-72.
- Fraser, P.D., and P.M. Bramley.** 2004. The biosynthesis and nutritional uses of carotenoids. *Prog Lipid Res.* 43:228-65.
- Gaillard, E., N. Bruck, Y. Brelivet, G. Bour, S. Lalevee, A. Bauer, O. Poch, D. Moras, and C. Rochette-Egly.** 2006. Phosphorylation by PKA potentiates retinoic acid receptor alpha activity by means of increasing interaction with and phosphorylation by cyclin H/cdk7. *Proc Natl Acad Sci U S A.* 103:9548-53.
- Gampe, R.T., Jr., V.G. Montana, M.H. Lambert, A.B. Miller, R.K. Bledsoe, M.V. Milburn, S.A. Kliewer, T.M. Willson, and H.E. Xu.** 2000. Asymmetry in the PPARgamma/RXRalpha crystal structure reveals the molecular basis of heterodimerization among nuclear receptors. *Mol Cell.* 5:545-55.
- Gareus, R., A. Di Nardo, V. Rybin, and W. Witke.** 2006. Mouse profilin 2 regulates endocytosis and competes with SH3 ligand binding to dynamin 1. *Journal of Biological Chemistry.* 281:2803-2811.
- Geese, M., K. Schluter, M. Rothkegel, B.M. Jockusch, J. Wehland, and A.S. Sechi.** 2000. Accumulation of profilin II at the surface of *Listeria* is concomitant with the onset of motility and correlates with bacterial speed. *Journal of Cell Science.* 113:1415-1426.
- Germain, P., L. Altucci, W. Bourguet, C. Rochette-Egly, and H. Gronemeyer.** 2003. Nuclear receptor superfamily: Principles of signaling. *Pure and Applied Chemistry.* 75:1619-1664.
- Germain, P., P. Chambon, G. Eichele, R.M. Evans, M.A. Lazar, M. Leid, A.R. de Lera, R. Lotan, D.J. Mangelsdorf, and H. Gronemeyer.** 2006b. International Union of Pharmacology. LXIII. Retinoid X receptors. *Pharmacological Reviews.* 58:760-772.
- Germain, P., S. Kammerer, E. Perez, C. Peluso-Iltis, D. Tortolani, F.C. Zusi, J. Starrett, P. Lapointe, J.P. Daris, A. Marinier, A.R. de Lera, N. Rochel, and H. Gronemeyer.** 2004. Rational design of RAR-selective ligands revealed by RARbeta crystal structure. *EMBO Rep.* 5:877-82.

- Gettemans, J., K. Van Impe, V. Delanote, T. Hubert, J. Vandekerckhove, and V. De Corte.** 2005. Nuclear actin-binding proteins as modulators of gene transcription. *Traffic*. 6:847-57.
- Gianni, M., A. Bauer, E. Garattini, P. Chambon, and C. Rochette-Egly.** 2002. Phosphorylation by p38MAPK and recruitment of SUG-1 are required for RA-induced RAR gamma degradation and transactivation. *EMBO J*. 21:3760-9.
- Giesemann, T., S. Rathke-Hartlieb, M. Rothkegel, J.W. Bartsch, S. Buchmeier, B.M. Jockusch, and H. Jockusch.** 1999. A role for polyproline motifs in the spinal muscular atrophy protein SMN. Profilins bind to and colocalize with smn in nuclear gems. *J Biol Chem*. 274:37908-14.
- Giesemann, T., G. Schwarz, R. Nawrotzki, K. Berhorster, M. Rothkegel, K. Schluter, N. Schrader, H. Schindelin, R.R. Mendel, J. Kirsch, and B.M. Jockusch.** 2003. Complex formation between the postsynaptic scaffolding protein gephyrin, profilin, and mena: A possible link of the microfilament system. *Journal of Neuroscience*. 23:8330-8339.
- Giglia-Mari, G., F. Coin, J.A. Ranish, D. Hoogstraten, A. Theil, N. Wijgers, N.G. Jaspers, A. Raams, M. Argentini, P.J. van der Spek, E. Botta, M. Stefanini, J.M. Egly, R. Aebersold, J.H. Hoeijmakers, and W. Vermeulen.** 2004. A new, tenth subunit of TFIIH is responsible for the DNA repair syndrome trichothiodystrophy group A. *Nat Genet*. 36:714-9.
- Glass, C.K.** 1994. Differential Recognition of Target Genes by Nuclear Receptor Monomers, Dimers, and Heterodimers. *Endocrine Reviews*. 15:391-407.
- Goodman, D.S., and H.S. Huang.** 1965. Biosynthesis of Vitamin a with Rat Intestinal Enzymes. *Science*. 149:879-80.
- Gottesman, M.E., L. Quadro, and W.S. Blaner.** 2001. Studies of vitamin A metabolism in mouse model systems. *Bioessays*. 23:409-19.
- Grenklo, S., T. Johansson, L. Bertilson, and R. Karlsson.** 2004. Anti-actin antibodies generated against profilin : actin distinguish between non-filamentous and filamentous actin, and label cultured cells in a dotted pattern. *European Journal of Cell Biology*. 83:413-423.
- Gupta, P., P.C. Ho, M.M. Huq, S.G. Ha, S.W. Park, A.A. Khan, N.P. Tsai, and L.N. Wei.** 2008. Retinoic acid-stimulated sequential phosphorylation, PML recruitment, and SUMOylation of nuclear receptor TR2 to suppress Oct4 expression. *Proc Natl Acad Sci U S A*. 105:11424-9.
- Gutsche-Perelroizen, I., J. Lepault, A. Ott, and M.F. Carrier.** 1999. Filament assembly from profilin-actin. *J Biol Chem*. 274:6234-43.
- Guyot, R., S. Vincent, J. Bertin, J. Samarut, and P. Ravel-Chapuis.** 2010. The transforming acidic coiled coil (TACC1) protein modulates the transcriptional activity of the nuclear receptors TR and RAR. *Bmc Molecular Biology*. 11.
- Ha, J.S., H.M. Lim, and S.S. Park.** 2010. Extracellular hydrogen peroxide contributes to oxidative glutamate toxicity. *Brain Res*. 1359:291-7.

- Haarer, B.K., S.H. Lillie, A.E.M. Adams, V. Magdolen, W. Bandlow, and S.S. Brown.** 1990. Purification of Profilin from *Saccharomyces-Cerevisiae* and Analysis of Profilin-Deficient Cells. *Journal of Cell Biology*. 110:105-114.
- Hagan, C.R., E.J. Faivre, and C.A. Lange.** 2009. Scaffolding actions of membrane-associated progesterone receptors. *Steroids*. 74:568-72.
- Haikarainen, T., W.Q. Chen, G. Lubec, and P. Kursula.** 2009. Structure, modifications and ligand-binding properties of rat profilin 2a. *Acta Crystallographica Section D-Biological Crystallography*. 65:303-311.
- Hajkova, L., C. Bjorkegren Sjogren, E. Korenbaum, P. Nordberg, and R. Karlsson.** 1997. Characterization of a mutant profilin with reduced actin-binding capacity: effects in vitro and in vivo. *Exp Cell Res*. 234:66-77.
- Hamy, F., P. Verwaerde, N. Helbecque, P. Formstecher, and J.P. Henichart.** 1991. Nuclear Targeting of a Viral-Cointernalized Protein by a Short Signal Sequence from Human Retinoic Acid Receptors. *Bioconjugate Chemistry*. 2:375-378.
- Han, Y.H., H. Zhou, J.H. Kim, T.D. Yan, K.H. Lee, H. Wu, F. Lin, N. Lu, J. Liu, J.Z. Zeng, and X.K. Zhang.** 2009. A unique cytoplasmic localization of retinoic acid receptor-gamma and its regulations. *J Biol Chem*. 284:18503-14.
- Haugwitz, M., A.A. Noegel, J. Karakesisoglou, and M. Schleicher.** 1994. Dictyostelium Amebas That Lack G-Actin-Sequestering Profilins Show Defects in F-Actin Content, Cytokinesis, and Development. *Cell*. 79:303-314.
- Hauksdottir, H., B. Farboud, and M.L. Privalsky.** 2003. Retinoic acid receptors beta and gamma do not repress, but instead activate target gene transcription in both the absence and presence of hormone ligand. *Mol Endocrinol*. 17:373-85.
- Heery, D.M., E. Kalkhoven, S. Hoare, and M.G. Parker.** 1997. A signature motif in transcriptional co-activators mediates binding to nuclear receptors. *Nature*. 387:733-6.
- Heinzel, T., R.M. Lavinsky, T.M. Mullen, M. Soderstrom, C.D. Laherty, J. Torchia, W.M. Yang, G. Brard, S.D. Ngo, J.R. Davie, E. Seto, R.N. Eisenman, D.W. Rose, C.K. Glass, and M.G. Rosenfeld.** 1997. A complex containing N-CoR, mSin3 and histone deacetylase mediates transcriptional repression. *Nature*. 387:43-48.
- Hong, W.K., and R. Lotan.** 1993. Retinoids in oncology. Marcel Dekker, Inc.
- Honore, B., P. Madsen, A.H. Andersen, and H. Leffers.** 1993. Cloning and Expression of a Novel Human Profilin Variant, Profilin-Ii. *Febs Letters*. 330:151-155.
- Horlein, A.J., A.M. Naar, T. Heinzel, J. Torchia, B. Gloss, R. Kurokawa, A. Ryan, Y. Kamel, M. Soderstrom, C.K. Glass, and M.G. Rosenfeld.** 1995. Ligand-Independent Repression by the Thyroid-Hormone Receptor-Mediated by a Nuclear Receptor Co-Repressor. *Nature*. 377:397-404.

- Hu, E.D., Z.X. Chen, T. Fredrickson, and Y. Zhu.** 2001. Molecular cloning and characterization of profilin-3: A novel cytoskeleton-associated gene expressed in rat kidney and testes. *Experimental Nephrology*. 9:265-274.
- Hu, X., Y. Chen, M. Farooqui, M.C. Thomas, C.M. Chiang, and L.N. Wei.** 2004. Suppressive effect of receptor-interacting protein 140 on coregulator binding to retinoic acid receptor complexes, histone-modifying enzyme activity, and gene activation. *J Biol Chem*. 279:319-25.
- Hu, X., and M.A. Lazar.** 1999. The CoRNR motif controls the recruitment of corepressors by nuclear hormone receptors. *Nature*. 402:93-96.
- Huang, Z.Q., J.W. Li, L.M. Sachs, P.A. Cole, and J.M. Wong.** 2003. A role for cofactor-cofactor and cofactor-histone interactions in targeting p300, SWI/SNF and Mediator for transcription. *Embo Journal*. 22:2146-2155.
- Huhtakangas, J.A., C.J. Olivera, J.E. Bishop, L.P. Zanello, and A.W. Norman.** 2004. The vitamin D receptor is present in caveolae-enriched plasma membranes and binds 1 alpha,25(OH)₂-vitamin D₃ in vivo and in vitro. *Mol Endocrinol*. 18:2660-71.
- Jockusch, B.M., K. Murk, and M. Rothkegel.** 2007. The profile of profilins. *Rev Physiol Biochem Pharmacol*. 159:131-49.
- Jockusch, B.M., C.A. Schoenenberger, J. Stetefeld, and U. Aebi.** 2006. Tracking down the different forms of nuclear actin. *Trends Cell Biol*. 16:391-6.
- Kambhampati, S., Y. Li, A. Verma, A. Sassano, B. Majchrzak, D.K. Deb, S. Parmar, N. Giafis, D.V. Kalvakolanu, A. Rahman, S. Uddin, S. Minucci, M.S. Tallman, E.N. Fish, and L.C. Platanias.** 2003. Activation of protein kinase C delta by all-trans-retinoic acid. *J Biol Chem*. 278:32544-51.
- Karakesisoglou, I., M. Schleicher, B.C. Gibbon, and C.J. Staiger.** 1996. Plant profilins rescue the aberrant phenotype of profilin-deficient Dictyostelium cells. *Cell Motil Cytoskeleton*. 34:36-47.
- Kast, D.J., and R. Dominguez.** 2011. Arp you ready for actin in the nucleus? *Embo J*. 30:2097-8.
- Kay, B.K., M.P. Williamson, and M. Sudol.** 2000a. The importance of being proline: the interaction of proline-rich motifs in signaling proteins with their cognate domains. *FASEB J*. 14:231-41.
- Kay, B.K., M.P. Williamson, and P. Sudol.** 2000b. The importance of being proline: the interaction of proline-rich motifs in signaling proteins with their cognate domains. *Faseb Journal*. 14:231-241.
- Keriel, A., A. Stary, A. Sarasin, C. Rochette-Egly, and J.M. Egly.** 2002. XPD mutations prevent TFIIH-dependent transactivation by nuclear receptors and phosphorylation of RARalpha. *Cell*. 109:125-35.
- Kiefer, C., S. Hessel, J.M. Lampert, K. Vogt, M.O. Lederer, D.E. Breithaupt, and J. von Lintig.** 2001. Identification and characterization of a mammalian enzyme catalyzing the asymmetric oxidative cleavage of provitamin A. *J Biol Chem*. 276:14110-6.

- Kim, J.H., H.W. Li, and M.R. Stallcup.** 2003. CoCoA, a nuclear receptor coactivator which acts through an N-terminal activation domain of p160 coactivators. *Molecular Cell*. 12:1537-1549.
- Kioka, N.** 2002. A novel adaptor protein family regulating cytoskeletal organization and signal transduction - Vinexin, CAP/ponsin, ArgBP2. *Seikagaku*. 74:1356-1360.
- Klaholz, B.P., A. Mitschler, and D. Moras.** 2000. Structural basis for isotype selectivity of the human retinoic acid nuclear receptor. *J Mol Biol*. 302:155-70.
- Krause, M., E.W. Dent, J.E. Bear, J.J. Loureiro, and F.B. Gertler.** 2003. Ena/VASP proteins: regulators of the actin cytoskeleton and cell migration. *Annu Rev Cell Dev Biol*. 19:541-64.
- Krauss, G.** 2008. Biochemistry of Signal Transduction and Regulation. Wiley-VCH.
- Kursula, P., I. Kursula, M. Massimi, Y.H. Song, J. Downer, W.A. Stanley, W. Witke, and M. Wilmanns.** 2008. High-resolution structural analysis of mammalian profilin 2a complex formation with two physiological ligands: The formin homology 1 domain of mDial and the proline-rich domain of VASP. *Journal of Molecular Biology*. 375:270-290.
- Lai, L., L. Yuan, Q. Chen, C. Dong, L. Mao, B. Rowan, T. Frasch, and S.M. Hill.** 2008. The Galphai and Galphaq proteins mediate the effects of melatonin on steroid/thyroid hormone receptor transcriptional activity and breast cancer cell proliferation. *J Pineal Res*. 45:476-88.
- Lalevee, S., G. Bour, M. Quinternet, E. Samarut, P. Kessler, M. Vitorino, N. Bruck, M.A. Delsuc, J.L. Vonesch, B. Kieffer, and C. Rochette-Egly.** 2010a. Vinexin beta, an atypical "sensor" of retinoic acid receptor gamma signaling: union and sequestration, separation, and phosphorylation. *Faseb Journal*. 24:4523-4534.
- Lalevee, S., G. Bour, M. Quinternet, E. Samarut, P. Kessler, M. Vitorino, N. Bruck, M.A. Delsuc, J.L. Vonesch, B. Kieffer, and C. Rochette-Egly.** 2010b. Vinexinss, an atypical "sensor" of retinoic acid receptor gamma signaling: union and sequestration, separation, and phosphorylation. *FASEB J*. 24:4523-34.
- Lambrechts, A., A. Braun, V. Jonckheere, A. Aszodi, L.M. Lanier, J. Robbens, I. Van Colen, J. Vandekerckhove, R. Fassler, and C. Ampe.** 2000. Profilin II is alternatively spliced, resulting in profilin isoforms that are differentially expressed and have distinct biochemical properties. *Mol Cell Biol*. 20:8209-19.
- Lambrechts, A., V. Jonckheere, D. Dewitte, J. Vandekerckhove, and C. Ampe.** 2002. Mutational analysis of human profilin I reveals a second PI(4,5)-P2 binding site neighbouring the poly(L-proline) binding site. *BMC Biochem*. 3:12.
- Lambrechts, A., J. van Damme, M. Goethals, J. Vandekerckhove, and C. Ampe.** 1995. Purification and characterization of bovine profilin II. Actin, poly(L-proline) and inositolphospholipid binding. *Eur J Biochem*. 230:281-6.
- Lambrechts, A., J.L. Verschelde, V. Jonckheere, M. Goethals, J. Vandekerckhove, and C. Ampe.** 1997. The mammalian profilin isoforms display complementary affinities for PIP2 and proline-rich sequences. *EMBO J*. 16:484-94.

- Lannigan, D.A.** 2003. Estrogen receptor phosphorylation. *Steroids*. 68:1-9.
- Lappalainen, P.** 2007. Actin-monomer-binding proteins. Landes Bioscience.
- Lappalainen, P., R. Karlsson, and U. Lindberg.** 2007. Profilin, an Essential Control Element for Actin Polymerization . Actin-Monomer-Binding Proteins. Springer New York. 29-44.
- Lassing, I., and U. Lindberg.** 1988. Specificity of the Interaction between Phosphatidylinositol 4,5-Bisphosphate and the Profilin - Actin Complex. *Journal of Cellular Biochemistry*. 37:255-267.
- Laudet, V., and H. Gronemeyer.** 2002. The nuclear receptor factsbook. Academic Press.
- Lavinsky, R.M., K. Jepsen, T. Heinzel, J. Torchia, T.M. Mullen, R. Schiff, A.L. Del-Rio, M. Ricote, S. Ngo, J. Gemsch, S.G. Hilsenbeck, C.K. Osborne, C.K. Glass, M.G. Rosenfeld, and D.W. Rose.** 1998. Diverse signaling pathways modulate nuclear receptor recruitment of N-CoR and SMRT complexes. *Proceedings of the National Academy of Sciences of the United States of America*. 95:2920-2925.
- Le Douarin, B., C. Zechel, J.M. Garnier, Y. Lutz, L. Tora, P. Pierrat, D. Heery, H. Gronemeyer, P. Chambon, and R. Losson.** 1995. The N-terminal part of TIF1, a putative mediator of the ligand-dependent activation function (AF-2) of nuclear receptors, is fused to B-raf in the oncogenic protein T18. *EMBO J*. 14:2020-33.
- Le Romancer, M., C. Poulard, P. Cohen, S. Sentis, J.M. Renoir, and L. Corbo.** 2011. Cracking the estrogen receptor's posttranslational code in breast tumors. *Endocr Rev*. 32:597-622.
- Le Romancer, M., I. Treilleux, N. Leconte, Y. Robin-Lespinasse, S. Sentis, K. Bouchekioua-Bouzaghrou, S. Goddard, S. Gobert-Gosse, and L. Corbo.** 2008. Regulation of estrogen rapid signaling through arginine methylation by PRMT1. *Mol Cell*. 31:212-21.
- Lederer, M., B.M. Jockusch, and M. Rothkegel.** 2005a. Profilin regulates the activity of p42(POP), a novel Myb-related transcription factor. *Journal of Cell Science*. 118:331-341.
- Lederer, M., B.M. Jockusch, and M. Rothkegel.** 2005b. Profilin regulates the activity of p42POP, a novel Myb-related transcription factor. *J Cell Sci*. 118:331-41.
- Lee, D.Y., J.P. Northrop, M.H. Kuo, and M.R. Stallcup.** 2006. Histone H3 lysine 9 methyltransferase G9a is a transcriptional coactivator for nuclear receptors. *Journal of Biological Chemistry*. 281:8476-8485.
- Lee, D.Y., C. Teyssier, B.D. Strahl, and M.R. Stallcup.** 2005. Role of protein methylation in regulation of transcription. *Endocr Rev*. 26:147-70.
- Lee, J.W., H.S. Choi, J. Gyuris, R. Brent, and D.D. Moore.** 1995. 2 Classes of Proteins Dependent on Either the Presence or Absence of Thyroid-Hormone for Interaction with the Thyroid-Hormone Receptor. *Molecular Endocrinology*. 9:243-254.
- Lee, M.S., S.A. Kliewer, J. Provencal, P.E. Wright, and R.M. Evans.** 1993. Structure of the retinoid X receptor alpha DNA binding domain: a helix required for homodimeric DNA binding. *Science*. 260:1117-21.

- Lefebvre, P., P.J. Martin, S. Flajollet, S. Dedieu, X. Billaut, and B. Lefebvre.** 2005. Transcriptional activities of retinoic acid receptors. *Vitam Horm.* 70:199-264.
- Leid, M., P. Kastner, and P. Chambon.** 1992. Multiplicity generates diversity in the retinoic acid signalling pathways. *Trends Biochem Sci.* 17:427-33.
- Li, D., T.L. Zimmerman, S. Thevananther, H.Y. Lee, J.M. Kurie, and S.J. Karpen.** 2002. Interleukin-1 beta-mediated suppression of RXR:RAR transactivation of the Ntcp promoter is JNK-dependent. *J Biol Chem.* 277:31416-22.
- Li, J.W., J. Wang, J.X. Wang, Z. Nawaz, J.M. Liu, J. Qin, and J.M. Wong.** 2000. Both corepressor proteins SMRT and N-CoR exist in large protein complexes containing HDAC3. *Embo Journal.* 19:4342-4350.
- Li, Y., M.H. Lambert, and H.E. Xu.** 2003. Activation of nuclear receptors: a perspective from structural genomics. *Structure.* 11:741-6.
- Lindberg, U., R. Karlsson, I. Lassing, C.E. Schutt, and A.S. Høglund.** 2008. The microfilament system and malignancy. *Seminars in Cancer Biology.* 18:2-11.
- Lindberg, U., C.E. Schutt, E. Hellsten, A.C. Tjader, and T. Hult.** 1988. The use of poly(L-proline)-Sepharese in the isolation of profilin and profilactin complexes. *Biochim Biophys Acta.* 967:391-400.
- Lippert, W.P., C. Burschka, K. Gotz, M. Kaupp, D. Ivanova, C. Gaudon, Y. Sato, P. Antony, N. Rochel, D. Moras, H. Gronemeyer, and R. Tacke.** 2009. Silicon analogues of the RXR-selective retinoid agonist SR11237 (BMS649): chemistry and biology. *ChemMedChem.* 4:1143-52.
- Littlefield, R., A. Almenar-Queralt, and V.M. Fowler.** 2001. Actin dynamics at pointed ends regulates thin filament length in striated muscle. *Nature Cell Biology.* 3:544-551.
- Liu, J., N.B. Perumal, C.J. Oldfield, E.W. Su, V.N. Uversky, and A.K. Dunker.** 2006. Intrinsic disorder in transcription factors. *Biochemistry.* 45:6873-88.
- Lo, W.S., R.C. Trievel, J.R. Rojas, L. Duggan, J.Y. Hsu, C.D. Allis, R. Marmorstein, and S.L. Berger.** 2000. Phosphorylation of serine 10 in histone H3 is functionally linked in vitro and in vivo to Gcn5-mediated acetylation at lysine 14. *Molecular Cell.* 5:917-926.
- Lohnes, D., P. Kastner, A. Dierich, M. Mark, M. Lemeur, and P. Chambon.** 1993. Function of Retinoic Acid Receptor-Gamma in the Mouse. *Cell.* 73:643-658.
- Lombardi, M., G. Castoria, A. Migliaccio, M.V. Barone, R. Di Stasio, A. Ciociola, D. Bottero, H. Yamaguchi, E. Appella, and F. Auricchio.** 2008. Hormone-dependent nuclear export of estradiol receptor and DNA synthesis in breast cancer cells. *J Cell Biol.* 182:327-40.
- Losel, R., and M. Wehling.** 2003. Nongenomic actions of steroid hormones. *Nat Rev Mol Cell Biol.* 4:46-56.

- Loudig, O., C. Babichuk, J. White, S. Abu-Abed, C. Mueller, and M. Petkovich.** 2000. Cytochrome P450RAI(CYP26) promoter: a distinct composite retinoic acid response element underlies the complex regulation of retinoic acid metabolism. *Mol Endocrinol.* 14:1483-97.
- Lufkin, T., D. Lohnes, M. Mark, A. Dierich, P. Gorry, M.P. Gaub, M. Lemeur, and P. Chambon.** 1993. High Postnatal Lethality and Testis Degeneration in Retinoic Acid Receptor-Alpha Mutant Mice. *Proceedings of the National Academy of Sciences of the United States of America.* 90:7225-7229.
- Luoma, J.I., M.I. Boulware, and P.G. Mermelstein.** 2008. Caveolin proteins and estrogen signaling in the brain. *Mol Cell Endocrinol.* 290:8-13.
- Machesky, L.M., N.B. Cole, B. Moss, and T.D. Pollard.** 1994. Vaccinia virus expresses a novel profilin with a higher affinity for polyphosphoinositides than actin. *Biochemistry.* 33:10815-24.
- Machesky, L.M., and T.D. Poland.** 1993. Profilin as a potential mediator of membrane-cytoskeleton communication. *Trends in Cell Biology.* 3:381-385.
- Macias, M.J., S. Wiesner, and M. Sudol.** 2002. WW and SH3 domains, two different scaffolds to recognize proline-rich ligands. *Febs Letters.* 513:30-37.
- Mahoney, N.M., P.A. Janmey, and S.C. Almo.** 1997. Structure of the profilin-poly-L-proline complex involved in morphogenesis and cytoskeletal regulation. *Nat Struct Biol.* 4:953-60.
- Mahoney, N.M., D.A. Rozwarski, E. Fedorov, A.A. Fedorov, and S.C. Almo.** 1999. Profilin binds proline-rich ligands in two distinct amide backbone orientations. *Nat Struct Biol.* 6:666-71.
- Mangelsdorf, D.J., and R.M. Evans.** 1995. The RXR heterodimers and orphan receptors. *Cell.* 83:841-50.
- Mangelsdorf, D.J., K. Umesono, S.A. Kliewer, U. Borgmeyer, E.S. Ong, and R.M. Evans.** 1991. A direct repeat in the cellular retinol-binding protein type II gene confers differential regulation by RXR and RAR. *Cell.* 66:555-61.
- Mann, K.K., A.M. Padovani, Q. Guo, A.L. Colosimo, H.Y. Lee, J.M. Kurie, and W.H. Miller, Jr.** 2005. Arsenic trioxide inhibits nuclear receptor function via SEK1/JNK-mediated RXRalpha phosphorylation. *J Clin Invest.* 115:2924-33.
- Marquez, D.C., H.W. Chen, E.M. Curran, W.V. Welshons, and R.J. Pietras.** 2006. Estrogen receptors in membrane lipid rafts and signal transduction in breast cancer. *Mol Cell Endocrinol.* 246:91-100.
- Masia, S., S. Alvarez, A.R. de Lera, and D. Baretino.** 2007. Rapid, nongenomic actions of retinoic Acid on phosphatidylinositol-3-kinase signaling pathway mediated by the retinoic Acid receptor. *Mol Endocrinol.* 21:2391-402.
- Matthews, L., A. Berry, V. Ohanian, J. Ohanian, H. Garside, and D. Ray.** 2008. Caveolin mediates rapid glucocorticoid effects and couples glucocorticoid action to the antiproliferative program. *Mol Endocrinol.* 22:1320-30.

- Mayboroda, O., K. Schluter, and B.M. Jockusch.** 1997. Differential colocalization of profilin with microfilaments in PtK2 cells. *Cell Motil Cytoskeleton.* 37:166-77.
- Mendoza-Parra, M.A., M. Walia, M. Sankar, and H. Gronemeyer.** 2011. Dissecting the retinoid-induced differentiation of F9 embryonal stem cells by integrative genomics. *Mol Syst Biol.* 7:538.
- Michaelsen, K., K. Murk, M. Zagrebelsky, A. Dreznjak, B.M. Jockusch, M. Rothkegel, and M. Korte.** 2010. Fine-tuning of neuronal architecture requires two profilin isoforms. *Proc Natl Acad Sci U S A.* 107:15780-5.
- Migliaccio, A., G. Castoria, M. Di Domenico, A. de Falco, A. Bilancio, M. Lombardi, M.V. Barone, D. Ametrano, M.S. Zannini, C. Abbondanza, and F. Auricchio.** 2000. Steroid-induced androgen receptor-oestradiol receptor beta-*Src* complex triggers prostate cancer cell proliferation. *EMBO J.* 19:5406-17.
- Migliaccio, A., D. Piccolo, G. Castoria, M. Di Domenico, A. Bilancio, M. Lombardi, W. Gong, M. Beato, and F. Auricchio.** 1998. Activation of the *Src/p21ras/Erk* pathway by progesterone receptor via cross-talk with estrogen receptor. *Embo J.* 17:2008-18.
- Miloso, M., D. Villa, M. Crimi, S. Galbiati, E. Donzelli, G. Nicolini, and G. Tredici.** 2004. Retinoic acid-induced neuritogenesis of human neuroblastoma SH-SY5Y cells is ERK independent and PKC dependent. *J Neurosci Res.* 75:241-52.
- Mizuno, N., and H. Itoh.** 2009. Functions and regulatory mechanisms of Gq-signaling pathways. *Neurosignals.* 17:42-54.
- Moore, T.** 1930. Vitamin A and carotene: The absence of the liver oil vitamin A from carotene. VI. The conversion of carotene to vitamin A in vivo. *Biochem J.* 24:692-702.
- Moras, D., and H. Gronemeyer.** 1998. The nuclear receptor ligand-binding domain: structure and function. *Curr Opin Cell Biol.* 10:384-91.
- Mullins, R.D., J.F. Kelleher, J. Xu, and T.D. Pollard.** 1998. Arp2/3 complex from *Acanthamoeba* binds profilin and cross-links actin filaments. *Mol Biol Cell.* 9:841-52.
- Murk, K., S. Buchmeier, B.M. Jockusch, and M. Rothkegel.** 2009. In birds, profilin-2a is ubiquitously expressed and contributes to actin-based motility. *J Cell Sci.* 122:957-64.
- Nagpal, S., S. Friant, H. Nakshatri, and P. Chambon.** 1993. RARs and RXRs: evidence for two autonomous transactivation functions (AF-1 and AF-2) and heterodimerization in vivo. *EMBO J.* 12:2349-60.
- Nagpal, S., M. Saunders, P. Kastner, B. Durand, H. Nakshatri, and P. Chambon.** 1992. Promoter context- and response element-dependent specificity of the transcriptional activation and modulating functions of retinoic acid receptors. *Cell.* 70:1007-19.
- Nagy, L., H.Y. Kao, D. Chakravarti, R.J. Lin, C.A. Hassig, D.E. Ayer, S.L. Schreiber, and R.M. Evans.** 1997. Nuclear receptor repression mediated by a complex containing SMRT, mSin3A, and histone deacetylase. *Cell.* 89:373-380.

- Nagy, L., H.Y. Kao, J.D. Love, C. Li, E. Banayo, J.T. Gooch, V. Krishna, K. Chatterjee, R.M. Evans, and J.W.R. Schwabe.** 1999. Mechanism of corepressor binding and release from nuclear hormone receptors. *Genes & Development*. 13:3209-3216.
- Napoli, J.L.** 1996. Biochemical pathways of retinoid transport, metabolism, and signal transduction. *Clin Immunol Immunopathol*. 80:S52-62.
- Nelson, C.J., H. Santos-Rosa, and T. Kouzarides.** 2006. Proline isomerization of histone H3 regulates lysine methylation and gene expression. *Cell*. 126:905-16.
- Niederreither, K., V. Fraulob, J.M. Garnier, P. Chambon, and P. Dolle.** 2002. Differential expression of retinoic acid-synthesizing (RALDH) enzymes during fetal development and organ differentiation in the mouse. *Mech Dev*. 110:165-71.
- Norman, A.W., H.L. Henry, J.E. Bishop, X.D. Song, C. Bula, and W.H. Okamura.** 2001. Different shapes of the steroid hormone 1 α ,25(OH) $_2$ -vitamin D $_3$ act as agonists for two different receptors in the vitamin D endocrine system to mediate genomic and rapid responses. *Steroids*. 66:147-58.
- Norman, A.W., M.T. Mizwicki, and D.P. Norman.** 2004. Steroid-hormone rapid actions, membrane receptors and a conformational ensemble model. *Nat Rev Drug Discov*. 3:27-41.
- O'Malley, B.W., and R. Kumar.** 2008. Nuclear Receptor Coregulators and Human. World Scientific.
- Obermann, H., I. Raabe, M. Balvers, B. Brunswig, W. Schulze, and C. Kirchhoff.** 2005. Novel testis-expressed profilin IV associated with acrosome biogenesis and spermatid elongation. *Molecular Human Reproduction*. 11:53-64.
- Olson, J.A., and O. Hayaishi.** 1965. The enzymatic cleavage of beta-carotene into vitamin A by soluble enzymes of rat liver and intestine. *Proc Natl Acad Sci U S A*. 54:1364-70.
- Ordonez-Moran, P., M.J. Larriba, H.G. Palmer, R.A. Valero, A. Barbachano, M. Dunach, A.G. de Herreros, C. Villalobos, M.T. Berciano, M. Lafarga, and A. Munoz.** 2008. RhoA-ROCK and p38MAPK-MSK1 mediate vitamin D effects on gene expression, phenotype, and Wnt pathway in colon cancer cells. *J Cell Biol*. 183:697-710.
- Ostrander, D.B., J.A. Gorman, and G.M. Carman.** 1995. Regulation of profilin localization in *Saccharomyces cerevisiae* by phosphoinositide metabolism. *J Biol Chem*. 270:27045-50.
- Paik, J., S. Vogel, L. Quadro, R. Piantedosi, M. Gottesman, K. Lai, L. Hamberger, M. Vieira Mde, and W.S. Blaner.** 2004. Vitamin A: overlapping delivery pathways to tissues from the circulation. *J Nutr*. 134:276S-280S.
- Pan, J., Y.L. Kao, S. Joshi, S. Jeetendran, D. Dipette, and U.S. Singh.** 2005. Activation of Rac1 by phosphatidylinositol 3-kinase in vivo: role in activation of mitogen-activated protein kinase (MAPK) pathways and retinoic acid-induced neuronal differentiation of SH-SY5Y cells. *J Neurochem*. 93:571-83.
- Pantaloni, D., and M.F. Carlier.** 1993. How Profilin Promotes Actin Filament Assembly in the Presence of Thymosin-Beta-4. *Cell*. 75:1007-1014.

- Pares, X., J. Farres, N. Kedishvili, and G. Duester.** 2008. Medium- and short-chain dehydrogenase/reductase gene and protein families : Medium-chain and short-chain dehydrogenases/reductases in retinoid metabolism. *Cell Mol Life Sci.* 65:3936-49.
- Park, S.S., J.E. Kim, Y.A. Kim, Y.C. Kim, and S.W. Kim.** 2005. Caveolin-1 is down-regulated and inversely correlated with HER2 and EGFR expression status in invasive ductal carcinoma of the breast. *Histopathology.* 47:625-30.
- Pavri, R., B. Lewis, T.K. Kim, F.J. Dilworth, H. Erdjument-Bromage, P. Tempst, G. de Murcia, R. Evans, P. Chambon, and D. Reinberg.** 2005. PARP-1 determines specificity in a retinoid signaling pathway via direct modulation of mediator. *Mol Cell.* 18:83-96.
- Pedram, A., M. Razandi, R.C. Sainson, J.K. Kim, C.C. Hughes, and E.R. Levin.** 2007. A conserved mechanism for steroid receptor translocation to the plasma membrane. *J Biol Chem.* 282:22278-88.
- Perissi, V., A. Aggarwal, C.K. Glass, D.W. Rose, and M.G. Rosenfeld.** 2004. A corepressor/coactivator exchange complex required for transcriptional activation by nuclear receptors and other regulated transcription factors. *Cell.* 116:511-26.
- Perissi, V., and M.G. Rosenfeld.** 2005. Controlling nuclear receptors: The circular logic of cofactor cycles. *Nature Reviews Molecular Cell Biology.* 6:542-554.
- Perissi, V., L.M. Staszewski, E.M. McInerney, R. Kurokawa, A. Kronen, D.W. Rose, M.H. Lambert, M.V. Milburn, C.K. Glass, and M.G. Rosenfeld.** 1999. Molecular determinants of nuclear receptor-corepressor interaction. *Genes & Development.* 13:3198-3208.
- Pike, L.J.** 2003. Lipid rafts: bringing order to chaos. *J Lipid Res.* 44:655-67.
- Piskunov, A., and C. Rochette-Egly.** 2011a. A retinoic acid receptor RARalpha pool present in membrane lipid rafts forms complexes with G protein alphaQ to activate p38MAPK. *Oncogene.*
- Piskunov, A., and C. Rochette-Egly.** 2011b. MSK1 and Nuclear Receptors Signaling. Landes Bioscience Books, Austin, TX, USA.
- Pogenberg, V., J.F. Guichou, V. Vivat-Hannah, S. Kammerer, E. Perez, P. Germain, A.R. de Lera, H. Gronemeyer, C.A. Royer, and W. Bourguet.** 2005. Characterization of the interaction between retinoic acid receptor/retinoid X receptor (RAR/RXR) heterodimers and transcriptional coactivators through structural and fluorescence anisotropy studies. *J Biol Chem.* 280:1625-33.
- Poon, M.M., and L. Chen.** 2008. Retinoic acid-gated sequence-specific translational control by RAR alpha. *Proceedings of the National Academy of Sciences of the United States of America.* 105:20303-20308.
- Pufall, M.A., G.M. Lee, M.L. Nelson, H.S. Kang, A. Velyvis, L.E. Kay, L.P. McIntosh, and B.J. Graves.** 2005. Variable control of Ets-1 DNA binding by multiple phosphates in an unstructured region. *Science.* 309:142-5.

- Qian, A., Y. Cai, T.R. Magee, and Y.J. Wan.** 2000. Identification of retinoic acid-responsive elements on the HNF1alpha and HNF4alpha genes. *Biochem Biophys Res Commun.* 276:837-42.
- Qiu, J., M.A. Bosch, S.C. Tobias, D.K. Grandy, T.S. Scanlan, O.K. Ronnekleiv, and M.J. Kelly.** 2003. Rapid signaling of estrogen in hypothalamic neurons involves a novel G-protein-coupled estrogen receptor that activates protein kinase C. *J Neurosci.* 23:9529-40.
- Rastinejad, F., T. Wagner, Q. Zhao, and S. Khorasanizadeh.** 2000. Structure of the RXR-RAR DNA-binding complex on the retinoic acid response element DR1. *EMBO J.* 19:1045-54.
- Rawe, V.Y., C. Payne, and G. Schatten.** 2006. Profilin and actin-related proteins regulate microfilament dynamics during early mammalian embryogenesis. *Human Reproduction.* 21:1143-1153.
- Reid, J., S.M. Kelly, K. Watt, N.C. Price, and I.J. McEwan.** 2002. Conformational analysis of the androgen receptor amino-terminal domain involved in transactivation. Influence of structure-stabilizing solutes and protein-protein interactions. *J Biol Chem.* 277:20079-86.
- Reijntjes, S., E. Gale, and M. Maden.** 2004. Generating gradients of retinoic acid in the chick embryo: Cyp26C1 expression and a comparative analysis of the Cyp26 enzymes. *Dev Dyn.* 230:509-17.
- Reinhard, M., K. Giehl, K. Abel, C. Haffner, T. Jarchau, V. Hoppe, B.M. Jockusch, and U. Walter.** 1995. The proline-rich focal adhesion and microfilament protein VASP is a ligand for profilins. *EMBO J.* 14:1583-9.
- Ren, X., Y. Li, X. Ma, L. Zheng, Y. Xu, and J. Wang.** 2007. Activation of p38/MEF2C pathway by all-trans retinoic acid in cardiac myoblasts. *Life Sci.* 81:89-96.
- Renaud, J.P., and D. Moras.** 2000. Structural studies on nuclear receptors. *Cell Mol Life Sci.* 57:1748-69.
- Renaud, J.P., N. Rochel, M. Ruff, V. Vivat, P. Chambon, H. Gronemeyer, and D. Moras.** 1995. Crystal structure of the RAR-gamma ligand-binding domain bound to all-trans retinoic acid. *Nature.* 378:681-9.
- Ridley, A.J., M.A. Schwartz, K. Burridge, R.A. Firtel, M.H. Ginsberg, G. Borisy, J.T. Parsons, and A.R. Horwitz.** 2003. Cell migration: Integrating signals from front to back. *Science.* 302:1704-1709.
- Rochel, N., F. Ciesielski, J. Godet, E. Moman, M. Roessle, C. Peluso-Iltis, M. Moulin, M. Haertlein, P. Callow, Y. Mely, D.I. Svergun, and D. Moras.** 2011. Common architecture of nuclear receptor heterodimers on DNA direct repeat elements with different spacings. *Nat Struct Mol Biol.* 18:564-70.
- Rochette-Egly, C.** 2003. Nuclear receptors: integration of multiple signalling pathways through phosphorylation. *Cell Signal.* 15:355-66.

- Rochette-Egly, C.** 2005. Dynamic combinatorial networks in nuclear receptor-mediated transcription. *Journal of Biological Chemistry*. 280:32565-32568.
- Rochette-Egly, C., S. Adam, M. Rossignol, J.M. Egly, and P. Chambon.** 1997. Stimulation of RAR alpha activation function AF-1 through binding to the general transcription factor TFIID and phosphorylation by CDK7. *Cell*. 90:97-107.
- Rochette-Egly, C., and P. Germain.** 2009. Dynamic and combinatorial control of gene expression by nuclear retinoic acid receptors (RARs). *Nucl Recept Signal*. 7:e005.
- Rochette-Egly, C., M. Oulad-Abdelghani, A. Staub, V. Pfister, I. Scheuer, P. Chambon, and M.P. Gaub.** 1995. Phosphorylation of the retinoic acid receptor-alpha by protein kinase A. *Mol Endocrinol*. 9:860-71.
- Rochette-Egly, C., J.L. Plassat, R. Taneja, and P. Chambon.** 2000. The AF-1 and AF-2 activating domains of retinoic acid receptor-alpha (RARalpha) and their phosphorylation are differentially involved in parietal endodermal differentiation of F9 cells and retinoid-induced expression of target genes. *Mol Endocrinol*. 14:1398-410.
- Rosenfeld, M.G., V.V. Lunyak, and C.K. Glass.** 2006. Sensors and signals: a coactivator/corepressor/epigenetic code for integrating signal-dependent programs of transcriptional response. *Genes Dev*. 20:1405-28.
- Rothkegel, M., O. Mayboroda, M. Rohde, C. Wucherpfennig, R. Valenta, and B.M. Jockusch.** 1996. Plant and animal profilins are functionally equivalent and stabilize microfilaments in living animal cells. *J Cell Sci*. 109 (Pt 1):83-90.
- Samarut, E., I. Amal, G.V. Markov, R. Stote, A. Dejaegere, V. Laudet, and C. Rochette-Egly.** 2012. Evolution of nuclear retinoic acid receptor alpha (RARalpha) phosphorylation sites. Serine gain provides fine-tuned regulation. *Mol Biol Evol*. 28:2125-37.
- Sande, S., and M.L. Privalsky.** 1996. Identification of TRACs (T-3 receptor-associating cofactors), a family of cofactors that associate with, and modulate the activity of, nuclear hormone receptors. *Molecular Endocrinology*. 10:813-825.
- Schlüter, K., B.M. Jockusch, and M. Rothkegel.** 1997. Profilins as regulators of actin dynamics. *Biochimica et Biophysica Acta (BBA) - Molecular Cell Research*. 1359:97-109.
- Schutt, C.E., J.C. Myslik, M.D. Rozycki, N.C. Goonesekere, and U. Lindberg.** 1993. The structure of crystalline profilin-beta-actin. *Nature*. 365:810-6.
- Shibata, H., Z. Nawaz, S.Y. Tsai, B.W. OMalley, and M.J. Tsai.** 1997. Gene silencing by chicken ovalbumin upstream promoter-transcription factor I (COUP-TFI) is mediated by transcriptional corepressors, nuclear receptor-corepressor (N-CoR) and silencing mediator for retinoic acid receptor and thyroid hormone receptor (SMRT). *Molecular Endocrinology*. 11:714-724.
- Si, J., L. Mueller, and S.J. Collins.** 2007. CaMKII regulates retinoic acid receptor transcriptional activity and the differentiation of myeloid leukemia cells. *J Clin Invest*. 117:1412-21.

- Simoës-Costa, M.S., A.P. Azambuja, and J. Xavier-Neto.** 2008. The search for non-chordate retinoic acid signaling: lessons from chordates. *J Exp Zool B Mol Dev Evol.* 310:54-72.
- Simons, K., and D. Toomre.** 2000. Lipid rafts and signal transduction. *Nat Rev Mol Cell Biol.* 1:31-9.
- Sims, R.J., and D. Reinberg.** 2008. Is there a code embedded in proteins that is based on post-translational modifications? *Nature Reviews Molecular Cell Biology.* 9:815-820.
- Skare, P., and R. Karlsson.** 2002. Evidence for two interaction regions for phosphatidylinositol(4,5)-bisphosphate on mammalian profilin I. *FEBS Lett.* 522:119-24.
- Skare, P., J.P. Kreivi, A. Bergstrom, and R. Karlsson.** 2003. Profilin I colocalizes with speckles and Cajal bodies: a possible role in pre-mRNA splicing. *Experimental Cell Research.* 286:12-21.
- Smith, W.C., H. Nakshatri, P. Leroy, J. Rees, and P. Chambon.** 1991. A retinoic acid response element is present in the mouse cellular retinol binding protein I (mCRBPI) promoter. *EMBO J.* 10:2223-30.
- Soderberg, O., M. Gullberg, M. Jarvius, K. Ridderstrale, K.J. Leuchowius, J. Jarvius, K. Wester, P. Hydbring, F. Bahram, L.G. Larsson, and U. Landegren.** 2006. Direct observation of individual endogenous protein complexes in situ by proximity ligation. *Nat Methods.* 3:995-1000.
- Sohn, R.H., and P.J. Goldschmidtclermont.** 1994. Profilin - at the Crossroads of Signal-Transduction and the Actin Cytoskeleton. *Bioessays.* 16:465-472.
- Spencer, T.E., G. Jenster, M.M. Burcin, C.D. Allis, J.X. Zhou, C.A. Mizzen, N.J. McKenna, S.A. Onate, S.Y. Tsai, M.J. Tsai, and B.W. OMalley.** 1997. Steroid receptor coactivator-1 is a histone acetyltransferase. *Nature.* 389:194-198.
- Sporn, M.B., A.B. Roberts, and D.W.S. Goodman.** 1994. The Retinoids: biology, chemistry, and medicine. Raven Press.
- Srinivas, H., D.M. Juroske, S. Kalyankrishna, D.D. Cody, R.E. Price, X.C. Xu, R. Narayanan, N.L. Weigel, and J.M. Kurie.** 2005. c-Jun N-terminal kinase contributes to aberrant retinoid signaling in lung cancer cells by phosphorylating and inducing proteasomal degradation of retinoic acid receptor alpha. *Mol Cell Biol.* 25:1054-69.
- Srinivas, H., D. Xia, N.L. Moore, I.P. Uray, H. Kim, L. Ma, N.L. Weigel, P.H. Brown, and J.M. Kurie.** 2006. Akt phosphorylates and suppresses the transactivation of retinoic acid receptor alpha. *Biochem J.* 395:653-62.
- Stallcup, M.R., J.H. Kim, C. Teyssier, Y.H. Lee, H. Ma, and D. Chen.** 2003. The roles of protein-protein interactions and protein methylation in transcriptional activation by nuclear receptors and their coactivators. *J Steroid Biochem Mol Biol.* 85:139-45.
- Staubach, S., and F.G. Hanisch.** 2011. Lipid rafts: signaling and sorting platforms of cells and their roles in cancer. *Expert Rev Proteomics.* 8:263-77.

- Stavridis, M.P., B.J. Collins, and K.G. Storey.** 2010. Retinoic acid orchestrates fibroblast growth factor signalling to drive embryonic stem cell differentiation. *Development*. 137:881-90.
- Steinmetz, A.C., J.P. Renaud, and D. Moras.** 2001. Binding of ligands and activation of transcription by nuclear receptors. *Annu Rev Biophys Biomol Struct.* 30:329-59.
- Sudol, M., K. Sliwa, and T. Russo.** 2001. Functions of WW domains in the nucleus. *Febs Letters*. 490:190-195.
- Sugawara, Y., H. Nishii, T. Takahashi, J. Yamauchi, N. Mizuno, K. Tago, and H. Itoh.** 2007. The lipid raft proteins flotillins/reggies interact with Galphaq and are involved in Gq-mediated p38 mitogen-activated protein kinase activation through tyrosine kinase. *Cell Signal*. 19:1301-8.
- Sun, K., V. Montana, K. Chellappa, Y. Brelivet, D. Moras, Y. Maeda, V. Parpura, B.M. Paschal, and F.M. Sladek.** 2007. Phosphorylation of a conserved serine in the deoxyribonucleic acid binding domain of nuclear receptors alters intracellular localization. *Mol Endocrinol*. 21:1297-311.
- Swindell, E.C., and G. Eichele.** 1999. Retinoid metabolizing enzymes in development. *Biofactors*. 10:85-9.
- Taimi, M., C. Helvig, J. Wisniewski, H. Ramshaw, J. White, M. Amad, B. Korczak, and M. Petkovich.** 2004. A novel human cytochrome P450, CYP26C1, involved in metabolism of 9-cis and all-trans isomers of retinoic acid. *J Biol Chem*. 279:77-85.
- Theodosiou, M., V. Laudet, and M. Schubert.** 2010. From carrot to clinic: an overview of the retinoic acid signaling pathway. *Cell Mol Life Sci*. 67:1423-45.
- Torchia, J., D.W. Rose, J. Inostroza, Y. Kamei, S. Westin, C.K. Glass, and M.G. Rosenfeld.** 1997. The transcriptional co-activator p/CIP binds CBP and mediates nuclear-receptor function. *Nature*. 387:677-84.
- Umesono, K., K.K. Murakami, C.C. Thompson, and R.M. Evans.** 1991. Direct Repeats as Selective Response Elements for the Thyroid-Hormone, Retinoic Acid, and Vitamin-D3 Receptors. *Cell*. 65:1255-1266.
- Underhill, C., M.S. Qutob, S.P. Yee, and J. Torchia.** 2000. A novel nuclear receptor corepressor complex, N-CoR, contains components of the mammalian SWI/SNF complex and the corepressor KAP-1. *J Biol Chem*. 275:40463-70.
- van Rheenen, J., X. Song, W. van Roosmalen, M. Cammer, X. Chen, V. Desmarais, S.C. Yip, J.M. Backer, R.J. Eddy, and J.S. Condeelis.** 2007. EGF-induced PIP2 hydrolysis releases and activates cofilin locally in carcinoma cells. *J Cell Biol*. 179:1247-59.
- Verheyen, E.M., and L. Cooley.** 1994. Profilin Mutations Disrupt Multiple Actin-Dependent Processes during Drosophila Development. *Development*. 120:717-728.
- Vicent, G.P., C. Ballare, A.S. Nacht, J. Clausell, A. Subtil-Rodriguez, I. Quiles, A. Jordan, and M. Beato.** 2006. Induction of progesterone target genes requires activation of Erk and Msk kinases and phosphorylation of histone H3. *Mol Cell*. 24:367-81.

- Vicent, G.P., A.S. Nacht, R. Zaurin, C. Ballare, J. Clausell, and M. Beato.** 2010. Minireview: role of kinases and chromatin remodeling in progesterone signaling to chromatin. *Mol Endocrinol.* 24:2088-98.
- Vicent, G.P., R. Zaurin, C. Ballare, A.S. Nacht, and M. Beato.** 2009. Erk signaling and chromatin remodeling in MMTV promoter activation by progestins. *Nucl Recept Signal.* 7:e008.
- Walders-Harbeck, B., S.Y. Khaitlina, H. Hinssen, B.M. Jockusch, and S. Illenberger.** 2002. The vasodilator-stimulated phosphoprotein promotes actin polymerization through direct binding to monomeric actin. *FEBS Lett.* 529:275-80.
- Wang, I.F., H.Y. Chang, and C.K. Shen.** 2006. Actin-based modeling of a transcriptionally competent nuclear substructure induced by transcription inhibition. *Exp Cell Res.* 312:3796-807.
- Wang, Z., W.W. Chen, E. Kono, T. Dang, and M.J. Garabedian.** 2007. Modulation of glucocorticoid receptor phosphorylation and transcriptional activity by a C-terminal-associated protein phosphatase. *Molecular Endocrinology.* 21:625-634.
- Warnmark, A., A. Wikstrom, A.P. Wright, J.A. Gustafsson, and T. Hard.** 2001. The N-terminal regions of estrogen receptor alpha and beta are unstructured in vitro and show different TBP binding properties. *J Biol Chem.* 276:45939-44.
- Weigel, N.L., and N.L. Moore.** 2007a. Steroid receptor phosphorylation: a key modulator of multiple receptor functions. *Mol Endocrinol.* 21:2311-9.
- Weigel, N.L., and N.L. Moore.** 2007b. Cyclins, cyclin dependent kinases, and regulation of steroid receptor action. *Mol Cell Endocrinol.* 265-266:157-61.
- Weigel, N.L., and N.L. Moore.** 2007c. Kinases and protein phosphorylation as regulators of steroid hormone action. *Nucl Recept Signal.* 5:e005.
- White, C.D., M. Coetsee, K. Morgan, C.A. Flanagan, R.P. Millar, and Z.L. Lu.** 2008. A crucial role for Galphaq/11, but not Galphai/o or Galphas, in gonadotropin-releasing hormone receptor-mediated cell growth inhibition. *Mol Endocrinol.* 22:2520-30.
- White, J.A., H. Ramshaw, M. Taimi, W. Stangle, A. Zhang, S. Everingham, S. Creighton, S.P. Tam, G. Jones, and M. Petkovich.** 2000. Identification of the human cytochrome P450, P450RAI-2, which is predominantly expressed in the adult cerebellum and is responsible for all-trans-retinoic acid metabolism. *Proc Natl Acad Sci U S A.* 97:6403-8.
- Witke, W.** 2004. The role of profilin complexes in cell motility and other cellular processes. *Trends in Cell Biology.* 14:461-469.
- Witke, W., A.V. Podtelejnikov, A. Di Nardo, J.D. Sutherland, C.B. Gurniak, C. Dotti, and M. Mann.** 1998. In mouse brain profilin I and profilin II associate with regulators of the endocytic pathway and actin assembly. *EMBO J.* 17:967-76.

- Witke, W., J.D. Sutherland, A. Sharpe, M. Arai, and D.J. Kwiatkowski.** 2001. Profilin I is essential for cell survival and cell division in early mouse development. *Proceedings of the National Academy of Sciences of the United States of America.* 98:3832-3836.
- Wurtz, J.M., W. Bourguet, J.P. Renaud, V. Vivat, P. Chambon, D. Moras, and H. Gronemeyer.** 1996. A canonical structure for the ligand-binding domain of nuclear receptors. *Nat Struct Biol.* 3:87-94.
- Xu, H.E., T.B. Stanley, V.G. Montana, M.H. Lambert, B.G. Shearer, J.E. Cobb, D.D. McKee, C.M. Galardi, K.D. Plunket, R.T. Nolte, D.J. Parks, J.T. Moore, S.A. Kliewer, T.M. Willson, and J.B. Stimmel.** 2002. Structural basis for antagonist-mediated recruitment of nuclear co-repressors by PPARalpha. *Nature.* 415:813-7.
- Yang, L., Q. Mei, A. Zielinska-Kwiatkowska, Y. Matsui, M.L. Blackburn, D. Benedetti, A.A. Krumm, G.J. Taborsky, Jr., and H.A. Chansky.** 2003. An ERG (ets-related gene)-associated histone methyltransferase interacts with histone deacetylases 1/2 and transcription co-repressors mSin3A/B. *Biochem J.* 369:651-7.
- Yoon, H.G., D.W. Chan, Z.Q. Huang, J. Li, J.D. Fondell, J. Qin, and J. Wong.** 2003. Purification and functional characterization of the human N-CoR complex: the roles of HDAC3, TBL1 and TBLR1. *EMBO J.* 22:1336-46.
- Yu, J.J., Y. Li, T. Ishizuka, M.G. Guenther, and M.A. Lazar.** 2003. A SANT motif in the SMRT corepressor interprets the histone code and promotes histone deacetylation. *Embo Journal.* 22:3403-3410.
- Zamir, I., H.P. Harding, G.B. Atkins, A. Horlein, C.K. Glass, M.G. Rosenfeld, and M.A. Lazar.** 1996. A nuclear hormone receptor corepressor mediates transcriptional silencing by receptors with distinct repression domains. *Molecular and Cellular Biology.* 16:5458-5465.
- Zanotto-Filho, A., M. Cammarota, D.P. Gelain, R.B. Oliveira, A. Delgado-Canedo, R.J. Dalmolin, M.A. Pasquali, and J.C. Moreira.** 2008. Retinoic acid induces apoptosis by a non-classical mechanism of ERK1/2 activation. *Toxicol In Vitro.* 22:1205-12.
- Zarrinpar, A., and W.A. Lim.** 2000. Converging on proline: the mechanism of WW domain peptide recognition. *Nature Structural Biology.* 7:611-613.
- Zechel, C., X.Q. Shen, P. Chambon, and H. Gronemeyer.** 1994. Dimerization interfaces formed between the DNA binding domains determine the cooperative binding of RXR/RAR and RXR/TR heterodimers to DR5 and DR4 elements. *EMBO J.* 13:1414-24.
- Zhang, J.S., M. Kalkum, B.T. Chait, and R.G. Roeder.** 2002. The N-CoR-HDAC3 nuclear receptor corepressor complex inhibits the JNK pathway through the integral subunit GPS2. *Molecular Cell.* 9:611-623.
- Zhao, J., Z. Zhang, Z. Vucetic, K.J. Soprano, and D.R. Soprano.** 2009. HACE1: A novel repressor of RAR transcriptional activity. *J Cell Biochem.* 107:482-93.
- Zheng, B., M. Han, M. Bernier, and J.K. Wen.** 2009a. Nuclear actin and actin-binding proteins in the regulation of transcription and gene expression. *Febs Journal.* 276:2669-2685.

Zheng, B., M. Han, M. Bernier, and J.K. Wen. 2009b. Nuclear actin and actin-binding proteins in the regulation of transcription and gene expression. *FEBS J.* 276:2669-85.

PUBLICATIONS

PUBLICATION 1

ORIGINAL ARTICLE

A retinoic acid receptor RAR α pool present in membrane lipid rafts forms complexes with G protein α Q to activate p38MAPK

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Retinoic acid (RA) regulates several gene programs by nuclear RA receptors (RARs) that are ligand-dependent transcriptional transregulators. The basic mechanism for switching on transcription of cognate-target genes involves RAR binding at specific response elements and a network of interactions with coregulatory protein complexes. In addition to these classical genomic effects, we recently demonstrated that RA also induces the rapid activation of the p38MAPK/MSK1 pathway, with characteristic downstream consequences on the phosphorylation of RARs and the expression of their target genes. Here, we aimed at deciphering the underlying mechanism of the rapid non-genomic effects of RA. We highlighted a novel paradigm in which a fraction of the cellular RAR α pool is present in membrane lipid rafts, where it forms complexes with G protein alpha Q (G α q) in response to RA. This rapid RA-induced formation of RAR α /G α q complexes in lipid rafts is required for the activation of p38MAPK that occurs in response to RA. Accordingly, in RA-resistant cancer cells, characterized by the absence of p38MAPK activation, RAR α present in membrane lipid rafts does not associate with G α q, pointing out the essential contribution of RAR α /G α q complexes in RA signaling.

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Keywords: retinoic acid; RAR; p38MAPK; G alpha Q; lipid rafts

Introduction

Retinoic acid (RA), a pleiotropic signaling molecule derived from vitamin A, regulates critical genetic programs that control development and homeostasis, cell proliferation and differentiation, as well as cell death or survival (Clagett-Dame and Knutson, 2011). This is the basis for the use of RA in cancer therapy (Altucci *et al.*, 2007). These effects of RA are mediated by specific nuclear receptors, RA receptors (RARs), which consist of three subtypes, α (NR1B1), β (NR1B2) and

γ (NR1B3) (Germain *et al.*, 2006a, b). The basics of RARs' structure and function have been recapitulated in several reviews (Laudet and Gronemeyer, 2001; Bastien and Rochette-Egly, 2004; Rochette-Egly and Germain, 2009). Briefly, RARs are multidomain proteins with a central DNA-binding domain linked to an N-terminal domain (NTD) and a C-terminal ligand-binding domain. Classically, RARs function as ligand-inducible transcriptional regulators, heterodimerized with retinoid X receptors (RXRs). As such they regulate the expression of subsets of target genes involved in cell proliferation and differentiation (Duong and Rochette-Egly, 2011; Samarut and Rochette-Egly, 2011). The basic mechanism for switching on gene transcription by RA relies on the binding of RAR/RXR heterodimers to specific sequence elements located in the promoters of target genes and on ligand-induced conformational changes, which cause the association/dissociation of a complex and ever-growing network of coregulatory proteins (Lefebvre *et al.*, 2005; Rochette-Egly and Germain, 2009).

In addition to this scenario, recent studies highlighted a novel paradigm in which, *in vivo*, RA also induces the rapid activation of p38MAPK and of the downstream MSK1 (Alsayed *et al.*, 2001; Gianni *et al.*, 2002; Bruck *et al.*, 2009). Most importantly, the activation of the p38MAPK/MSK1 pathway proved to be crucial for fine-tuning the expression of RAR-target genes through the phosphorylation of RARs and their coregulators (Gianni *et al.*, 2002, 2006; Bruck *et al.*, 2009). Most interestingly, the activation of p38MAPK by RA occurs very rapidly (within minutes), suggesting a non-genomic action of RA and RARs, as described for steroid hormone receptors (Losel and Wehling, 2003; Vasudevan and Pfaff, 2008). Therefore, we aimed at deciphering the underlying mechanism of these rapid non-genomic effects. Here, we showed that a fraction of the cellular RAR α pool is present in membrane lipid rafts, which are microdomains of cell membranes enriched not only in cholesterol and sphingolipids but also in signal-transducing molecules, such as flotillins, G proteins-coupled receptors, heterotrimeric G proteins, Rho and Rac GTPases, and their effectors (Pike, 2003; de Laurentiis *et al.*, 2007; Sugawara *et al.*, 2007; Yao *et al.*, 2009). In lipid rafts, G proteins consist of three subunits α , β and γ , and transmit signals to downstream effector molecules such as phospholipase C, protein-kinase C and p38MAPK (Mizuno and Itoh, 2009).

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We identified G protein alpha Q (G α q), a member of the G α group, as a new RAR α interacting protein in lipid rafts. Finally, both RAR α and G α q were found to mediate the activation of p38MAPK, with characteristic downstream consequences on the expression of the RA-target genes and on cell growth.

Results

RA activates p38MAPK through RAR α and G α q

P38MAPK was rapidly and transiently activated following RA treatment of several cell lines such as human mammary cancer cells (MCF7 cells), HeLa cells, mouse embryocarcinoma cell lines (F9 cells) and mouse embryonic fibroblasts (MEFs) (Figures 1a–d). Simultaneously, the upstream Rho-GTPases Rac and Rock were also strongly activated in response to RA (Figures 1e and f).

Now considerable evidence indicates that Rho-GTPases activation involves upstream G α q that interacts with scaffolding proteins in membranes (Sugawara *et al.*, 2007; Mizuno and Itoh, 2009). Therefore, we analyzed whether G α q is involved in the rapid RA-induced activation of the p38MAPK pathway. With this aim, G α q was knocked down with specific small interfering RNAs (siRNAs) in MCF7 and HeLa cells. No activation of p38MAPK was observed in both cell lines (Figures 2a and c), suggesting that the rapid activation of the p38MAPK pathway may be mediated by G α q. Most interestingly, the activation of p38MAPK was also inhibited upon RAR α knockdown in these two cell lines (Figures 2b and c), suggesting that the rapid activation of the p38MAPK pathway may be mediated by both G α q and RAR α . In line with this, p38MAPK was abrogated in F9 cells knockout for RAR α (F9 RAR α ^{-/-}) but not in F9 RAR γ ^{-/-} and RAR β ^{-/-} cells (Figure 1b). Finally, in MEF knockout for the three RARs, MEF (RAR α , β , γ)^{-/-} p38MAPK was restored upon re-expression of RAR α WT, but not of RAR γ WT (Figures 1c and d).

RAR α is present with G α q in membrane lipid rafts

There is increasing evidence that intracellular signaling pathways are orchestrated by specific, highly ordered membrane microdomains termed as ‘lipid rafts’ (Simons and Toomre, 2000; Pike, 2003). Indeed, lipid rafts are enriched in a large array of signal transduction components, suggesting that they would be ‘signaling centers’. As the rapid activation of p38MAPK by RA involves RAR α , we isolated these membrane subfractions in order to investigate whether they contain RAR α in addition to the signaling molecules.

MCF7 cells were disrupted and lipid rafts were extracted using a unique technique based on their relative insolubility in certain detergent conditions. Then lipid rafts were isolated by virtue of their high buoyancy when centrifuged on a discontinuous sucrose density gradient (Ostrom and Insel, 2006; Waugh and Hsuan, 2009) (Figure 3a). Such a technique has the

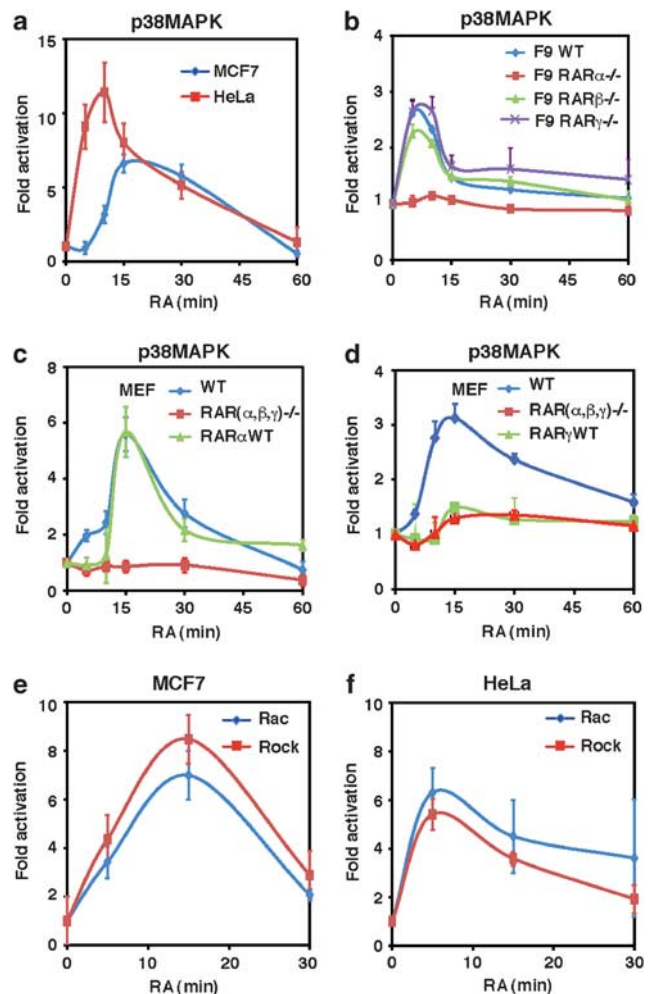


Figure 1 p38MAPK is activated in response to RA. (a–d) Analysis of p38MAPK activation (phospho p38MAPK ELISA (enzyme-linked immunosorbent assay)) in RA-treated MCF7 cells, HeLa cells, F9 cells (either WT, RAR α ^{-/-}, RAR γ ^{-/-} and RAR β ^{-/-}) and mouse embryonic fibroblasts (MEFs) [WT, RAR (α , β , γ)^{-/-}, or re-expressing RAR α WT or RAR γ WT in the RAR (α , β , γ) null background]. (e, f) Analysis of Rac-1 and Rock-2 activities in MCF7 cells (e) and HeLa cells (f) treated with RA for the indicated times. All results are the mean \pm s.d. of duplicates from three distinct experiments.

advantage of isolating buoyant rafts with their natural composition. Moreover, protein interactions and functions are maintained. As expected, after centrifugation, a faint light-scattering band, which consists of the buoyant lipid rafts material was visible at the 35% sucrose–5% sucrose interface (Ostrom and Insel, 2006). Then all sucrose gradient fractions were collected, resolved by SDS–polyacrylamide gel electrophoresis and analyzed by immunoblotting for lipid raft-associated proteins. Fractions 4 and 5, which correspond to buoyant rafts (Ostrom and Insel, 2006) contained flotillin-2, a marker of lipid rafts (Stuermer, 2011) (Figure 3b). They also contained other proteins that are well known to participate in signaling events, such as Rock-2, PKC δ and G α q, (Figure 3b), corroborating that these fractions correspond to lipid rafts and are signaling centers.

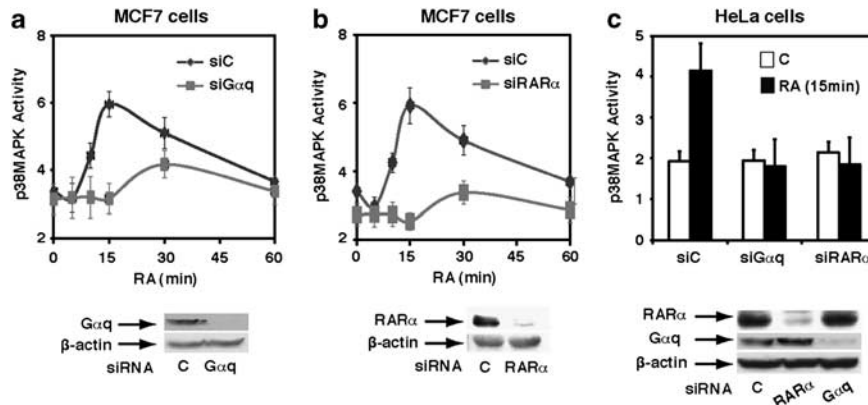


Figure 2 G protein alpha Q and RAR α are required for the RA-induced activation of p38MAPK (mitogen-activated protein kinase). Knockdown of G α q or RAR α with specific small interfering RNAs (siRNAs) in MCF7 cells (a, b) and HeLa cells (c) inhibit the activation of p38MAPK that occurs in response to RA. The results are the mean \pm s.d. of three experiments. The efficiency of the knockdown was checked by immunoblotting.

Most interestingly, RAR α (and not RAR γ and RAR β) could be detected in the same fractions corresponding to lipid rafts (Figure 3b). Of note is that the amount of RAR α present in lipid rafts was very low compared with the amount of RAR α present in the bottom fractions (fractions 8–12), which contain the rest of the cellular material, including the nuclear components. Indeed, in immunofluorescence experiments performed with MCF7 cells, RAR α was detected essentially in nuclei (Figure 3d). However, low levels of RAR α were also detected out of nuclei and colocalized with flotillin-2 (Figures 3f and g). Collectively, these results converge to the conclusion that a small population of RAR α is present out of nuclei in membrane lipid rafts.

Then the question is, how RAR α (and not RAR β nor RAR γ) is targeted to membranes. Given that the three RAR subtypes depict a very high degree of identity in the sequence of their DNA-binding domains and ligand-binding domains, one can speculate that the NTD might specifically target RAR α at the membrane. Therefore, we analyzed whether RAR α deleted for this domain (RAR α Δ NTD) was present or not in lipid rafts, taking advantage of the F9 cells re-expressing RAR α WT or Δ NTD in a RAR α null background (Rochette-Egly *et al.*, 2000). Remarkably, in contrast to RAR α WT, RAR α Δ NTD could not be detected in lipid rafts isolated from the corresponding rescue F9 cell line, indicating that the NTD would be involved in targeting RAR α to membranes. In contrast, RAR α deleted from the AF-2 domain (RAR α Δ H12) could be detected in rafts isolated from F9 cells expressing this mutant (Rochette-Egly *et al.*, 2000) (Figure 3h), validating our conclusions.

RAR α interacts with G α q in vitro and in vivo

Given that G α q proteins colocalize with RAR α in lipid rafts and are involved in the activation of the p38MAPK pathway, we investigated whether both proteins can interact with each other. First, the ability of RAR α to interact with G α q was analyzed with the recombinant proteins in *in vitro* protein–protein interaction and coimmunoprecipitation experiments. Recombinant

GST (glutathione S-transferase)-RAR α expressed in *E. coli* and bound to glutathione-sepharose beads interacted with *in vitro*-translated G α q (Figure 4a, lane 5). A similar interaction was observed with a constitutively active form of G α q (Figure 4a, lane 6). These results were confirmed in coimmunoprecipitation experiments performed with extracts from COS-1 cells over expressing RAR α and G α q, and treated or not with RA. Indeed, some G α q was detected in the RAR α immunoprecipitates in the absence of RA (Figure 4b, lane 4). Most interestingly, the efficiency of the interaction increased markedly after addition of RA (Figure 4b, lanes 5–8). Altogether, these results indicate that RAR α can form complexes with G α q and that these complexes are increased in the presence of RA.

Finally, whether endogenous RAR α and G α q form complexes *in vivo* in lipid rafts was investigated. High amounts of lipid rafts were prepared from RA-treated MCF7 cells and immunoprecipitated with RAR α antibodies. As shown in Figure 4c, G α q could be detected in RAR α immunoprecipitates corroborating that RAR α and G α q belong to a same complex in membrane lipid rafts.

Visualization of endogenous RAR α /G α q complexes, in situ, by proximity ligation

Next, *in situ* proximity ligation assay (PLA) (Soderberg *et al.*, 2006) was used to explore further the endogenous RAR α /G α q complexes. The assay is similar to fluorescence resonance energy transfer and allows the detection of proteins in sufficient proximity (<40 nm). It is based on the use of two primary antibodies raised in different species that recognize the antigens of interest. Then species-specific secondary antibodies, called PLA probes, each with a unique short DNA strand attached to it, are added. When the PLA probes are in close proximity, the DNA strands can be joined through the subsequent addition of a circle-forming DNA oligonucleotide that is amplified by rolling circle amplification using a polymerase. After the amplification reaction, several-hundred fold replication of the DNA circle has occurred, and labeled complementary oligonucleotide

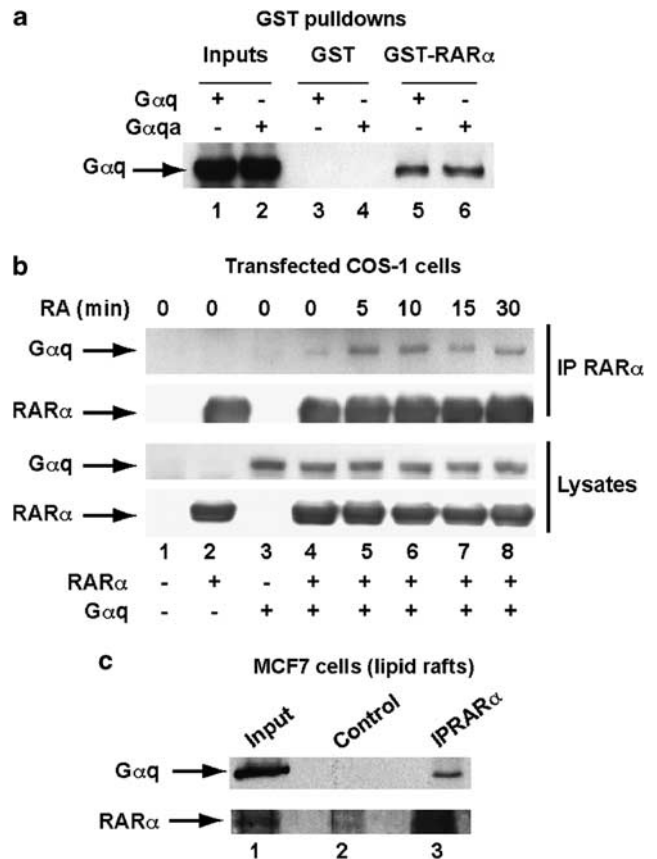
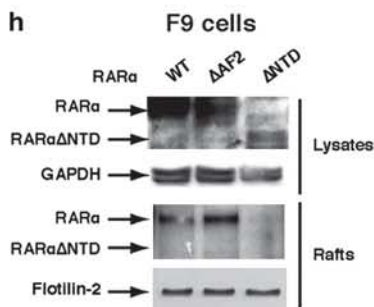
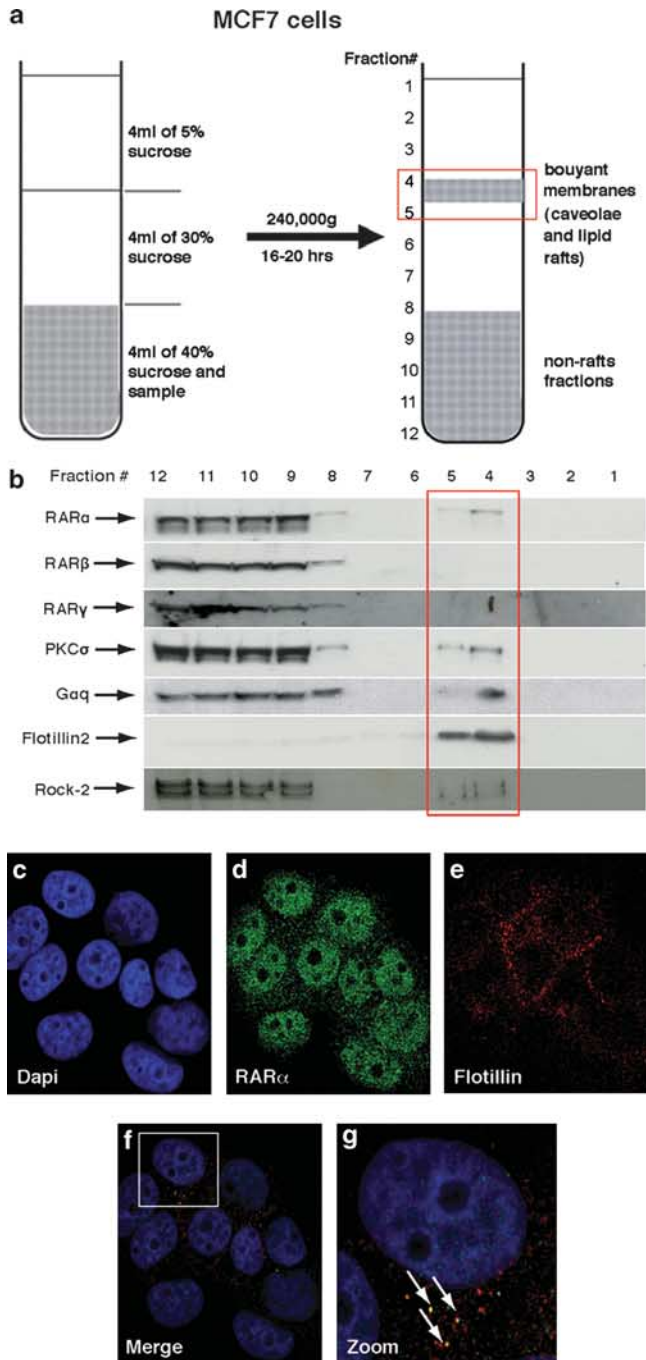


Figure 4 G protein alpha Q interacts with RAR α both *in vitro* and *in vivo*. (a) *In vitro* translated G α q and a constitutively active form of G α q (G α qa) were incubated with glutathione S-transferase (GST) or GST-RAR α immobilized on glutathione-sepharose beads. Bound G α q was analyzed by immunoblotting. (b) COS-1 cells were transfected with the RAR α vector along with G α q and treated with RA for the indicated times. Extracts were incubated with mouse monoclonal RAR α antibodies and protein G-sepharose beads. Immunocomplexes were resolved by SDS-polyacrylamide gel electrophoresis and immunoblotted with RP α (F) and G α q antibodies. The two bottom panels correspond to 5% of the amount of immunoprecipitated extracts. Lanes 1 to 3 correspond to the immunoprecipitation controls. (c) Lipid rafts were prepared from 2×10^8 MCF7 cells treated with RA for 10 min. The light scattering bands, which consist of the buoyant lipid rafts material were collected and immunoprecipitated with monoclonal RAR α antibodies. Bound G α q was analyzed by immunoblotting.

Figure 3 RAR α is present in membrane lipid rafts. (a) Schematic representation of the rafts isolation procedure by sucrose gradient centrifugation. (b) Immunoblotting analysis of the different gradient fractions showing that RAR α is present with Flotillin-2, G α q and other signaling components in lipid rafts. (c-g) Confocal microscopy analysis of MCF7 cells fixed and triple stained with 4,6-diamidino-2-phenyl indole (DAPI) (blue, c), anti-RAR α antibody (green, d), and anti-Flotillin-2 antibody (red, e). The merge images overlapping the red, green and blue fluorescence (f, g) show that though mainly nuclear, RAR α can be detected out of nuclei and colocalizes with flotillin-2. (h) Immunoblotting analysis of lipid rafts (fractions 4 and 5) isolated from F9 cells expressing RAR α , that is, WT, Δ NTD or Δ AF-2 in a RAR α null background, and showing that RAR α Δ NTD cannot be detected in rafts.

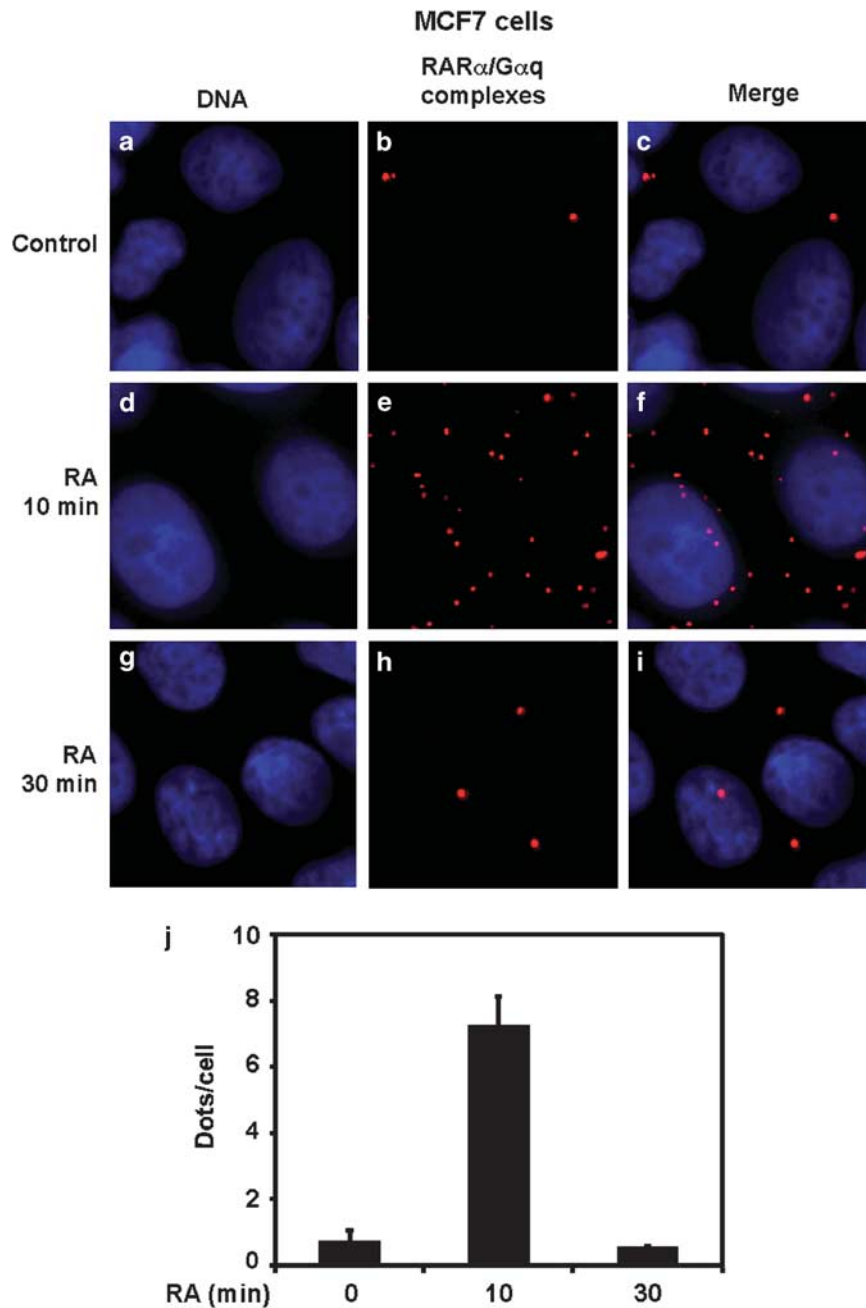


Figure 5 Analysis of RAR α /G α q complexes in MCF7 cells by immunofluorescence microscopy in combination with *in situ* proximity ligation assay (PLA). (a–i) PLA is highly specific for detecting physically interacting protein–protein complexes (red, panels b, e, h). DNA was counterstained with 4,6-diamidino-2-phenyl indole (DAPI) (blue, panels a, d, g). The merge between blue and red is also shown (panels c, f, i). A few RAR α /G α q complexes are shown in control MCF7 cells (b, c). The amount of complexes increased markedly out of nuclei in MCF7 cells treated with RA for 10 min (e, f) and returned to control values at 30 min (h, i). (j) Statistical analysis of the signals using the Blobfinder V3.2 software.

probes highlight the product. The resulting high concentration of fluorescence in each single-molecule amplification product is easily visible as a distinct bright spot when viewed under a fluorescence microscope.

Here, rabbit anti-RAR α and mouse anti-G α q antibodies were used under the PLA conditions to explore, *in situ*, endogenous RAR α /G α q complexes, in MCF7 cells treated with RA for different times. Quite few RAR α /G α q complexes were detected in the control untreated cells (Figures 5b and c). Considerable higher

amounts of complexes were seen in the RA-treated cells with a peak around 10 min (Figures 5e and f), which corresponds to the peak of p38 MAPK activation. Most interestingly, the signals were out of nuclei. Then the number of spots returned to control values at 30 min (Figures 5h and i). Spots number was quantified using the Blobfinder V3.2 software (Centre for Image Analysis, Uppsala University, Sweden, <http://www.cb.uu.se/~amin/BlobFinder/>) and the average values \pm s.d. from at least two experiments are shown (Figure 5j). No signal was seen

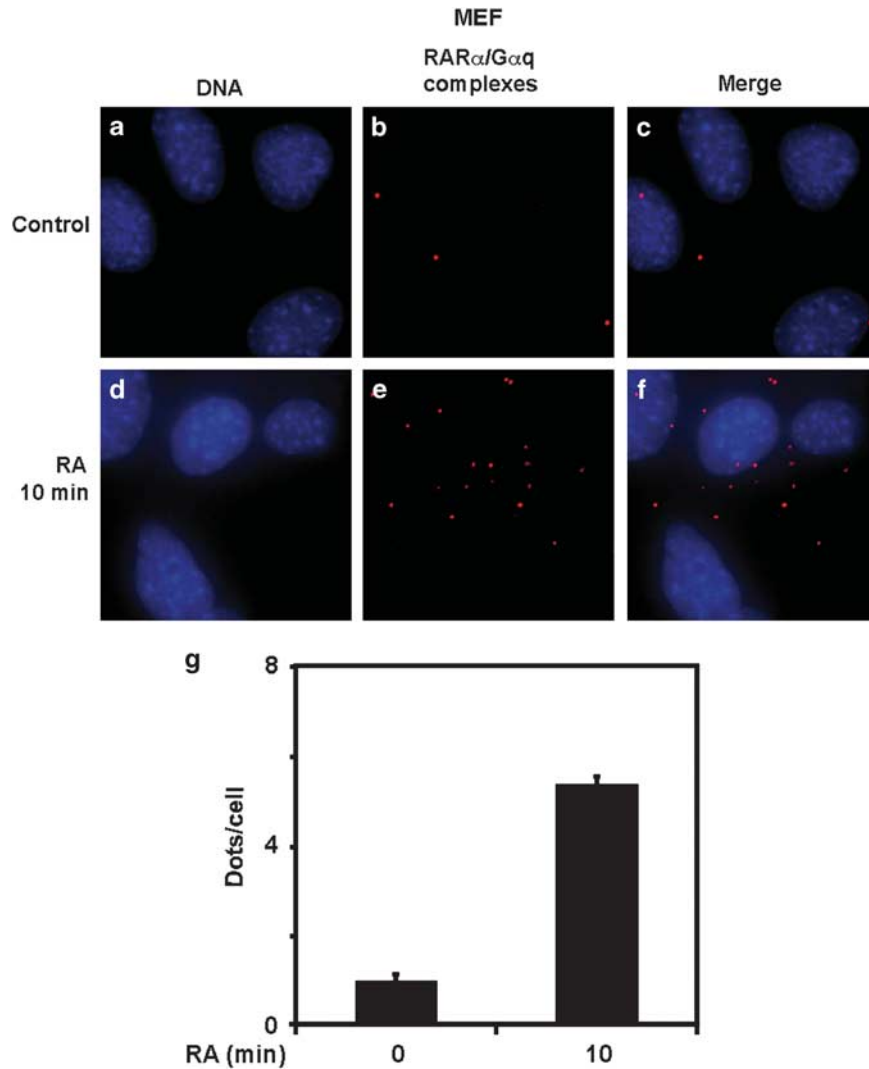


Figure 6 Analysis of RAR α /G α q complexes in mouse embryonic fibroblasts (MEFs) by immunofluorescence microscopy in combination with *in situ* proximity ligation assay (PLA). (a–f) The number of red dots corresponding to the RAR α /G α q complexes increases in MEFs treated with RA for 10 min as in Figure 5. (g) Statistical analysis as in Figure 5j.

when each primary antibody was used individually, validating the specificity of the technique. Similar results were obtained with several other RA-treated cells such as HeLa cells and MEF (Figure 6). Collectively, these results confirm that endogenous RAR α is present in a complex with endogenous G α q out of nuclei, in response to RA.

Note, however, that the increased number of RAR α /G α q complexes was observed specifically in response to RA. Indeed, the activation of the p38MAPK pathway that occurs in response to epidermal growth factor (EGF) through G α q proteins (Figure 7a), does not involve RAR α (Figure 7a). Accordingly, no increase in RAR α /G α q complexes could be observed in response to EGF as assessed in a PLA (Figure 7b).

In erbB-2 positive breast cancer cells, p38MAPK is not activated in response to RA and RAR α does not form complexes with G α q

Then, we asked whether RA-resistant cells exemplified by the human erbB-2 positive breast cancer cells also

depict an activation of p38MAPK and the formation of RAR α /G α q complexes in response to RA. First, the erbB-2 positive cells, BT474, SKBR3, MDA-MB453 and MDA-MB361 cells (Tari *et al.*, 2002) (Figure 8a) were compared with MCF7 cells for p38MAPK activation in response to RA. Remarkably, in these cell lines p38MAPK activation was decreased or abrogated up to 60 min after RA addition (Figure 8b).

Then, we concentrated on BT474 cells, which depict the highest levels of erbB-2 and are completely defective in p38MAPK activation. Membrane lipid rafts were isolated from these cells and were analyzed by immunoblotting. Both RAR α and G α q could be detected in lipid rafts from these cells (Figure 8c). However, no RAR α /G α q complexes could be visualized *in situ* by proximity ligation (Figures 8e–j), whereas a high amount of complexes were seen in MCF7 cells under the same conditions (Figures 8k–p). Note that the ability of EGF to activate p38MAPK was also abrogated in BT474 cells (Figure 8d), though this

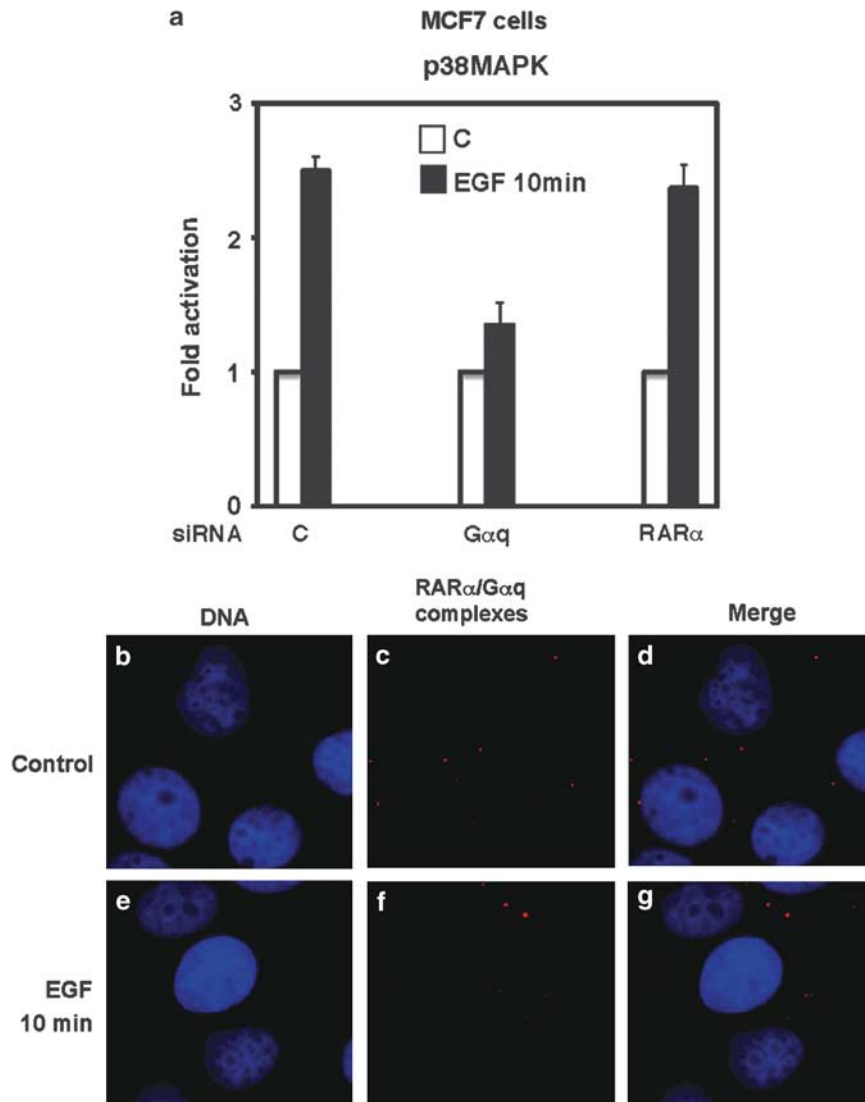


Figure 7 P38MAPK (mitogen-activated protein kinase) activation that occurs in response to epidermal growth factor (EGF) does not involve RAR α . **(a)** Analysis of the EGF-induced activation of p38MAPK in MCF7 cells knockdown for G α q or RAR α with specific small interfering RNA (siRNAs). **(b–g)** EGF does not induce the formation of RAR α /G α q complexes in MCF7 cells, as assessed by immunofluorescence microscopy in combination with *in situ* proximity ligation assay (PLA).

pathway does not involve the formation of RAR α /G α q complexes (see Figure 7). Collectively, these data highlight the importance of the initial formation of RAR α /G α q complexes in lipid rafts for p38MAPK activation in response to RA. They also suggest that the signaling pathways, involving G α q proteins, are affected in erbB-2 positive cells (see Discussion).

The integrity of the G α q/p38MAPK pathway is required for the full RA-induction of RAR α -target genes and the antiproliferative action of RA

According to our previous work, activation of the p38MAPK/MSK1 pathway is significant for the activation of RAR α -target genes in several cell lines, including MCF7 cells and MEF (Bruck *et al.*, 2009). Then, we asked whether upstream G α q is required for the

induction of RA-target genes. In MCF7 cells, RA treatment enhances the expression of the *Hoxa-1* and *Btg2* genes, which are the paradigm of the RA-target genes as assessed by quantitative real time-PCR. Knockdown of G α q decreased the RA-induced expression of both genes (Figures 9a and b). Most interestingly, it also reduced the antiproliferative action of RA (Figure 9c) in line with other studies (Lai *et al.*, 2008; White *et al.*, 2008). Of note is that knockdown of the downstream effectors p38MAPK and MSK1 also decreased the RA-induced expression of RA-target genes, though less efficiently than the knockdown of RAR α (Figure 8c), corroborating our previous studies (Bruck *et al.*, 2009). Collectively, these results highlight the importance of the G α q/p38MAPK/MSK1 pathway for RAR-target gene expression and growth arrest that occur in response to RA.

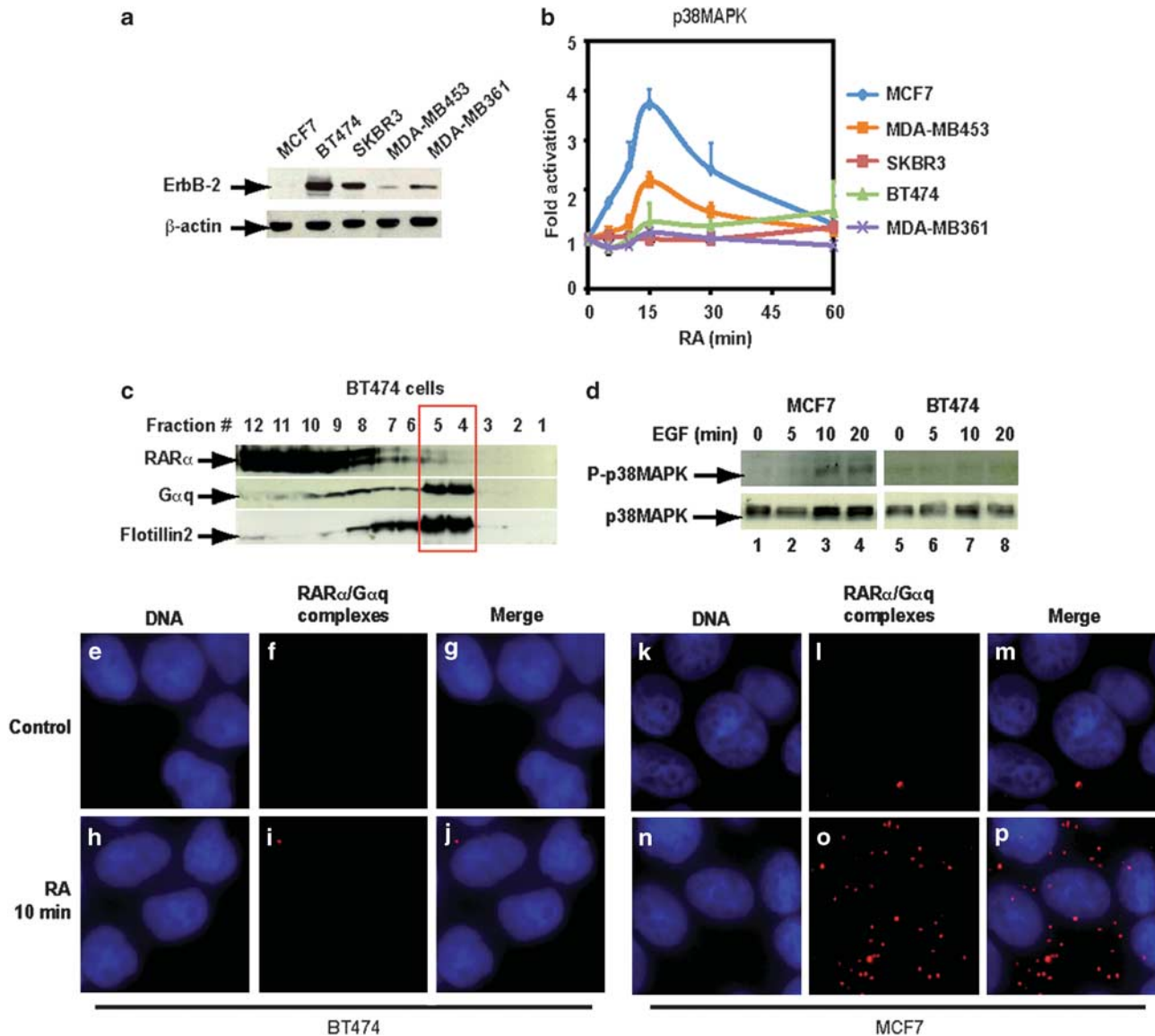


Figure 8 In erbB-2 positive breast cancer cells, p38MAPK (mitogen-activated protein kinase) is not activated in response to RA and RAR α does not form complexes with G α q. (a) ErbB-2 expression in MCF7, SKBR3, BT474, MDA-MD453 and MDA-MB361 human breast cancer cells. (b) Comparison of p38MAPK activation in RA-treated MCF7 and erbB-2 positive cells. (c) Lipid rafts prepared from BT474 cells contain RAR α and G α q. (d) In BT474 cells, p38MAPK is not activated in response to epidermal growth factor (EGF), as assessed by immunoblotting analysis of active phospho p38MAPK. (e–j) In BT474 cells, RAR α does not form complexes with G α q in response to RA, as assessed by immunofluorescence microscopy in combination with *in situ* proximity ligation assay (PLA). (k–p) RAR α /G α q complexes in RA-treated MCF7 cells as assessed by *in situ* PLA.

Discussion

Rapid responses, such as the activation of signaling pathways, are initiated at the plasma membrane in lipid rafts and then amplified by cascades of activation of downstream effectors including G proteins, Rho family small GTPases, phospholipase C, the Src family tyrosine kinases and p38MAPK. As RA activates very rapidly the p38MAPK pathway, we speculated that this effect would be non-genomic and mediated by a membrane-associated RAR. Here, we provide evidence that in various mammalian epithelial and fibroblastic cells, the RAR α subtype, which is normally found in the nucleus,

is also present in plasma membranes. Moreover, membrane-associated RAR α forms complexes with G α q to generate rapid p38MAPK activation in response to RA (see Figure 9e).

First of all, to find out the mechanism of activation of the p38MAPK pathway by RA, we investigated, which RAR subtype is involved and whether this RAR could be detected in membrane lipid rafts that are 'signaling centers'. Taking advantage of cell lines invalidated for one specific RAR subtype or re-expressing a specific RAR in a triple RAR (α , β , γ) null background, we demonstrated that the activation of p38MAPK in response to RA, involves specifically the RAR α subtype.

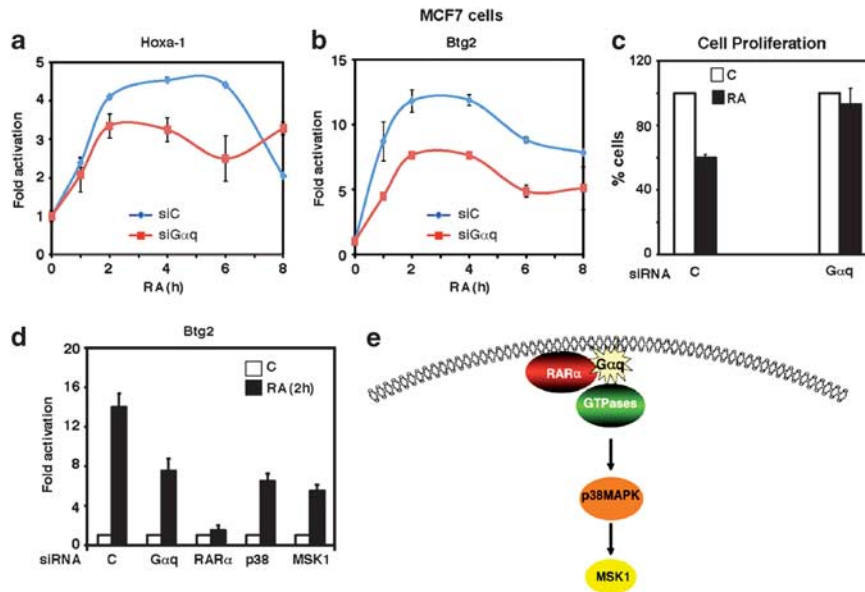


Figure 9 G α q is required for the RA-induction of the *Hoxa1* and *Btg2* genes and for the antiproliferative action of RA. In MCF7 cells, the RA-induced expression of the *Hoxa-1* (a) and *Btg2* (b) genes is decreased upon knockdown of G α q, as assessed by quantitative real time-PCR. (c) Knockdown of G α q also decreases the antiproliferative action of RA. (d) Knockdown of the downstream effectors p38MAPK (mitogen-activated protein kinase) and MSK1 also decreases the RA-induced expression of the *Btg2* gene. The results are the mean \pm s.d. of three individual experiments. (e) Model of the activation of the p38MAPK pathway through RAR α and G α q located in membranes.

However, in immunofluorescence confocal studies, RAR α was present essentially in nuclei and was hardly detected in plasma membranes, despite some spots suggesting a colocalization of RAR α with flotillin-2, a marker of lipid rafts. In fact, RAR α could be detected in detergent-insoluble membrane lipid rafts that are concentrated by sucrose equilibrium density gradients and that are enriched in components of signal transduction pathways (Pike, 2003; de Laurentiis *et al.*, 2007). RAR α was detected in the same low-density buoyant fractions as flotillin and G α q. The fact that RAR α colocalizes with flotillin-2 in lipid rafts is a novelty in the field. It is also in line with the new concept in which most of the classical so-called nuclear steroid and non-steroid receptors (ER, GR, PR, AR, VDR) can be found in specialized plasma membrane structures such as caveolae and lipid rafts (Huhtakangas *et al.*, 2004; Marquez *et al.*, 2006; Pedram *et al.*, 2007; Luoma *et al.*, 2008; Matthews *et al.*, 2008).

How RAR α is recruited to the plasma membrane is still ill-defined. Indeed, in contrast to the other steroid receptors, RAR α does not depict any palmitoylation motif that would facilitate its membrane localization (Pedram *et al.*, 2007). However, according to our results, the N-terminal domain that is not conserved between RARs, appears to be necessary for targeting specifically RAR α to lipid rafts. In addition, RAR α present in lipid rafts forms complexes with G α q proteins and the number of these complexes is increased in response to RA. These complexes were seen *in vitro* with the recombinant proteins by GST pull down and coimmunoprecipitation and were corroborated *in vivo*, with the endogenous proteins in coimmunoprecipitation experiments performed with enriched lipid rafts. In fact, the originality of the present study resides in the use of a

'PLA', which can reveal transient endogenous protein complexes even when present at very low levels (Soderberg *et al.*, 2006). Such a technique allowed us to visualize, *in situ*, a rapid and transient increase (10–15 min after RA addition) in RAR α /G α q complexes. It also revealed that the complexes are out of the nuclei, confirming the hypothesis that the non-genomic effects of RA involve a pool of extra nuclear RAR α .

The interesting point is that G α q is involved with RAR α in the activation of p38MAPK (Figure 8d). This is a novelty in the field of the non-genomic effects of RA and is in agreement with the well-known role of G α q in the activation of the p38MAPK pathway (Sugawara *et al.*, 2007; White *et al.*, 2008; Mizuno and Itoh, 2009). It is worth noting that this pathway was activated by RA in epithelial and fibroblastic cells but not in neuronal and sertoli cells, where RA rather activates the p42/p44MAPK (Erk) pathway through Src and PI3K (Pan *et al.*, 2005; Dey *et al.*, 2007; Masia *et al.*, 2007; Chen and Napoli, 2008; Zanutto-Filho *et al.*, 2008). Thus, the mechanism of the non-genomic effects of RA appears to involve different membrane-associated complexes, depending on the MAPK pathway that is RA-activated and on the cell type. Similarly, the non-genomic effects of the other nuclear receptors involve different kinases and different membrane molecular complexes, depending on their functional significance (Losel and Wehling, 2003; Norman *et al.*, 2004). As an example, in breast cancer cells and in response to its cognate ligand, the estrogen receptor ER α activates the Erk pathway through complexes containing c-Src and the regulatory subunit of PI3K (p85 α) (Migliaccio *et al.*, 1998; Le Romancer *et al.*, 2008). In contrast, in neuronal cells, ER rather activates protein kinase C through G α q

and phospholipase C (Qiu *et al.*, 2003). In the same line of idea, depending on the cell type, VDR activates either the RhoA-Rock-p38MAPK pathway (Ordonez-Moran *et al.*, 2008) or the Raf/Erk pathway (Norman *et al.*, 2001; Losel and Wehling, 2003).

The present study also corroborates the new concept, according to which the non-genomic effects of RA influence the genomic effects (Rochette-Egly and Germain, 2009; Piskunov and Rochette-Egly, 2011). Indeed, our results indicate that the knockdown of G α q and its downstream effectors, p38MAPK and MSK1, decreases the expression of RAR-target genes. The modes of interaction between the non-genomic and genomic effects of RA are complex, but according to other studies from our laboratory, the downstream effectors of the non-genomic effects, p38MAPK and MSK1, phosphorylate the actors of the genomic action of RA, that is, histones, RARs and their coregulators such as SRC-3 (Gianni *et al.*, 2002, 2006; Bruck *et al.*, 2009). As such, the RA-induced phosphorylation cascades control protein-protein and DNA-protein interactions, and the dynamics of transcription. Thus, one can conclude that the non-genomic effects of RA cross talk with the genomic processes for assuming the specificity of RAR-target genes expression.

Finally, our results highlight that in RA-resistant breast cancer cells characterized by aberrant receptor tyrosine kinase expression and/or activity (exemplified by erbB-2 breast cancers), the formation of RAR α /G α q complexes is suppressed, resulting in the abrogation of the non-genomic effects of RA, that is, the activation of p38MAPK. Remarkably, other signaling pathways involving G α q proteins, such as the EGF pathway, are also affected in such cells. It is important to note that most signaling pathways are controlled by essential scaffolding proteins of lipid rafts such as caveolin-1 (Sugawara *et al.*, 2007; Staubach and Hanisch, 2011). Moreover, caveolin-1 is frequently downregulated in erbB-2 positive cells (Park *et al.*, 2005). Therefore, one can speculate that the integrity of lipid rafts composition would be required for the formation of G α q-based complexes including RAR α /G α q complexes, and thereby for the activation of the signaling pathways. Whether there is a correlation between these observations and the resistance of such cancer cells to the antiproliferative action of RA would require further investigations, but is out of the scope of this study. Nevertheless, our results and others (Lai *et al.*, 2008; White *et al.*, 2008; Staubach and Hanisch, 2011) suggest that G α q proteins, as well as several components of lipid rafts, would have an important role in the control of not only gene expression but also cell growth.

Materials and methods

Plasmids, antibodies and reagents

The pSG5-based expression vector for RAR α and the prokaryotic pGEX-2T vector encoding RAR α fused to GST were previously described (Bour *et al.*, 2005). The pcDNA3.1 G α q vectors (WT and constitutively active) were purchased from Missouri S&T cDNA Resource Center (Rolla, MO, USA).

Mouse monoclonal antibodies (Ab10 α (A) and Ab9 α (F)) as well as rabbit polyclonal antibodies (RP α (F)) raised against RAR α were described earlier (Gaub *et al.*, 1992). Rabbit polyclonal antibodies against PKC δ (C-17), goat polyclonal antibodies against β -actin (C-11) and Rock-2 as well as mouse monoclonal antibodies against G α q and Flotillin-2 were obtained from Santa Cruz Biotechnology Inc. (Santa Cruz, CA, USA). The rabbit polyclonal antibodies against RAR α (C-20), used in the immunofluorescence experiments were also from Santa Cruz. Antibodies against p38 MAPK, phospho-p38 MAPK (Thr180/Tyr182) and HER2/ErbB2 antibodies were purchased from Cell Signalling Technology (Danvers, MA, USA). Rabbit polyclonal antibodies against GAPDH were from Sigma Aldrich Chemie (Saint Quentin Fallavier, France), as well as all trans RA and epidermal growth factor (EGF).

Cell culture, proliferation, transfections and immunoprecipitations

MCF7, BT474, SKBR3, MDA-MB453, MDA-MB361 and HeLa cells were cultured under standard conditions. MEFs with all three RARs deleted and re-expressing RAR α WT or RAR γ WT were previously described (Bruck *et al.*, 2009). Mouse embryocarcinoma cells (F9 cells), WT, RAR α -/-, RAR γ -/- and RAR β -/-, were previously described (Taneja *et al.*, 1997; Faria *et al.*, 1999), as well as F9 cells re-expressing RAR α , WT, Δ NTD and Δ AF-2 in a RAR α null background (Rochette-Egly *et al.*, 2000). COS-1 cells were transiently transfected using the FuGENE 6 reagent (Roche, Meylan, France) according to the manufacturer's protocol. When they have reached 80–90% confluency, cells were treated with RA (10^{-7} M) or EGF (100 ng/ml), after 24 h in a medium containing 1% fetal calf serum (Bruck *et al.*, 2009). Extracts were prepared, immunoblotted or immunoprecipitated as described (Bruck *et al.*, 2009).

Cell proliferation was analyzed by using the XTT (2,3-bis-(2-methoxy-4-nitro-5-sulphophenyl)-2H-tetrazolium-5-carboxanilide) assay kit according to the manufacturer's instructions (Roche Diagnostics).

Detection of active p38MAPK, Rac1 and Rock2

Phosphorylated p38MAPK was detected by using a phospho p38MAPK (Thr (P)-180/Tyr (P)-182) ELISA kit (Biosource Invitrogen Corporation). Where indicated it was also analyzed by immunoblotting with antibodies recognizing specifically the active phosphorylated form of p38MAPK. Activation of Rho family GTPases was analyzed using the Rac1, Rac 3 and 3 G-LISA Rac activation assay Biochem Kit (Cytoskeleton, Denver, CO, USA), and the Rock activity assay kit (Cell Biolabs, San Diego, CA, USA).

GST pull-down assays

Equimolar amounts of GST and GST-fusion proteins expressed in *Escherichia coli* were purified on glutathione-sepharose 4B beads (Amersham Biosciences, GE Healthcare Europe GmbH, Branch France, Velizy-Villacoublay, France) and incubated as previously described (Bour *et al.*, 2005), with *in vitro*-translated G α q produced in Quick Coupled Transcription/Translation System (Promega, Charbonnières les Bains, France).

Small interfering RNA

The ON-TARGET plus SMART pool siRNA against human G α q (M-008562-00-0005), human RAR α (L-003437-00-0005), human p38MAPK α (L-003512-00), human MSK1 (M-004665-01) and the control non-targeting siRNA pool (D-001206-13) were purchased from Dharmacon (Thermo Fisher Scientific, Illkirch, France). Cells were transfected with siRNAs (50 nM) according to

the manufacturer's protocol and treated with RA (10^{-7} M) 48 h post-transfection. Then at the indicated times, the cells were harvested and subjected to RNA and protein analysis.

Rafts Isolation

Membrane lipid rafts were isolated using the procedure described in Ostrom and Insel (2006) and Waugh and Hsuan (2009). Briefly, 6×10^7 cells grown in petri dishes were washed twice in phosphate-buffered saline and then lysed for 1 min on ice in 1 ml of 10 mM Tris-HCl (pH 7.4) containing 1% (v/v) Triton X-100, 1 mM EDTA, 0.5 mM ethylene glycol tetraacetic acid and protease/phosphatase inhibitors. Then the cell lysate was scrapped, transferred to a 2-ml Dounce homogenizer and homogenized with 10 strokes on ice. The lysate was adjusted to 2 ml and an equal volume of 80% sucrose was added. The two solutions were then mixed thoroughly by pipetting up and down several times to give a final concentration of 40% sucrose in a 4-ml volume. Then 4 ml of 30% sucrose and 4 ml of 5% sucrose were layered carefully. After centrifugation at $240\,000 \times g$ for 16 h at 4°C , samples were collected from the top of the tube as 1-ml fractions (12 fractions in total). Fractions were analyzed by SDS-polyacrylamide gel electrophoresis and immunoblotting. A faint light-scattering band, which consists of the buoyant lipid rafts material, was often visible at the 35%-5% sucrose interface (fractions 4 and 5).

For further immunoprecipitation of rafts proteins, rafts were prepared from 2×10^8 cells. After sucrose gradient centrifugation, fractions corresponding to rafts were collected, centrifuged ($100\,000 \times g$ for 1 h at 4°C) and the final pellet was resuspended in immunoprecipitation buffer.

Immunofluorescence

Cells grown on coverslips were fixed in 4% paraformaldehyde-phosphate-buffered saline for 20 min, permeabilized with 0.5% Triton X-100 and blocked with 1% bovine serum albumin in phosphate-buffered saline for 30 min. Then the cells were incubated with the primary antibodies, followed by ALEXAFluor 448 or 555 conjugated secondary antibodies (Invitrogen, Villebon sur Yvette, France). Nuclei were counterstained with 4,6-diamidino-2-phenyl indole (Sigma-Aldrich Chimie). Cells were analyzed by fluorescence microscopy using a LEICA DMRX microscope (LEICA Microsystems, Rueil Malmaison, France) equipped with a LEICA True Confocal Scanner TCS SP. The used objective was Leica HCX PL APO 63 \times 1.40 LBL.

Proximity ligation assay (PLA)

Cells were grown on coverslips, fixed, permeabilized, blocked and incubated with primary antibodies (anti-RAR α and anti

G α q), as described for immunofluorescence experiments. Duolink II (Eurogentec, Angers, France) *in situ* PLA was performed according to the manufacturer's protocol. PLA probes were incubated for 1 h at 37°C , followed by hybridization, ligation, amplification and detection. Nuclei were counterstained with 4,6-diamidino-2-phenyl indole. Slides were analyzed by fluorescence microscopy using a LEICA DM4000B microscope (LEICA Microsystems) equipped with a Cool SNAP photometric camera. The used objective was Leica HCX PLAN APO 40x0, 75 PH 2. The number of fluorescent signals and nuclei in an image were counted, and were statistically analyzed using the Blobfinder V3.2 software from the Centre for Image Analysis at Uppsala University (<http://www.cb.uu.se/~amin/BlobFinder/>). Statistical significance was accepted when $P < 0.05$ using one-tailed Student t test. Values are presented as means \pm s.d.

RNA isolation and quantitative real time-PCR

Total RNAs were isolated and subjected to quantitative real time-PCR as described (Bruck *et al.*, 2009). All primers are QuantiTect Primer Assays from Qiagen (Courtaboeuf, France; Hs_BTG2_1_SG QuantiTect Primer Assay QT00240247; Hs_HOXA1_1_SG QuantiTect Primer Assay QT00011963). Transcript levels were normalized according to β -actin transcripts, which are unresponsive to RA.

Conflict of interest

The authors declare no conflict of interest.

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References

- Alsayed Y, Uddin S, Mahmud N, Lekmine F, Kalvakolanu DV, Minucci S *et al.* (2001). Activation of Rac1 and the p38 mitogen-activated protein kinase pathway in response to all-trans-retinoic acid. *J Biol Chem* **276**: 4012-4019.
- Altucci L, Leibowitz MD, Ogilvie KM, de Lera AR, Gronemeyer H. (2007). RAR and RXR modulation in cancer and metabolic disease. *Nat Rev Drug Discov* **6**: 793-810.
- Bastien J, Rochette-Egly C. (2004). Nuclear retinoid receptors and the transcription of retinoid-target genes. *Gene* **328**: 1-16.
- Bour G, Gaillard E, Bruck N, Lalevee S, Plassat JL, Busso D *et al.* (2005). Cyclin H binding to the RAR{alpha} activation function (AF)-2 domain directs phosphorylation of the AF-1 domain by cyclin-dependent kinase 7. *Proc Natl Acad Sci USA* **102**: 16608-16613.
- Bruck N, Vitoux D, Ferry C, Duong V, Bauer A, de The H *et al.* (2009). A coordinated phosphorylation cascade initiated by p38MAPK/MSK1 directs RARalpha to target promoters. *EMBO J* **28**: 34-47.
- Chen N, Napoli JL. (2008). All-trans-retinoic acid stimulates translation and induces spine formation in hippocampal neurons through a membrane-associated RARalpha. *FASEB J* **22**: 236-245.
- Clagett-Dame M, Knutson D. (2011). Vitamin A in reproduction and development. *Nutrients* **3**: 385-428.

- de Laurentiis A, Donovan L, Arcaro A. (2007). Lipid rafts and caveolae in signaling by growth factor receptors. *Open Biochem J* 1: 12–32.
- De N, De PK, Wang M, Zhang H, Dobrota EA, Robertson KA *et al.* (2007). CSK controls retinoic acid receptor (RAR) signaling: a RAR-c-SRC signaling axis is required for neurogenic differentiation. *Mol Cell Biol* 27: 4179–4197.
- Duong V, Rochette-Egly C. (2011). The molecular physiology of nuclear retinoic acid receptors. From health to disease. *Biochim Biophys Acta* 1812: 1023–1031.
- Faria TN, Mendelsohn C, Chambon P, Gudas LJ. (1999). The targeted disruption of both alleles of RARbeta(2) in F9 cells results in the loss of retinoic acid-associated growth arrest. *J Biol Chem* 274: 26783–26788.
- Gaub MP, Rochette-Egly C, Lutz Y, Ali S, Matthes H, Scheuer I *et al.* (1992). Immunodetection of multiple species of retinoic acid receptor alpha: evidence for phosphorylation. *Exp Cell Res* 201: 335–346.
- Germain P, Chambon P, Eichele G, Evans RM, Lazar MA, Leid M *et al.* (2006a). International Union of Pharmacology. LX. Retinoic acid receptors. *Pharmacol Rev* 58: 712–725.
- Germain P, Staels B, Dacquet C, Spedding M, Laudet V. (2006b). Overview of nomenclature of nuclear receptors. *Pharmacol Rev* 58: 685–704.
- Gianni M, Bauer A, Garattini E, Chambon P, Rochette-Egly C. (2002). Phosphorylation by p38MAPK and recruitment of SUG-1 are required for RA-induced RAR γ degradation and transactivation. *EMBO J* 21: 3760–3769.
- Gianni M, Parrella E, Raska I, Gaillard E, Nigro EA, Gaudon C *et al.* (2006). P38MAPK-dependent phosphorylation and degradation of SRC-3/AIB1 and RARalpha-mediated transcription. *EMBO J* 25: 739–751.
- Huhtakangas JA, Olivera CJ, Bishop JE, Zanello LP, Norman AW. (2004). The vitamin D receptor is present in caveolae-enriched plasma membranes and binds 1 alpha,25(OH)₂-vitamin D₃ *in vivo* and *in vitro*. *Mol Endocrinol* 18: 2660–2671.
- Lai L, Yuan L, Chen Q, Dong C, Mao L, Rowan B *et al.* (2008). The G α i and G α q proteins mediate the effects of melatonin on steroid/thyroid hormone receptor transcriptional activity and breast cancer cell proliferation. *J Pineal Res* 45: 476–488.
- Laudet V, Gronemeyer H. (2001). *Nuclear Receptor Factsbook*. Academic Press: London.
- Le Romancer M, Treilleux I, Leconte N, Robin-Lespinasse Y, Sentis S, Bouchekioua-Bouzaghrou K *et al.* (2008). Regulation of estrogen rapid signaling through arginine methylation by PRMT1. *Mol Cell* 31: 212–221.
- Lefebvre P, Martin PJ, Flajollet S, Dedieu S, Billaut X, Lefebvre B. (2005). Transcriptional activities of retinoic acid receptors. *Vitam Horm* 70: 199–264.
- Losel R, Wehling M. (2003). Nongenomic actions of steroid hormones. *Nat Rev Mol Cell Biol* 4: 46–56.
- Luoma JI, Boulware MI, Mermelstein PG. (2008). Caveolin proteins and estrogen signaling in the brain. *Mol Cell Endocrinol* 290: 8–13.
- Marquez DC, Chen HW, Curran EM, Welshons WV, Pietras RJ. (2006). Estrogen receptors in membrane lipid rafts and signal transduction in breast cancer. *Mol Cell Endocrinol* 246: 91–100.
- Masia S, Alvarez S, de Lera AR, Baretino D. (2007). Rapid, nongenomic actions of retinoic acid on phosphatidylinositol-3-kinase signaling pathway mediated by the retinoic acid receptor. *Mol Endocrinol* 21: 2391–2402.
- Matthews L, Berry A, Ohanian V, Ohanian J, Garside H, Ray D. (2008). Caveolin mediates rapid glucocorticoid effects and couples glucocorticoid action to the antiproliferative program. *Mol Endocrinol* 22: 1320–1330.
- Migliaccio A, Piccolo D, Castoria G, Di Domenico M, Bilancio A, Lombardi M *et al.* (1998). Activation of the Src/p21ras/Erk pathway by progesterone receptor via cross-talk with estrogen receptor. *EMBO J* 17: 2008–2018.
- Mizuno N, Itoh H. (2009). Functions and regulatory mechanisms of Gq-signaling pathways. *Neurosignals* 17: 42–54.
- Norman AW, Henry HL, Bishop JE, Song XD, Bula C, Okamura WH. (2001). Different shapes of the steroid hormone 1alpha,25(OH)₂-vitamin D₃ act as agonists for two different receptors in the vitamin D endocrine system to mediate genomic and rapid responses. *Steroids* 66: 147–158.
- Norman AW, Mizwicki MT, Norman DP. (2004). Steroid-hormone rapid actions, membrane receptors and a conformational ensemble model. *Nat Rev Drug Discov* 3: 27–41.
- Ordenez-Moran P, Larriba MJ, Palmer HG, Valero RA, Barbachano A, Dunach M *et al.* (2008). RhoA-ROCK and p38MAPK-MSK1 mediate vitamin D effects on gene expression, phenotype, and Wnt pathway in colon cancer cells. *J Cell Biol* 183: 697–710.
- Ostrom RS, Insel PA. (2006). Methods for the study of signaling molecules in membrane lipid rafts and caveolae. *Methods Mol Biol* 332: 181–191.
- Pan J, Kao YL, Joshi S, Jeetendran S, Dipette D, Singh US. (2005). Activation of Rac1 by phosphatidylinositol 3-kinase *in vivo*: role in activation of mitogen-activated protein kinase (MAPK) pathways and retinoic acid-induced neuronal differentiation of SH-SY5Y cells. *J Neurochem* 93: 571–583.
- Park SS, Kim JE, Kim YA, Kim YC, Kim SW. (2005). Caveolin-1 is down-regulated and inversely correlated with HER2 and EGFR expression status in invasive ductal carcinoma of the breast. *Histopathology* 47: 625–630.
- Pedram A, Razandi M, Sainson RC, Kim JK, Hughes CC, Levin ER. (2007). A conserved mechanism for steroid receptor translocation to the plasma membrane. *J Biol Chem* 282: 22278–22288.
- Pike LJ. (2003). Lipid rafts: bringing order to chaos. *J Lipid Res* 44: 655–667.
- Piskunov A, Rochette-Egly C. (2011). MSK1 and Nuclear Receptors Signaling. In: Vermeulen L and Arthur JSC (eds). *MSKs*. Landes Bioscience Books: Austin, TX, USA.
- Qiu J, Bosch MA, Tobias SC, Grandy DK, Scanlan TS, Ronnekleiv OK *et al.* (2003). Rapid signaling of estrogen in hypothalamic neurons involves a novel G-protein-coupled estrogen receptor that activates protein kinase C. *J Neurosci* 23: 9529–9540.
- Rochette-Egly C, Germain P. (2009). Dynamic and combinatorial control of gene expression by nuclear retinoic acid receptors. *Nucl Receptor Signaling* 7: e005.
- Rochette-Egly C, Plassat JL, Taneja R, Chambon P. (2000). The AF-1 and AF-2 activating domains of retinoic acid receptor-alpha (RARalpha) and their phosphorylation are differentially involved in parietal endodermal differentiation of F9 cells and retinoid-induced expression of target genes. *Mol Endocrinol* 14: 1398–1410.
- Samarut E, Rochette-Egly C. (2011). Nuclear retinoic acid receptors: conductors of the retinoic acid symphony during development. *Mol Cell Endocrinol* (e-pub ahead of print 8 April 2011).
- Simons K, Toomre D. (2000). Lipid rafts and signal transduction. *Nat Rev Mol Cell Biol* 1: 31–39.
- Soderberg O, Gullberg M, Jarvius M, Ridderstrale K, Leuchowius KJ, Jarvius J *et al.* (2006). Direct observation of individual endogenous protein complexes *in situ* by proximity ligation. *Nat Methods* 3: 995–1000.
- Staubach S, Hanisch FG. (2011). Lipid rafts: signaling and sorting platforms of cells and their roles in cancer. *Expert Rev Proteomics* 8: 263–277.
- Stuermer CA. (2011). Reggie/flotillin and the targeted delivery of cargo. *J Neurochem* 116: 708–713.
- Sugawara Y, Nishii H, Takahashi T, Yamauchi J, Mizuno N, Tago K *et al.* (2007). The lipid raft proteins flotillins/reggies interact with G α q and are involved in Gq-mediated p38 mitogen-activated protein kinase activation through tyrosine kinase. *Cell Signal* 19: 1301–1308.
- Taneja R, Rochette-Egly C, Plassat JL, Penna L, Gaub MP, Chambon P. (1997). Phosphorylation of activation functions AF-1 and AF-2 of RAR alpha and RAR gamma is indispensable for differentiation of F9 cells upon retinoic acid and cAMP treatment. *EMBO J* 16: 6452–6465.

- Tari AM, Lim SJ, Hung MC, Esteva FJ, Lopez-Berestein G. (2002). Her2/neu induces all-trans retinoic acid (ATRA) resistance in breast cancer cells. *Oncogene* **21**: 5224–5232.
- Vasudevan N, Pfaff DW. (2008). Non-genomic actions of estrogens and their interaction with genomic actions in the brain. *Front Neuroendocrinol* **29**: 238–257.
- Waugh MG, Hsuan JJ. (2009). Preparation of membrane rafts. *Methods Mol Biol* **462**: 403–414.
- White CD, Coetsee M, Morgan K, Flanagan CA, Millar RP, Lu ZL. (2008). A crucial role for G alpha q/11, but not G alpha i/o or G alpha s, in gonadotropin-releasing hormone receptor-mediated cell growth inhibition. *Mol Endocrinol* **22**: 2520–2530.
- Yao Y, Hong S, Zhou H, Yuan T, Zeng R, Liao K. (2009). The differential protein and lipid compositions of noncaveolar lipid microdomains and caveolae. *Cell Res* **19**: 497–506.
- Zanotto-Filho A, Cammarota M, Gelain DP, Oliveira RB, Delgado-Canedo A, Dalmolin RJ *et al.* (2008). Retinoic acid induces apoptosis by a non-classical mechanism of ERK1/2 activation. *Toxicol In Vitro* **22**: 1205–1212.

PUBLICATION 2

**Profilin IIA: a novel coregulator of the N-terminal domain of the
Retinoic acid receptor alpha (RAR α)**

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ABSTRACT

Nuclear retinoic acid (RA) receptors (RARs) are ligand-dependent regulators of transcription. Their transcriptional activity relies mainly on their recruitment to specific DNA response elements and on their interactions with several coregulators at the ligand-binding domain. However, the N-terminal domain (NTD) also plays a role through its phosphorylation. Here, using a yeast two-hybrid system, we isolated profilin IIA as a novel partner of the NTD of the RAR α subtype. Profilin IIA is a small ubiquitous actin-binding protein with an SH3-like domain. We demonstrated that the SH3-like domain of profilin IIA interacts with the proline-rich motif (PRM) located in RAR α NTD. The interaction was not affected by the phosphorylation of the serine residue located in the PRM or by RA addition. *In vivo*, profilin IIA modulates positively RAR α -mediated transcription of several target genes. In the absence of RA, profilin IIA interacts with RAR α in nuclei. In response to RA, profilin IIA is corecruited with RAR α to the promoters of RA-target genes and modulates their expression.

INTRODUCTION

Retinoic Acid (RA) influences the differentiation, proliferation and apoptosis of a variety of cell types through modifications in the expression of target genes. The effects of RA are mediated by specific nuclear receptors, RA receptors (RARs), which consist of three subtypes α , β and γ and function as ligand-dependent regulators of transcription heterodimerized with other nuclear receptors, the Retinoid X receptors (RXRs) (for reviews see (Bastien & Rochette-Egly, 2004; Rochette-Egly & Germain, 2009; Samarut & Rochette-Egly, 2012)).

The basic mechanism for switching on gene transcription by RAR/RXR heterodimers relies on binding to specific elements located in the promoters of target genes and on ligand-induced conformational changes that cause the association/dissociation of a complex network of coregulatory proteins (Rochette-Egly & Germain, 2009). At the end, these events alter the chromatin structure surrounding the promoter of target genes and pave the way for the recruitment of the transcriptional machinery.

However, in addition to this classical scenario, which is directed by the LBD, it is now evident that, the N-terminal domain (NTD), although of naturally disordered structure, also plays a role, increasing the complexity of RAR-mediated transcription mechanisms (Ang et al, 2005; Bour et al, 2007; Liu et al, 2006). In this context, we recently highlighted that the NTD of RARs depicts a proline-rich motif (PRM) containing a serine residue, which becomes rapidly phosphorylated subsequently to non-genomic effects of RA, i.e. the activation of kinase cascades (Bruck et al, 2009; Lalevee et al, 2010; Piskunov & Rochette-Egly, 2011). *In fine*, phosphorylation of this residue drives the recruitment of RARs to promoters (Bruck et al, 2009; Lalevee et al, 2010).

The interesting point is that PRMs are well known to bind proteins with SH3 or WW domains (Ball et al, 2005; Freund et al, 2008; Kay et al, 2000). In that context we found that the PRM of the RAR γ subtype interacts with vinexin β (Bour et al, 2005b; Lalevee et al, 2010), an adaptor protein with SH3 domains, which is generally associated as a scaffold to complexes involved in cytoskeleton organization and signal transduction. However it is also one of the growing number of actin-binding that are nuclear and modulate transcription (Kast & Dominguez, 2011; Zheng et al, 2009) and we found that vinexin β represses the transcriptional

activity of RAR γ through sequestering the non phosphorylated form of the receptor out of gene promoters (Lalevee et al, 2010). Remarkably, vinexin β dissociates in response to RA subsequently to RAR γ phosphorylation, making the phosphorylated form of RAR γ able to occupy promoters and to initiate transcription. This was the first report of a RAR corepressor association/dissociation out of promoters and regulated by phosphorylation.

Here, we aimed at identifying new partners of the NTD of the RAR α subtype, which like RAR γ , depicts a N-terminal PRM with a phosphorylation site (Samarut et al, 2011). Yeast two-hybrid screenings led to the identification of profilin IIA as a novel partner of the NTD of RAR α . Profilin IIA is an other cytoskeleton actin-binding protein with an SH3-like domain, and is a regulator of the actin microfilament system (Haikarainen et al, 2009; Jockusch et al, 2007). We demonstrated that the interaction involves the SH3-like domain of profilin IIA and the PRM of RAR α and we determined the affinity of the interaction. However, the role of profilin IIA in transcription proved to be different from that of vinexin β and the classical coregulators. Indeed profilin IIA is present in the nucleus, is recruited with RAR α to the promoters of target genes and modulates positively RAR α -mediated transcription. However the interaction of profilin IIA is not modulated by the phosphorylation of RAR α or by RA, suggesting a novel regulation mechanism.

MATERIALS AND METHODS

Plasmids and reagents

The pSG5-based expression vectors for mouse RAR α 1 (WT, S77A, S77E, ΔA and ΔAB) and RAR γ 1 have been previously described as well as the prokaryotic pGEX-2T vectors encoding RAR α 1 (WT, DEF and ABC) RAR β 2 and RAR γ 1 fused to glutathione S-transferase (GST) (Bour et al, 2005a; Nagpal et al, 1992). The yeast pBTM116mod plasmid encoding N-terminal domain of RAR α S77A fused to the LexA-DNA-binding domain was described in (Bour et al, 2005b).

Drs M. Noda and H. Kitayama (Xu et al, 2007) provided the pcDNA3.1-profilin IIA vector. The cDNA of profilin IIA was amplified by PCR from the pcDNA3.1 vector and inserted into XhoI/BamHI-digested pSG5 containing the epitope B of human estrogen receptor as a tag (a gift from T. Lerouge). It was also inserted into EcoRI/BamHI-digested pGEX-2T. Profilin IIA (Y7A/N10D) and profilin IIA (Y134S/F140A) in pSG5-B10 were constructed by double PCR amplification. All constructs were generated using standard cloning procedures and were verified by restriction enzyme analysis and automated DNA sequencing.

Mouse GIPZ lentiviral shRNAmir control (RHS4346) or targeting profilin IIA (RMM4532-NM_019410), as well as On-target plus SMART Pool human PFN2 (L-063038-01) and non targeting siRNA (D-001210-01-05) were from Thermofisher Scientific. All-trans Retinoic Acid was from Sigma-Aldrich.

Antibodies

Rabbit polyclonal antibodies raised against the F region of RAR α (RP α (F)) were described earlier (Bruck et al, 2009) and were purified by application onto sulfolink gel columns (Thermo Scientific Pierce) coupled with the corresponding synthetic peptides (Buchanan et al, 2011; Vernet et al, 2006). Mouse monoclonal antibodies recognizing specifically RAR α phosphorylated at position S77 (MAb 27 α) have been described previously (Bruck et al, 2009; Gaillard et al, 2006), as well as antibodies against the epitope B of the N-terminal domain of the estrogen receptor (B10) (Ali et al, 1993). Mouse monoclonal antibodies against profilin IIA (sc-1000955), goat antibodies against β -actin (sc-1615) and rabbit polyclonal antibodies against RAR α for CHIP experiments (sc-551-X) were from Santa Cruz

Biotechnology Inc. (USA). Mouse monoclonal antibodies recognizing GAPDH (MAB374) were from Merk-Millipore.

Yeast two-hybrid screening

Yeast two-hybrid screening was performed as previously described (Bour et al, 2005b), using the L40 reporter strain harboring the HIS3 and LacZ reporter genes, both under the control of LexA binding sites. The mouse embryo (12.5 days pc) cDNA library in yeast VP16-AAD fusion vector pASV3 was introduced by lithium acetate transformation into the reporter strain expressing the LexA-RAR α 1(A/B)(S77A) fusion protein from the pBTM116mod vector. Approximately 2.10^6 yeast transformants were screened for their ability to grow on medium lacking histidine and containing 30 mM 3 amino-1,2,4 triazole (3-AT) (ICN Pharmaceuticals, France) and to express β -galactosidase. After several rounds of replica plating on selective medium, library plasmids were recovered from the positive clones, amplified, subjected to restriction analysis and sequenced.

GST Pull-down Assays

Equimolar amounts of GST and GST fusion proteins expressed in *Escherichia coli* were purified on glutathione-Sepharose 4B beads (Amersham Biosciences) and incubated with COS-1 cell extracts expressing B-tagged profilin IIA protein as described (Bour et al, 2005b).

Surface Plasmon resonance measurements.

SPR experiments were carried out with a BIAcore T100 instrument and research grade CM5 sensor chips (Altschuh et al, 2006; Lalevee et al, 2010). The ligand (GST-profilin IIA) was captured via anti-GST antibodies that were immobilized on the sensor surface using standard amine coupling procedures and following the manufacturer's instructions. Synthetic peptides corresponding to the proline-rich motif of RAR γ or RAR α (with S77 phosphorylated or not) (Table 1) were diluted in running buffer (HBS EP: 10 mM Hepes (pH 7.4), 150 mM NaCl, 3.4 mM EDTA, 0.005% (v/v) surfactant P20) and injected over the surface in a continuous flow at 25°C.

Cells, Transfections and Immunoprecipitations

COS-1 cells, human neuroblastoma SH-SY-5Y cells, human acute promyelocytic leukemia (NB4) cells, mouse hippocampus HT22 cells, human breast cancer cells (MCF7 and SKBR3 cell lines), mouse embryocarcima cells (F9 and P19 cell lines) and mouse embryonic fibroblasts (MEF WT and MEF RAR($\alpha\beta\gamma$)-/-) (Bruck et al, 2009) were cultured according to standard procedures.

COS-1 cells, MCF7 cells and MEFs were transiently transfected using the Lipofectamine 2000 reagent (Invitrogen), according to the manufacturer's protocol. When 80–90% confluent, cells were treated with RA (10^{-7} M) after 24 h in a medium containing 1% fetal calf serum. Extracts were prepared, immunoblotted or immunoprecipitated as described (Bruck et al 2009).

Immunofluorescence

Cells grown on coverslips were fixed in 4% formaldehyde (PFA)-PBS for 20 minutes, permeabilized with 0,1% Triton X-100 and blocked with 1% BSA in PBS for 30 minutes. Then the cells were incubated with the primary antibodies, followed by ALEXAFluor™ 448 or 555 conjugated secondary antibodies (Invitrogen). Cells were also incubated with fluorescent green 488 phalloidin (Biotium, Inc. Hayward USA). Nuclei were counterstained with DAPI (Sigma-Aldrich Chimie, France). Cells were analyzed by fluorescence microscopy using a LEICA DMRX microscope equipped with a LEICA True Confocal Scanner TCS SP. The used objective was Leica HCX PL APO 63x1.40 LBL.

Proximity Ligation Assay (PLA)

Duo link II (Eurogentec, France) *in situ* proximity ligation assay (PLA) was performed according to the manufacturer's protocol and as previously described (Ferry et al, 2011; Piskunov & Rochette-Egly, 2011). Cells were grown on coverslips, fixed, permeabilized, blocked and incubated with primary antibodies (rabbit anti-RAR α and mouse anti profilin IIA) as described for immunofluorescence experiments then PLA probes were incubated for 1 h at 37°C, followed by hybridization, ligation, amplification and detection. Nuclei were counterstained with Dapi. Slides were analyzed by fluorescence microscopy using a LEICA DM4000B microscope equipped with a Cool SNAP Photometric camera. The used objective was

Leica HCX PLAN APO 40x0, 75 PH 2.

RNA isolation and quantitative RT-PCR was performed as described (Ferry et al, 2009). Primer sequences are as follows: Mouse RAR β 2: 5'-TTTGGCACGTAGGCTGTTGG-3' and 5'-GAGCGAGCCTGGAAAATGGT-3'; Mouse Cyp26A1: 5'-GGGCTTACTTTGCAAGAGCA-3' and 5'-GAAGGCCTCCTCCAAATGGA-3'; Mouse GAPDH: 5'-GTCTTCTGGGTGGCAGTGAT -3' and 5'-CTGCACCACCAACTGCTTAG -3'. Human primers were from QIAGEN SA: BTG2 QUANTITECT PRIMER ASSAY QT00240247, CYP26A1 QUANTITECT PRIMER ASSAY QT00026817, and ACTIN QUANTITECT PRIMER ASSAY QT00095431.

Chromatin immunoprecipitation (ChIP) and ChIP western experiments

ChIPs were performed with sub confluent MCF7 cells and MEFs as previously described (Bruck et al, 2009; Ferry et al, 2011; Ferry et al, 2009). The primers pairs used for qPCR amplification are as follows: Mouse 36B4 5'-TTTGCTGTACT GACTCGGTGA-3' and 5'-CCTCCCACAACAAAACAACC-3'; Human 36B4, 5'-AGGACTCCATGTTCCCAAAG-3' and 5'-CGCAGCCAATAGACAGGAG-3'; Mouse Cyp26A1: R2, 5'-AAACAGGAGCAGGCTGAACT-3' and 5'-CGCTGCCACTGTCATATCTT-3'; R1, 5'-GGTAACTCGGAGCTCTGCAC-3' and 5'-CCAGGTTACTGCCCACGTTA-3'; Human Cyp26A1: R1, 5'-GCGGAACAAACGGTTAAAGA-3' and 5'-GCAGTACAGGTCCCAGAGCTT-3'; R2, 5'-GAGTTCACTCGATGTCACG-3' and 5'-ATCGCGCTGGAGGTAATTCT-3'; Mouse RAR β 2: 5'-CGATCCCAAGT TCTCCCTTC-3' and 5'-CAGACTGGT TGGGTCATTTG-3'; Human BTG2: 5'-CCCGGCTACACTGTATATTGACTTGG -3' and 5'-GGGTTTCATCACGTTGGTCAGGAT -3'.

Occupancy of the promoters was calculated by normalizing the PCR signals from the immunoprecipitated samples to the signals obtained from the input DNA.

For ChIP-Western experiments, the precipitated chromatin complexes were proceeded as described (Bruck et al, 2009) and bound proteins were revealed by immunoblotting.

RESULTS

Profilin IIA, a new partner of the N-terminal domain of RAR α

In order to identify proteins that interact with the N-terminal domain (NTD) of RAR α , a yeast two-hybrid screen of a mouse embryo cDNA library was performed as previously described (Bour et al, 2005b), using as a bait the NTD (A and B regions) of mouse (m) RAR α in which the phosphorylatable serine residue (S77) was substituted with an alanine (RAR α (AB)(S77A) (Fig. 1B). Among the positive clones we isolated, one contained a 430 kb cDNA insert displaying 96% sequence identity to human profilin IIA (NM_053024.3). This DNA fragment encoded a 140 amino acids protein that corresponds to full length profilin IIA (Fig. 1C). The encoded protein contained the N- and C-terminal sequence regions that form an SH3-like domain involved in the binding of poly-L-proline stretches.

The SH3-like domain of profilin IIA interacts specifically with the N-terminal PRM of RAR α .

The data obtained by yeast two-hybrid screening were further investigated in *in vitro* protein-protein interaction assays using recombinant GST-RAR α expressed in E-Coli and bound to glutathione-sepharose beads. When expressed in E. Coli, GST-RAR α WT is not phosphorylated at S77 within the NTD. After incubation with extracts from COS-1 cells over expressing B-tagged profilin IIA, GST-RAR α WT interacted with profilin IIA (Fig. 2A). We also assessed whether profilin IIA could interact with the other RAR subtypes. Interestingly we did not observe any significant binding of profilin IIA with RAR γ 1 and RAR β 2 in GST pull down experiments (Fig. 2A).

Profilin IIA being characterized by the presence of an SH3-like domain known to interact with PRMs (Kursula et al, 2008), we investigated whether the PRM of RAR α (located in the B region of the NTD) is indeed involved in the interaction. First we corroborated the yeast two-hybrid data by showing that profilin IIA interacts with the isolated N-terminal (A to C) regions and not with the C-terminal (D-F) ones of RAR α fused to GST (Fig. 2B). Then a synthetic peptide corresponding to the PRM of RAR α , PI 80 (Table 1) was generated and assayed for its ability to prevent the interaction between RAR α and profilin IIA. PI 80 efficiently

disrupted the interaction (Fig. 2C), indicating that profilin IIA interacts with RAR α via the PRM located in the B region of the receptor. These results were confirmed in coimmunoprecipitation experiments performed with extract from COS-1 cells over expressing B-10 tagged profilin IIA and RAR α deletion mutants. Indeed deletion of the whole NTD (A and B regions) and not of the A region abrogated the interaction of RAR α with profilin IIA (Fig. 2D)

Finally we investigated whether the SH3-like domain of profilin IIA is indeed involved in the interaction. The SH3-like domain of profilin IIA encompasses the N and C terminal helices (Haikarainen et al, 2009). Given that two residues in the C-terminal helix (Tyr 134 and Phe140) and two in the N-terminal one (Tyr 7 and Asn 10) have been shown to be important for the interaction with proline-rich ligands (Haikarainen et al, 2009) (Fig. 2E), we investigated whether mutation of these residues abrogates the interaction with RAR α . We found that profilin IIA mutated at the two residues located in the N-terminal helix [Profilin IIA(Y7S/N10D)] as well as profilin IIA mutated at the C-terminal ones [Profilin IIA(Y134S/F140A)] have lost their ability to interact with RAR α in GST-pull down experiments (Fig. 2F).

Collectively all these results confirm that the SH3-like domain of profilin IIA interacts specifically with the PRM of RAR α , located in the NTD.

Profilin IIA interaction is not affected by RAR α phosphorylation.

The PRM of RAR α involved in the interaction with profilin IIA contains a serine residue (S77), which can be phosphorylated *in vitro* and *in vivo* (Bruck et al, 2009; Rochette-Egly et al, 1997). Therefore, we aimed at investigating whether phosphorylation of S77 modulates the interaction of RAR α with profilin IIA.

First, coimmunoprecipitation experiments were performed with COS-1 cells over expressing B-tagged profilin IIA in combination with RAR α WT or RAR α mutants with S77 substituted with a glutamic acid (RAR α S77E) or an alanine (RAR α S77A), which mimic the phosphorylated and non-phosphorylated forms respectively (Fig.1A). After immunoprecipitation of the extracts with B10 antibodies, immunoblotting of RAR α showed that the RAR α mutants interacted as efficiently as RAR α WT with profilin IIA (Fig.3A, lanes 10-12).

In transfected COS-1 cells, RA induced the rapid phosphorylation of RAR α at S77 as assessed by immunoblotting after immunoprecipitation of RAR α with a monoclonal antibody recognizing specifically RAR α phosphorylated at this residue (Fig. 3B). However the interaction of RAR α with profilin IIA was not affected upon RA addition (Fig.3C, lanes 12-16). Altogether these results converge towards the conclusion that the interaction is not modulated by the phosphorylation of RAR α at S77.

Affinity of the interaction between profilin IIA and the PRM of RAR α .

We used Surface Plasmon Resonance (SPR) to measure the equilibrium affinity and kinetic parameters of interaction of profilin IIA with synthetic peptides corresponding to the PRM of RAR α (Table 1) (Lalevee et al, 2010). Affinity between profilin IIA and peptide PI 80 that corresponds to the non-phosphorylated form was calculated with the simple Langmuir 1:1 model and the Biacore T100 evaluation software (v 1.1.1), and found to be 0,1 mM (Table 1). Affinity for peptide PI 81 in which S77 is phosphorylated was similar, in line with the *in vivo* results. A 10 times lower affinity was found for peptide PI121, which corresponds to the PRM of RAR γ , corroborating the specificity of the interaction.

Endogenous Profilin IIA and RAR α interact in the nuclei of neuronal and fibroblastic cells.

Then we aimed at determining whether profilin IIA interacts with RAR α *in vivo*. Profilin IIA is well known to be expressed mainly in brain and neuronal cells (Birbach, 2008; Michaelsen et al, 2010). Accordingly, significant levels of profilin IIA were detected by immunoblotting in human SH-SY-5Y neuroblastoma cells line and mouse hippocampus HT22 cells (Fig. 4A lanes 2 and 3). Profilin IIA was also present in mouse embryonic fibroblasts (MEFs) (Fig.4A, lanes 4 and 5) and in human breast cancer cells (MCF7 and SKBR3 cell lines) (Fig.4A, lanes 8 and 9). In contrast, profilin IIA was hardly detectable in mouse embryo carcinoma cells (F9 and P19 cell lines) (Fig. 4A, lanes 1 and 6) and no profilin IIA could be detected in human acute promyelocytic leukemia (APL) cells (NB4 cell line, Fig. 4A, lane 7).

The presence of profilin IIA in SH-SY-5Y, HT22, MCF7 cells and MEFs was corroborated in immunofluorescence experiments (Fig. 4B). Most interestingly, in

all these cells, profilin IIA was nuclear (Fig.4B), like RAR α (Fig. 5A), raising the question whether profilin IIA interacts with RAR α in the nuclear compartment.

With that aim we performed proximity ligation assays (PLA), which allow the detection *in situ* of interacting endogenous proteins (Ferry et al, 2011; Piskunov & Rochette-Egly, 2011; Soderberg et al, 2006). Rabbit anti-RAR α and mouse anti-profilin IIA antibodies were used followed by species-specific secondary antibodies, called PLA probes, each attached with a unique short DNA strand. When the PLA probes are in close proximity, the DNA strands can be joined through the addition of a circle-forming DNA oligonucleotide that can be amplified using a polymerase. Then the amplified products are revealed with labeled complementary oligonucleotide probes and are easily visible as bright red spots under a fluorescence microscope.

RAR α /profilin IIA complexes were seen in the nuclei of MCF7 cells and MEFs (Fig.5B). The number of complexes did not change after RA addition up to 1 hour (Fig. 5B, compare panels f and I and panels l and o), in line with the absence of regulation of the interaction in response to RA and upon RAR α phosphorylation (see Figure 3). No signal was seen when each primary antibody was used individually and with MEF invalidated for RARs (Fig.5B, panels a-c), validating the specificity of the technique.

Altogether these results indicate that profilin IIA interacts with RAR α in the nuclei of fibroblastic and breast cancer cells.

Profilin IIA modulates the transcriptional activity of RAR α

Then the question is the functional role of the nuclear RAR α -profilin IIA interaction. With that aim we analyzed the consequences of profilin IIA knockdown on the expression of RA-target genes.

MEFs respond to RA through the expression of several target genes such as the *Cyp26A1* and *RAR β 2* genes as assessed by quantitative RT-PCR (Fig. 6A). The RA-induced expression of these genes was previously shown to depend on RAR α (Bruck et al, 2009). Transfection of MEFs cells with an shRNA targeting profilin IIA reduced significantly the protein levels of profilin IIA, without affecting RAR α levels, as shown by immunoblotting (Fig. 6A). Remarkably, when profilin IIA was reduced, the

RA-induced expression of both *Cyp26A1* and *RARβ2* genes was significantly down-regulated (Fig. 6A), indicating that proflin IIA plays a positive role in the expression of these target genes.

Similar results were obtained with MCF7 cells, which also respond to RA through $RAR\alpha$ -mediated expression of several genes such as *Cyp26A1* and *Btg2* (Bruck et al, 2009; Ferry et al, 2011; Piskunov & Rochette-Egly, 2011). Knockdown of proflin IIA with specific siRNA significantly reduced the RA-induced expression of *Btg2* (Fig. 6B). However the expression of *Cyp26A1* was not affected (Fig. 6B). Altogether, these results indicate that proflin IIA plays a positive role in the expression of $RAR\alpha$ -target genes but that this effect can differ depending on the cell type.

Proflin IIA is recruited with $RAR\alpha$ to the promoters of RA-target genes

Given that proflin IIA modulates positively the expression of $RAR\alpha$ target genes, one can hypothesize that proflin IIA is recruited with $RAR\alpha$ at the promoters of these genes. Therefore ChIP experiments were performed with MEF and MCF7 cells to assess the occupancy of the promoters. Antibodies directed against $RAR\alpha$ or proflin IIA were used to immunoprecipitate $RAR\alpha$ and/or proflin IIA-bound DNA fragments that were further analyzed by quantitative PCR using specific pairs of primers spanning the RAREs (Fig. 7A). The specificity of the experimental conditions was checked in the absence of antibodies and with the promoter of the control 36B4 gene, which does not contain any RARE.

In MEFs, at 1 hour after RA addition, there was an enrichment of $RAR\alpha$ bound at the *RARβ2* promoter region (Fig. 7B), in line with previous studies (Bruck et al, 2009). Concerning the *cyp26A1* gene promoter, which contains two functional DR5 RAREs, a proximal one (R1) and a distal one (R2) (Fig. 7A), the R2 region was also specifically enriched after RA addition (Fig. 7B) (Bruck et al, 2009). Interestingly, after RA addition, there was also an enrichment of proflin IIA bound at the *RARβ2* promoter and the R2 promoter region of *Cyp26A1* (Fig. 7C).

ChIP experiments performed with MCF7 cells also showed that both $RAR\alpha$ and proflin IIA are recruited to the promoter region of the *Btg2* gene (Fig. 7D and 7E). However, in the case of the *Cyp26A1* gene promoter, $RAR\alpha$ only was recruited

and not profilin IIA, in line with the inability of the latter to modulate the expression of this gene in this cell line (Fig. 7D and 7E).

Altogether these results indicate that profilin II can be recruited with RAR α to the promoters of some target genes

Finally profilin IIA interaction with RAR α in chromatin was analyzed in CHIP western experiments. As shown in Figure 7F, immunoprecipitated profilin IIA interacted with RAR α . This interaction was not affected after RA addition, corroborating the *in vitro* coimmunoprecipitation (see Figure 3) and PLA results (see Figure 5).

DISCUSSION

Up to now, only a few proteins have been reported to interact with the N-terminal domain of nuclear receptors including RARs (Boonyaratanakornkit et al, 2001; Bour et al, 2007; Bour et al, 2005b; Zhao et al, 2009). The novelty of the present study is the isolation of profilin IIA as a novel coregulator of the RAR β subtype. Profilin IIA is a small (MW = 12-16 kDa) actin-binding protein that was originally identified as a key regulator of the actin microfilament system, especially in the cytoplasm of neuronal cells (Haikarainen et al, 2009; Jockusch et al, 2007). Here we present evidence that profilin IIA is also present in nuclei of several non-neuronal cells, where it interacts with the NTD of RAR α and controls positively its transcriptional activity.

The main characteristic of the profilin IIA protein is the presence of an SH3-like domain, which is known to interact with PRMs (Ball et al, 2005; Kursula et al, 2008). RARs contain such a PRM in their NTD (Lalevee et al, 2010). Although this PRM is well conserved between RARs (Samarut et al, 2011), according to our data, the interaction with profilin IIA appears to concern only RAR α and not the other RAR subtypes. Similarly the interaction of vinexin β , another protein with an SH3 domain, was specific for the RAR γ subtype and did not concern RAR α . It must be noted that PRMs adopt a secondary structure known as poly proline II helix (PPII), which is determined by the pattern and number of the consecutive proline residues and by the presence of other amino acids interleaved with the proline residues. The PRM of RAR α differs from that of RAR γ by the substitution of one of the 5 consecutive prolines by a leucine. This may be at the basis of the specific interaction of each RAR with a particular SH3 domain.

According to our data, the interaction of profilin IIA with RAR α is not affected by the phosphorylation of the serine residue flanking the PRM. This was in contrast to the traditional model in which phosphorylation of serine residues flanking the proline motifs have the ability to positively or negatively regulate the binding of SH3 domains (Kay et al, 2000; Lalevee et al, 2010). It is also in contrast to our previous report where we demonstrated that phosphorylation of the serine residue flanking the proline stretch of RAR γ induces the dissociation of vinexin β . Nevertheless, such

results challenge the hypothesis that profilin IIA would control the activity of RAR α via a mechanism different from that, which was described for vinexin β and RAR γ .

An important clue in the present study is that profilin IIA participates positively to the transcription of RAR α -target genes. Moreover profilin IIA is present in chromatin and is recruited with RAR α to the promoters of target genes in response to RA. Such results are in line with another study showing that nuclear profilin plays a role in transcription (Lederer et al, 2005). Most importantly, they also corroborate the ever-growing evidence that actin, actin-related proteins and actin-binding proteins are constituents of nuclear protein complexes and play a role in transcription (Bettinger et al, 2004; Jockusch et al, 2006; Zheng et al, 2009). Indeed a number of actin-binding proteins have been shown to regulate the activity of several transcription factors including nuclear receptors through the recruitment of multiple components of transcription complexes such as chromatin-remodeling, histone acetyl transferase complexes (Archer et al, 2005; Blessing et al, 2004; Gettemans et al, 2005). Such a role of actin-binding proteins in transcription complexes emerged only recently and up to now there are no data showing that profilin IIA belongs to nuclear complexes. However one can propose that, as in the cytoplasm, profilin IIA might have a role in regulating the properties of nuclear actin through its ability to promote ADP to ATP exchange in G-actin (Fenn et al, 2011; Kast & Dominguez, 2011). Such a role might explain why nuclear forms of actin are prominently found in monomer states within transcription complexes.

Nevertheless it will require further experiments to test whether profilin IIA has such a role in maintaining the pool of monomer actin in the nucleus, when complexes with RAR α at RA-target genes promoters. Moreover, it would be interesting to address whether profilin IIA also modulates the activity of the coregulatory complexes of RAR α through nucleotide-dependent conformational transitions. Finally whether other processes than RA signaling can modulate the interaction of RAR α with profilin IIA or RAR α phosphorylation would provide important insights into the role of this adaptor in RA signaling.

In conclusion this study opened new concepts and avenues in the regulation of RA-target genes transcription via an actin-binding protein interacting with the NTD of the RAR α subtype.

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REFERENCES

- Ali S, Lutz Y, Bellocq JP, Chenard-Neu MP, Rouyer N, Metzger D (1993) Production and characterization of monoclonal antibodies recognising defined regions of the human oestrogen receptor. *Hybridoma* **12**(4): 391-405
- Altschuh D, Oncul S, Demchenko AP (2006) Fluorescence sensing of intermolecular interactions and development of direct molecular biosensors. *J Mol Recognit* **19**(6): 459-477
- Ang WH, Pilet S, Scopelliti R, Bussy F, Juillerat-Jeanneret L, Dyson PJ (2005) Synthesis and characterization of platinum(IV) anticancer drugs with functionalized aromatic carboxylate ligands: influence of the ligands on drug efficacies and uptake. *J Med Chem* **48**(25): 8060-8069
- Archer SK, Claudianos C, Campbell HD (2005) Evolution of the gelsolin family of actin-binding proteins as novel transcriptional coactivators. *Bioessays* **27**(4): 388-396
- Ball LJ, Kuhne R, Schneider-Mergener J, Oschkinat H (2005) Recognition of proline-rich motifs by protein-protein-interaction domains. *Angew Chem Int Ed Engl* **44**(19): 2852-2869
- Bastien J, Rochette-Egly C (2004) Nuclear retinoid receptors and the transcription of retinoid-target genes. *Gene* **328**: 1-16
- Bettinger BT, Gilbert DM, Amberg DC (2004) Actin up in the nucleus. *Nat Rev Mol Cell Biol* **5**(5): 410-415
- Birbach A (2008) Profilin, a multi-modal regulator of neuronal plasticity. *Bioessays* **30**(10): 994-1002
- Blessing CA, Ugrinova GT, Goodson HV (2004) Actin and ARPs: action in the nucleus. *Trends Cell Biol* **14**(8): 435-442
- Boonyaratanakornkit V, Scott MP, Ribon V, Sherman L, Anderson SM, Maller JL, Miller WT, Edwards DP (2001) Progesterone receptor contains a proline-rich motif that directly interacts with SH3 domains and activates c-Src family tyrosine kinases. *Mol Cell* **8**(2): 269-280
- Bour G, Gaillard E, Bruck N, Lalevee S, Plassat JL, Busso D, Samama JP, Rochette-Egly C (2005a) Cyclin H binding to the RARalpha activation function (AF)-2 domain directs phosphorylation of the AF-1 domain by cyclin-dependent kinase 7. *Proc Natl Acad Sci U S A* **102**(46): 16608-16613
- Bour G, Lalevee S, Rochette-Egly C (2007) Protein kinases and the proteasome join in the combinatorial control of transcription by nuclear retinoic acid receptors. *Trends Cell Biol* **17**(6): 302-309
- Bour G, Plassat JL, Bauer A, Lalevee S, Rochette-Egly C (2005b) Vinexin {beta} Interacts with the Non-phosphorylated AF-1 Domain of Retinoid Receptor {gamma}

(RAR $\{\gamma\}$) and Represses RAR $\{\gamma\}$ -mediated Transcription. *J Biol Chem* **280**(17): 17027-17037

Bruck N, Vitoux D, Ferry C, Duong V, Bauer A, de The H, Rochette-Egly C (2009) A coordinated phosphorylation cascade initiated by p38MAPK/MSK1 directs RAR α to target promoters. *Embo J* **28**(1): 34-47

Buchanan FQ, Rochette-Egly C, Asson-Batres MA (2011) Detection of variable levels of RAR α and RAR γ proteins in pluripotent and differentiating mouse embryonal carcinoma and mouse embryonic stem cells. *Cell Tissue Res* **346**(1): 43-51

Fenn S, Breitsprecher D, Gerhold CB, Witte G, Faix J, Hopfner KP (2011) Structural biochemistry of nuclear actin-related proteins 4 and 8 reveals their interaction with actin. *Embo J* **30**(11): 2153-2166

Ferry C, Gaouar S, Fischer B, Boeglin M, Paul N, Samarut E, Piskunov A, Pankotai-Bodo G, Brino L, Rochette-Egly C (2011) Cullin 3 mediates SRC-3 ubiquitination and degradation to control the retinoic acid response. *Proc Natl Acad Sci U S A* **108**(51): 20603-20608

Ferry C, Gianni M, Lalevee S, Bruck N, Plassat JL, Raska I, Jr., Garattini E, Rochette-Egly C (2009) SUG-1 plays proteolytic and non-proteolytic roles in the control of retinoic acid target genes via its interaction with SRC-3. *J Biol Chem* **284**(12): 8127-8135

Freund C, Schmalz HG, Sticht J, Kuhne R (2008) Proline-rich sequence recognition domains (PRD): ligands, function and inhibition. *Handb Exp Pharmacol*(186): 407-429

Gaillard E, Bruck N, Brelivet Y, Bour G, Lalevee S, Bauer A, Poch O, Moras D, Rochette-Egly C (2006) Phosphorylation by PKA potentiates retinoic acid receptor alpha activity by means of increasing interaction with and phosphorylation by cyclin H/cdk7. *Proc Natl Acad Sci U S A* **103**(25): 9548-9553

Gettemans J, Van Impe K, Delanote V, Hubert T, Vandekerckhove J, De Corte V (2005) Nuclear actin-binding proteins as modulators of gene transcription. *Traffic* **6**(10): 847-857

Haikarainen T, Chen WQ, Lubec G, Kursula P (2009) Structure, modifications and ligand-binding properties of rat profilin 2a. *Acta Crystallogr D Biol Crystallogr* **65**(Pt 4): 303-311

Jockusch BM, Murk K, Rothkegel M (2007) The profile of profilins. *Rev Physiol Biochem Pharmacol* **159**: 131-149

Jockusch BM, Schoenenberger CA, Stetefeld J, Aebi U (2006) Tracking down the different forms of nuclear actin. *Trends Cell Biol* **16**(8): 391-396

Kast DJ, Dominguez R (2011) Arp you ready for actin in the nucleus? *Embo J* **30**(11): 2097-2098

Kay BK, Williamson MP, Sudol M (2000) The importance of being proline: the interaction of proline-rich motifs in signaling proteins with their cognate domains. *FASEB J* **14**(2): 231-241

Kursula P, Kursula I, Massimi M, Song YH, Downer J, Stanley WA, Witke W, Wilmanns M (2008) High-resolution structural analysis of mammalian profilin 2a complex formation with two physiological ligands: the formin homology 1 domain of mDia1 and the proline-rich domain of VASP. *J Mol Biol* **375**(1): 270-290

Lalevee S, Bour G, Quinternet M, Samarut E, Kessler P, Vitorino M, Bruck N, Delsuc MA, Vonesch JL, Kieffer B, Rochette-Egly C (2010) Vinexinss, an atypical "sensor" of retinoic acid receptor gamma signaling: union and sequestration, separation, and phosphorylation. *FASEB J* **24**(11): 4523-4534

Lederer M, Jockusch BM, Rothkegel M (2005) Profilin regulates the activity of p42POP, a novel Myb-related transcription factor. *J Cell Sci* **118**(Pt 2): 331-341

Liu J, Perumal NB, Oldfield CJ, Su EW, Uversky VN, Dunker AK (2006) Intrinsic disorder in transcription factors. *Biochemistry* **45**(22): 6873-6888

Michaelsen K, Murk K, Zagrebelsky M, Dreznjak A, Jockusch BM, Rothkegel M, Korte M (2010) Fine-tuning of neuronal architecture requires two profilin isoforms. *Proc Natl Acad Sci U S A* **107**(36): 15780-15785

Nagpal S, Saunders M, Kastner P, Durand B, Nakshatri H, Chambon P (1992) Promoter context- and response element-dependent specificity of the transcriptional activation and modulating functions of retinoic acid receptors. *Cell* **70**: 1007-1019

Piskunov A, Rochette-Egly C (2012) A retinoic acid receptor RARalpha pool present in membrane lipid rafts forms complexes with G protein alphaQ to activate p38MAPK. *Oncogene* in press

Rochette-Egly C, Adam S, Rossignol M, Egly JM, Chambon P (1997) Stimulation of RAR alpha activation function AF-1 through binding to the general transcription factor TFIID and phosphorylation by CDK7. *Cell* **90**(1): 97-107

Rochette-Egly C, Germain P (2009) Dynamic and combinatorial control of gene expression by nuclear retinoic acid receptors. *Nuclear Receptor Signaling* **7**: e005

Samarut E, Amal I, Markov GV, Stote R, Dejaegere A, Laudet V, Rochette-Egly C (2011) Evolution of nuclear retinoic acid receptor alpha (RARalpha) phosphorylation sites. Serine gain provides fine-tuned regulation. *Mol Biol Evol* **28**(7): 2125-2137

Samarut E, Rochette-Egly C (2012) Nuclear retinoic acid receptors: conductors of the retinoic acid symphony during development. *Mol Cell Endocrinol* **348**(2): 348-360

Soderberg O, Gullberg M, Jarvius M, Ridderstrale K, Leuchowius KJ, Jarvius J, Wester K, Hydbring P, Bahram F, Larsson LG, Landegren U (2006) Direct observation of individual endogenous protein complexes in situ by proximity ligation. *Nat Methods* **3**(12): 995-1000

Vernet N, Dennefeld C, Rochette-Egly C, Oulad-Abdelghani M, Chambon P, Ghyselinck NB, Mark M (2006) Retinoic acid metabolism and signaling pathways in the adult and developing mouse testis. *Endocrinology* **147**(1): 96-110

Xu J, Shi S, Matsumoto N, Noda M, Kitayama H (2007) Identification of Rgl3 as a potential binding partner for Rap-family small G-proteins and profilin II. *Cell Signal* **19**(7): 1575-1582

Zhao J, Zhang Z, Vucetic Z, Soprano KJ, Soprano DR (2009) HACE1: A novel repressor of RAR transcriptional activity. *J Cell Biochem* **107**(3): 482-493

Zheng B, Han M, Bernier M, Wen JK (2009) Nuclear actin and actin-binding proteins in the regulation of transcription and gene expression. *FEBS J* **276**(10): 2669-2685

LEGENDS TO FIGURES

Figure 1: Profilin IIA a new partner of the N-terminal domain of RAR α

A. Schematic representation (not to scale) of the RAR α 1 protein with the known functional domains and the N-terminal phosphorylation site. The RAR α PRM with S77 substituted with alanine or glutamic acid residues is also shown. B. Schematic representation of the LexA-RAR α (A/B) proteins used as a bait in the yeast two-hybrid experiments. C. Alignment of the protein sequence deduced from our isolated mouse clone with those of human profilin IIA and IIB.

Figure 2: The SH3-like domain of Profilin IIA interacts with the N-terminal PRM of RAR α

A. *In vitro* pull down experiments showing that B10-profilin IIA over expressed in COS-1 cells, interacts with RAR α but not with the other RAR β and RAR γ subtypes. B. *In vitro*, B10-profilin IIA interacts with the N-terminal A-C regions and not with the C-terminal DEF regions of RAR α fused to GST. C. Immobilized GST-RAR α proteins were incubated with B10-profilin IIA in the absence or presence of increasing amounts of the synthetic peptide PI80 corresponding to the PRM of RAR α . D. COS-1 cells were transfected with the B10-profilin IIA vector along with RAR α either WT, Δ A or Δ AB and whole cell extracts were incubated with B10 antibodies. Immunocomplexes were resolved by SDS-PAGE and incubated with RP α (F) and B10 antibodies. Lanes 1-6 correspond to 5% of the amount of immunoprecipitated extracts. E. Amino acid sequence of the N-terminal and C-terminal ends of profilin IIA. The mutations affecting the interaction with proline rich ligands are shown. F. *In vitro* pulldown experiments showing that the profilin IIA mutants (Y7S/N10D) and (Y134S/F140A) do not interact with RAR α fused to GST.

Figure 3: Phosphorylation of the serine residue located in the PRM of RAR α does not affect the interaction with profilin IIA

A. Coimmunoprecipitation experiments showing that in transfected COS-1 cells, substitution of serine 77 with a glutamic acid or an alanine does not affect the interaction of RAR α with profilin IIA. B. In transfected COS-1 cells RA induces the

rapid phosphorylation of RAR α at S77. Phosphorylated RAR α was immunoprecipitated with monoclonal antibodies recognizing specifically the receptor phosphorylated at S77 and immunoblotted with RP α (F). Bottom panel corresponds to the inputs. C. Coimmunoprecipitation experiments showing that after RA addition, the interaction between RAR α and profilin IIA is not affected.

Figure 4. Profilin IIA is expressed in the nuclei of neuronal cells, fibroblasts and breast cancer cell lines

A. immunoblotting experiments showing that profilin IIA is expressed in human SH-YH-5H neuroblastoma cells, mouse HT22 hippocampus cells, MEF, MCF7 and SKBR3 breast cancer cells, but not in mouse embryo carcinoma cells (P19 and F9 cell lines) and acute promyelocytic leukemia cells (NB4 cell line).

B. Immunofluorescence experiments showing that profilin IIA is present mainly in the nuclear compartments of SH-YH-5H, HT22, MEF and MCF7 cells. Cells were double stained with DAPI (blue) and profilin IIA antibodies (red). The merge images overlapping the blue and red are shown.

Figure 5: Nuclear Profilin IIA interacts with RAR α

A. immunofluorescence experiments showing the nuclear localization of both RAR α and profilin IIA in MEFs (panels a-d) and MCF7 cells (e-h). Cells were triple stained with DAPI (blue), profilin IIA (red) and RAR α (green) antibodies. The merge images overlapping the red, green and blue fluorescence are shown (panels d and h).

B. PLA (Proximity Ligation Assay) showing the profilin IIA/RAR α complexes (red) in MEFs WT (panels d-i), MEF RAR KO (panels a-c) and MCF7 cells (panels j-o) treated or not with RA for 1 hour. DNA was counterstained with Dapi (blue). The merge between blue, green and red is also shown (panels c, f, i, l, o).

Figure 6: Profilin IIA participates in the transcription of RA-target genes

A. Silencing of profilin IIA decreases the RA-induced expression of the *cyp26A1* and *RARB2* genes in MEFs as monitored by quantitative qRT-PCR. B. Silencing of profilin IIA decreases the RA-induced expression of the *Btg2* gene but not of the *cyp26A1* one in MCF7 cells. In all cases, values are the mean \pm SD of three different experiments. Knockdown efficiency was controlled by immunoblotting.

Figure 7: Profilin IIA occupies with RAR α the promoters of target genes

A. Schematic representation of the promoter regions of the *Cyp26A1*, *RAR β 2* and *Btg2* genes with the primer pairs used for qPCR amplification. B and C. Kinetic ChIP experiments performed with RA-treated MEFs and showing the recruitment of RAR α (B) and profilin IIA (C) to the R1 and R2 regions of the *cyp26A1* gene promoter, to the *RAR β 2* gene promoter and to the control *36B4* gene. Values (% of the inputs) correspond to a representative experiment among 3.

D and E. Same kinetic ChIP experiments, showing that profilin IIA is recruited with RAR α to the *Btg2* promoter but not to the *Cyp26A1* one in RA-treated MCF7 cells.

F. ChIP western experiments performed with MEFs treated or not with RA for 1 hour. The complexes immunoprecipitated with profilin IIA or RAR α antibodies were immunoblotted with RAR α and profilin IIA antibodies.

Figure 1

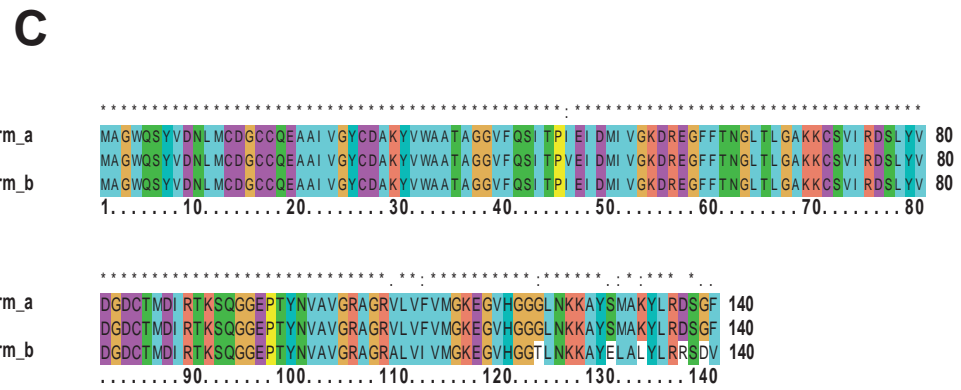
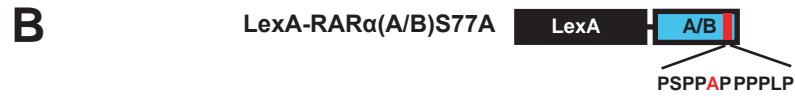
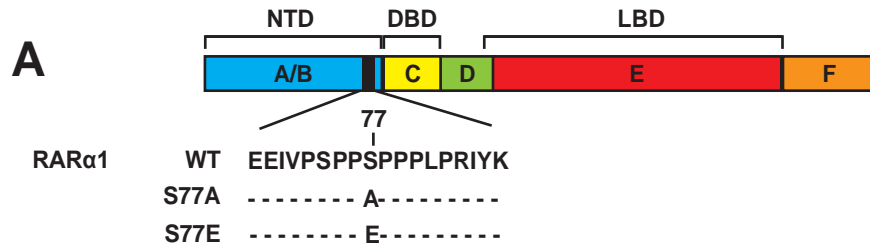


Figure 2

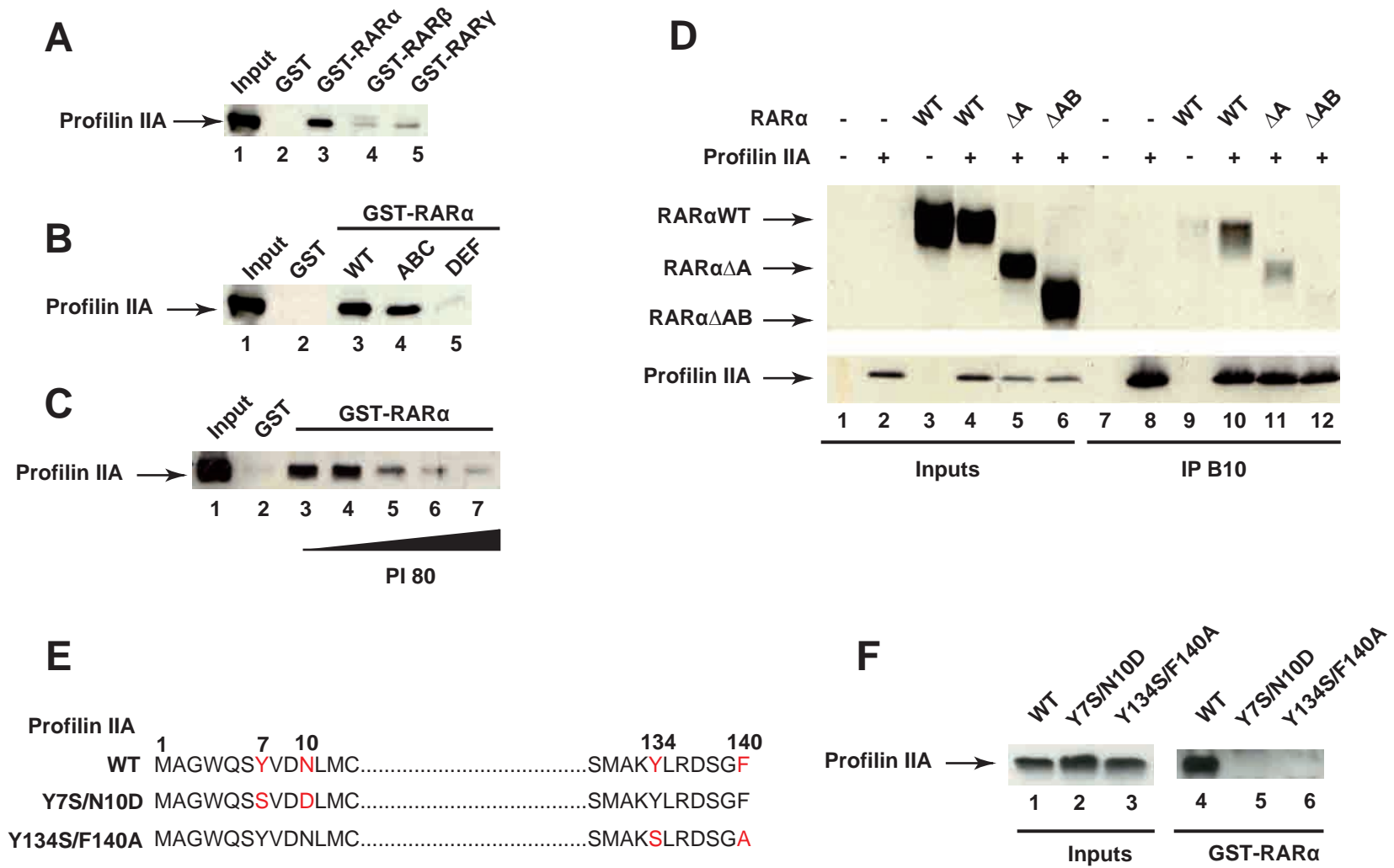
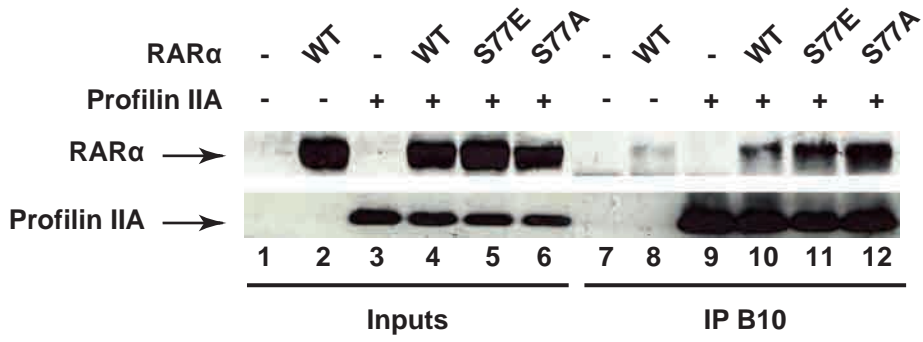
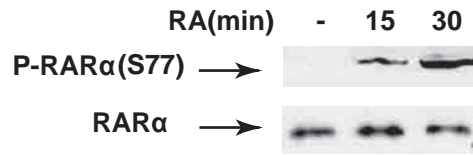


Figure 3

A



B



C

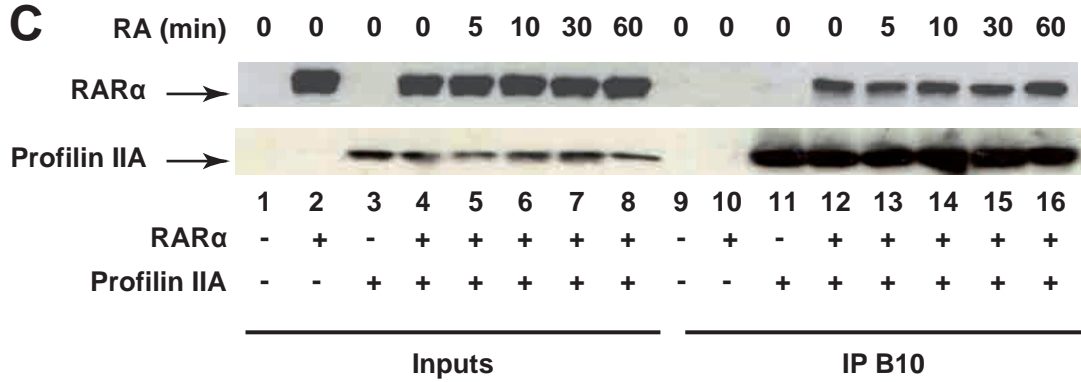


Figure 4

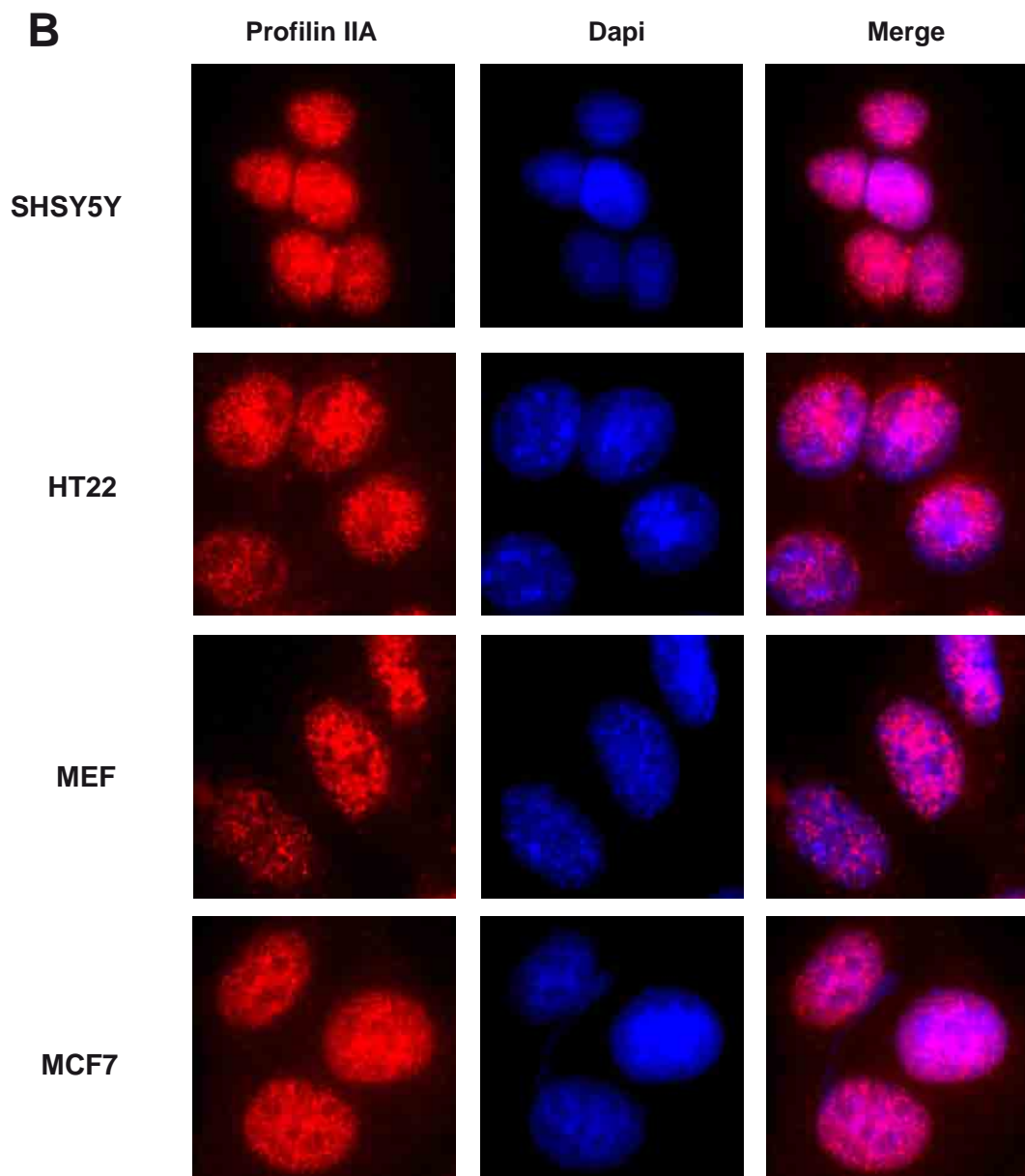
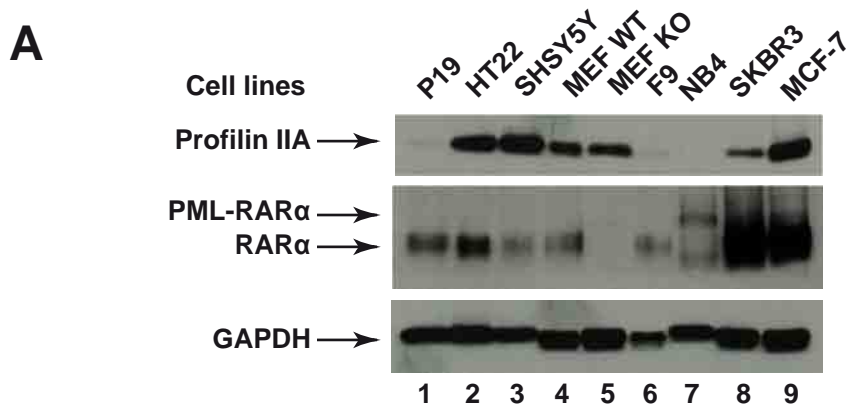


Figure 5

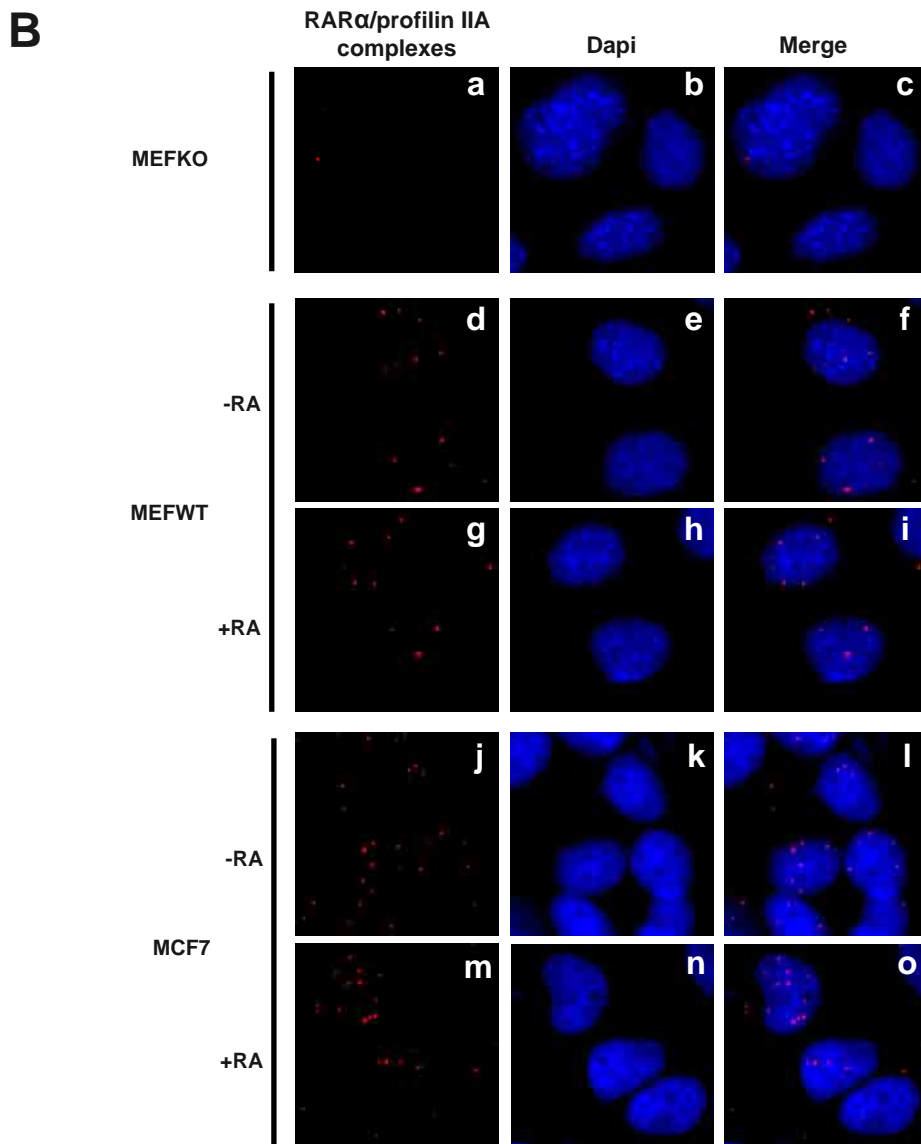
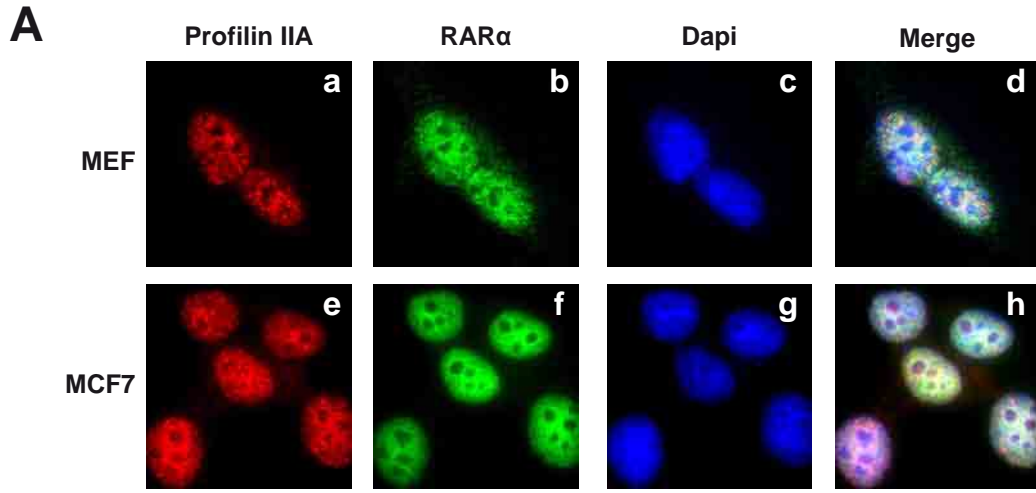
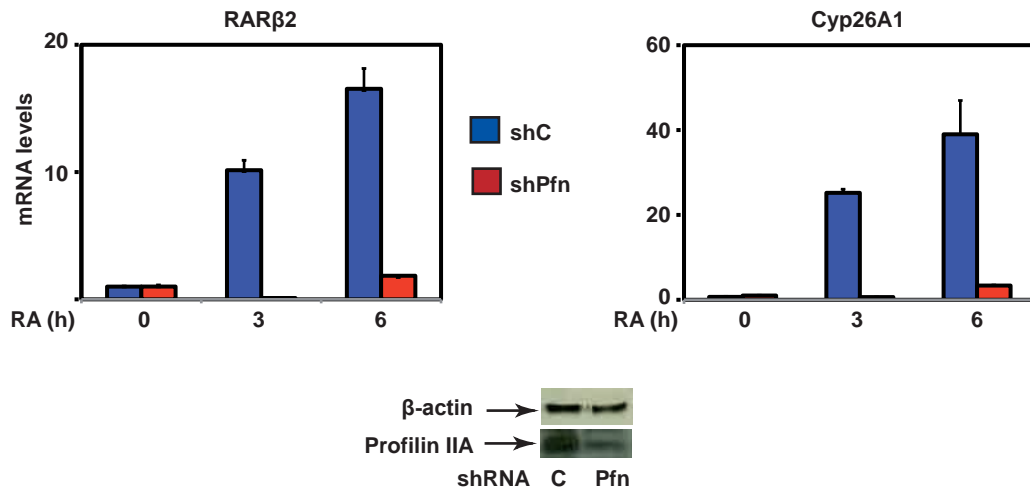


Figure 6

A MEF



B MCF7

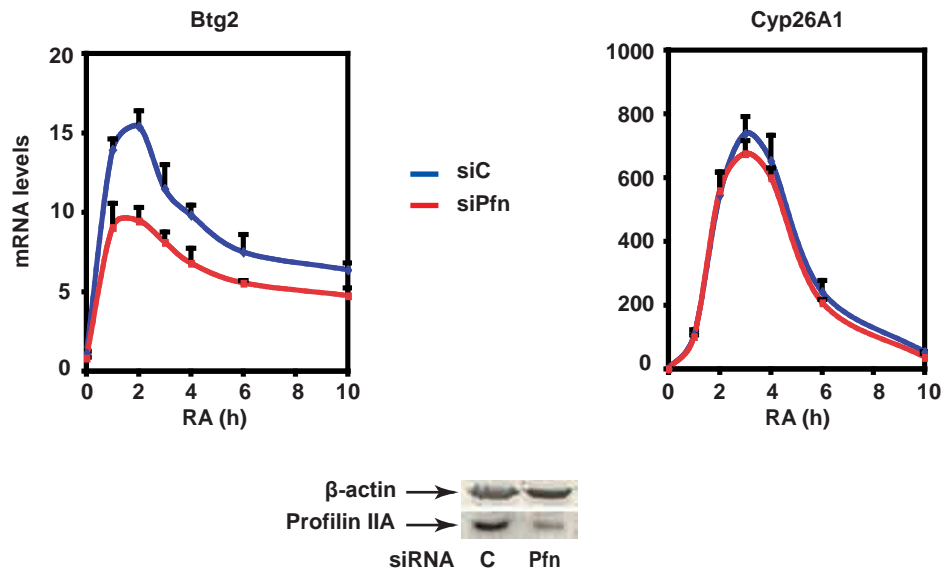
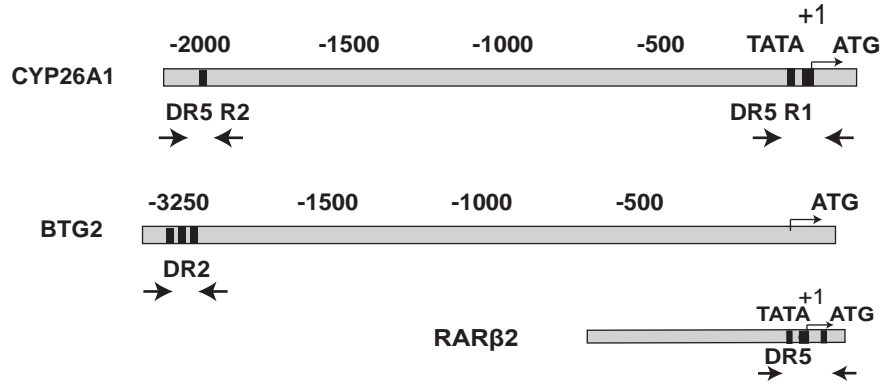
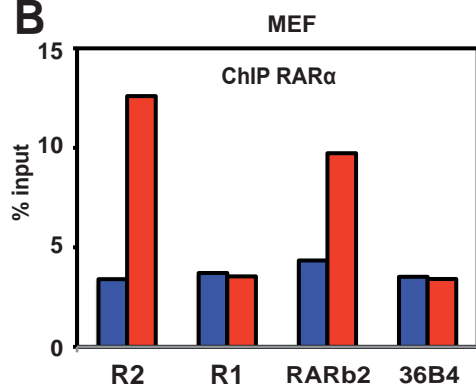


Figure 7

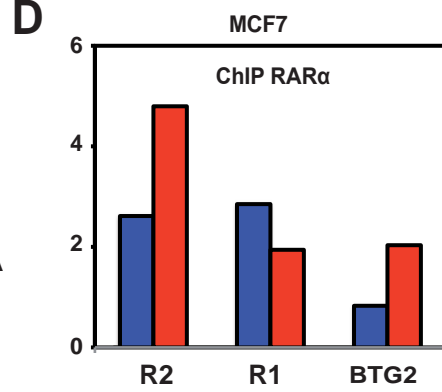
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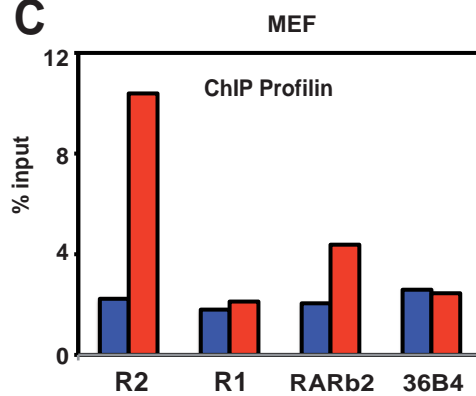
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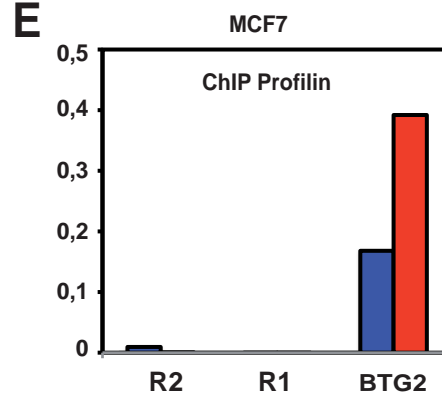
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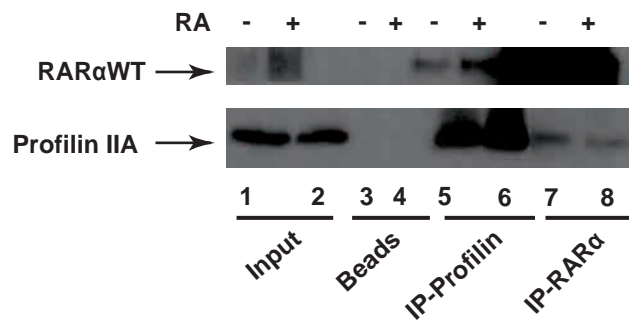


E



F

ChIP Western MEF



Peptide	Amino Acid sequence	Description	Affinity for Profilin IIA
PI 80	EEIVSPPPLPRIYK	Non phosphorylated PRD of RAR α	0,1 mM
PI 81	EEIVSPPPLPRIYK P	PRD of RAR α phosphorylated at S77	0,1 mM
PI 121	EEMVPSSPSPPPPRVYK	Non phosphorylated PRD of RAR γ	1 mM

Table 1: SPR analysis of the interaction between GST-profilin IIA and synthetic peptides corresponding to the phosphorylated and non phosphorylated PRM of RAR α and RAR γ . GST and GST-profilin IIA were immobilized on a sensor chip. Peptides were injected at different concentrations ($0,5-5 \times 10^{-4}$ M) for 60 s. GST signal [relative units (RU)] was subtracted from the GST-profilin IIA signals. Nonlinear curve fitting of the equilibrium responses vs peptide concentration was used to derive equilibrium K_d values.

PUBLICATION 3

CHAPTER

MSK1 and Nuclear Receptors Signaling

Aleksandr Piskunov and Cécile Rochette-Egly*

Abstract

Nuclear receptors for steroid and non-steroid hormones act through both genomic and non-genomic mechanisms. Genomic events involve binding to cognate specific DNA sequences and subsequent recruitment of a battery of coregulators at the promoter. Non-genomic events involve the rapid activation of kinase cascades and steroid as well as non-steroid hormones trigger NR-mediated activation of the MAPK/MSK1 pathway. Here we review the recent insights concerning the crosstalk between the genomic and non-genomic actions of NRs, focusing on the mechanisms of MSK1 activation and influence on NR-target genes transcriptional regulation.

Introduction

Nuclear receptors (NRs) form a super family of ligand-regulated transcription factors, which regulate various physiological functions from development and reproduction to homeostasis and metabolism. This super family includes receptors for steroid hormones [Estrogen receptors (ER), Progesterone receptors (PR), Androgen receptors (AR) and Glucocorticoid receptors (GR)] and for non-steroid ligands [Vitamin D receptor (VDR), Retinoic Acid receptors (RAR), Retinoic X receptors (RXR) and the Peroxisome Proliferator Activated Receptors (PPAR)]. They also include a large number of so-called orphan receptors for which ligands do not exist or have not been identified yet.¹⁻³

Classically NRs are known to act through genomic events, which involve binding of liganded homo or heterodimerized NRs to cognate specific DNA sequences followed by recruitment of coactivators and remodeling of chromatin at the promoter sequences of the activated genes.^{1,4}

In addition to these so-called genomic effects, steroid and non-steroid hormones and their cognate NRs crosstalk with kinase cascades activated by signals impinging on membrane receptors. As an example, progestins and retinoic acid (RA) have been shown to activate the Mitogen-Activated Protein Kinase (MAPK) pathways and the downstream Mitogen- and Stress-activated protein Kinase 1 (MSK1).^{5,6} Traditionally, the non-genomic and genomic effects of steroid and non-steroid hormones have been considered as independent pathways. However it appeared that hormone-activated MSK1 is involved in the regulation of NR-target genes by phosphorylating NRs themselves and/or chromatin associated proteins. Here we will review the current knowledge on MSK1 activation by steroid and non-steroid hormones and on MSK1 molecular targets, focusing on recent insights into the role of MSK1 in transcriptional regulation of NR-target genes.

The Classical Picture of NRs: Ligand-Dependent Regulators of Transcription

NRs have a well-defined domain organization and structure, consisting mainly of two highly conserved and structured domains: the central DNA-binding domain (DBD) linked to the C-terminal Ligand-Binding Domain (LBD). The structure of the DBDs and LBDs has been

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determined by nuclear magnetic resonance and crystallographic studies^{1,2,7} (Fig. 1). Briefly, the DBD contains two typical cysteine-rich zinc-binding motifs and two α -helices, which cross at right angles and fold into a globular conformation to form the core of the DBD. In contrast, the LBD is more complex because it contains not only the ligand-binding pocket, but also the main dimerization domain and a hydrophobic cleft involved in coregulators binding. The LBD shows a common fold comprising 12 conserved α -helices and a short β -turn, separated by exposed and flexible loops and arranged in three layers to form an antiparallel alpha-helical sandwich.

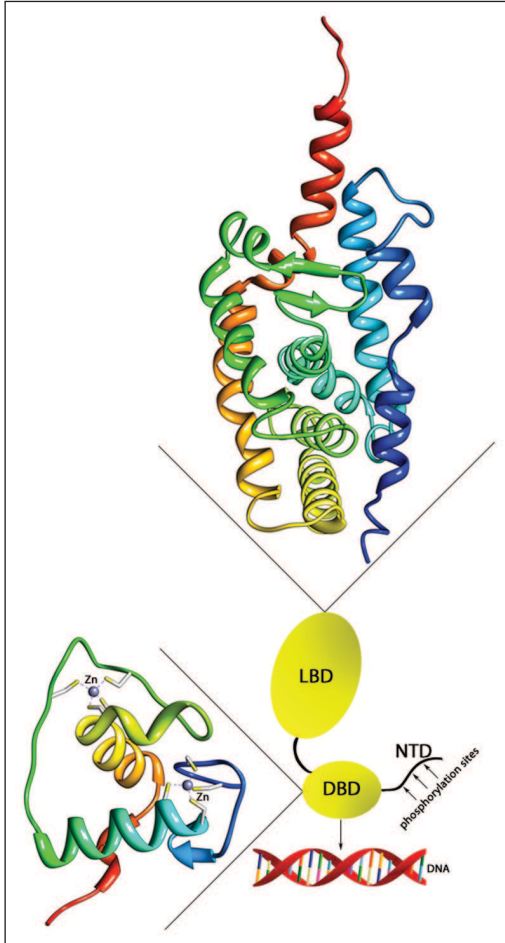


Figure 1. Structural organization of nuclear receptors. Nuclear receptors consist mainly of a central DNA-binding domain (DBD) linked to a C-terminal ligand-binding domain (LBD) and an N-terminal domain (NTD). The DBD (PDB1DSZ)⁷⁷ is composed of two zinc-nucleated modules, two α -helices and a COOH-terminal extension. Helices cross at right angles to form the core of the DBD. This structure provides sequence-specific DNA recognition. The LBD (PDB1LBD)⁷⁸ is composed of 12 conserved α -helices and a β -turn separated by exposed and flexible loops. In RARs, loop L9–10 contains a serine residue, which can be phosphorylated by MSK1. Phosphorylation of this residue increases the flexibility of the nearby loop L8–9 and the N-terminal part of H9 and thereby the docking of cyclin H to this domain. The N-terminal domain (NTD) is natively disordered and contains several serine residues within proline-rich motifs, which can be phosphorylated by cdk's or MAPKs.

Gene induction by NRs is based on a complex network of NRs conformational changes and dynamic interactions with coregulatory proteins.^{2,7,8} Ligand binding is the first and crucial molecular event that switches NRs from inactive to active state by inducing conformational changes in the LBD. These changes favor the dimerization of NRs and increase their DNA affinity. They also create a new surface for coactivators binding, which initiates an ordered and coordinated dissociation and/or recruitment of a series of coregulator complexes with different enzymatic activities including Histone Acetyl- and Methyl-Transferases, and DNA-dependent ATPases.⁹ In fine, these events alter the chromatin structure surrounding the promoter of target genes and pave the way for the recruitment of the transcription machinery including RNA Polymerase II and general transcription factors.

NRs Are Phosphoproteins

In addition to this scenario NRs are targets for phosphorylation processes, which modulate their transcriptional activity.^{8,10} A number of studies demonstrated that the majority of the phosphorylated residues lie within the N-terminal domain (NTD) (Fig. 1). The phosphorylation sites located in the NTD of NRs are serine residues surrounded by prolines and therefore correspond to consensus sites for cyclin-dependent protein kinases (cdks) and Mitogen-Activated Protein Kinases (MAPKs). Accordingly, the NTD of PR, ER, AR, GR, RARs and PPARs were reported to be substrates for cdks, p42/p44MAPK (also called Erk1/2), p38MAPK, and c-Jun N-terminal kinases (JNKs).¹⁰⁻¹⁶ Note that VDR is an exception, probably due to its very short NTD.

It must be noted that, in contrast to the DBDs and LBDs, the NTDs of NRs are not conserved and there are still no high-resolution structures available. Several biochemical studies coupled to structure prediction algorithms suggested that the NTDs of any member of the NR family are naturally disordered,^{17,18} providing the flexibility that is needed for modifications by enzymes such as kinases.¹⁹ Such modifications would induce changes in the structural properties of the domain with profound impacts on its interactions with coregulators and/or on the dynamics of adjacent structural domains.^{5,20}

Interestingly, loops between the α -helices of the LBDs are exposed and flexible and thus are accessible for phosphorylation processes. As an example, in the LBD of RARs, loop L9–10 contains a serine residue located within an arginine/lysine rich motif, which corresponds to a consensus phosphorylation site for several kinases including MSK1^{5,21} (Fig. 1).

A New Picture of NRs: NRs Are Associated to the Cell Membrane and Activate MAPK Signaling Pathways

It is becoming increasingly evident that NRs induce rapid non-genomic responses in addition to their classical genomic effects. These non-genomic effects involve the rapid and transient activation of several kinase cascades mediated by a subpopulation of NRs anchored at the cytoplasmic side of the cell membrane.

Indeed, most of the classical steroid receptors (ER, PR, GR, AR) have been found in specialized plasma membrane structures such as caveolae and lipid rafts²²⁻²⁴ that contain lipids, structural proteins like flotillin and caveolin, and several proteins involved in signal transduction including heterodimeric G proteins, c-Src, Rho and RAC GTPases and Phosphoinositide 3-kinase (PI3K).^{25,26} The membrane localization of steroid NRs depends on post-translational modifications and it has been shown that palmitoylation of a highly conserved nine-amino acids motif in the LBD is critical for membrane localization of ER and PR via caveolin-1 association.²⁷ In addition, steroid NRs are part of membrane molecular complexes, which differ depending on the cell type and context and contain c-Src, the regulatory subunit of PI3K (p85 α) and heterodimeric G α proteins.^{25,28,29} In response to the hormone, ER α rapidly activates the Src/p21ras/Erk pathway via direct interaction with the SH2 domain of c-Src (Fig. 2). Progestins and androgens also activate this signaling cascade via direct interaction of the cognate receptor with the SH3 domain of c-Src or with ER α which itself activates c-Src³⁰⁻³³ (Fig. 2). Note however that, in response to glucocorticoids, GR does not activate Erk but p38MAPK and JNKs^{11,34} (Fig. 2).

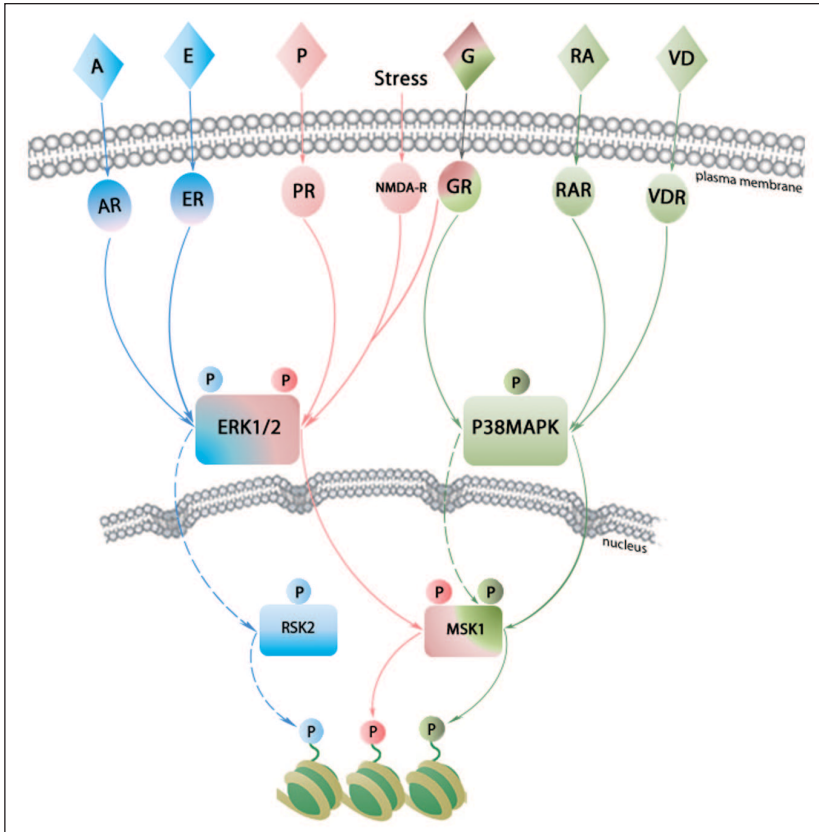


Figure 2. A subpopulation of the classical steroid receptors (ER, PR, GR, AR) and non-steroid receptors (VDR and RARs) is associated to cell membranes and initiates cascades of kinase activations upon binding of their cognate ligands. Accordingly, liganded non-steroid receptors RAR and VDR activate p38MAPK and the downstream MSK1 kinase. Among the steroid receptors, GR bound to glucocorticoids also activates p38MAPK but there is no data indicating whether MSK1 is activated or not. However, upon the concomitant activation of NMDA-R under stress conditions, liganded GR activates MSK1 but through Erks. The other steroid receptors PR, ER and AR also activate Erks but only PR was found to activate the downstream MSK1. In the case of ER and AR another downstream effector of Erks, RSK2 would be an interesting candidate.

Non-steroid receptors such as VDR and RARs have been also found associated to cell membrane fractions, in association with caveolin-1,³⁵ PI3K,³⁶ c-Src³⁷ or G alpha Q proteins.³⁸ However, vitamin D³⁹ and RA^{5,40-42} rather activate p38MAPK (Fig. 2). Activation of this pathway occurs very rapidly through the transient activation of small GTPases such as RhoA and its immediate effector ROCK⁴³ or RAC-1^{37,40} suggesting a non-genomic activation event similar to that described for steroid receptors. Of note is that this process appears to be cell specific as RA has been shown to activate Erks in neuronal and Sertoli cells.^{36,44-46}

NRs Activate MSK1, Downstream of Erk and p38MAPK

Among the targets of NRs-activated Erk and p38MAPK, there is MSK1 (Mitogen- and stress-activated protein kinase), which presents a large structural analogy with the N-terminal ribosomal S6 kinase (RSK) domain.⁴⁷⁻⁴⁹ MSK1 is predominantly localized in the nucleus and is composed of

two kinase domains connected with a linker region. A C-terminal docking domain assures binding of activating Erk or p38MAPK, which then phosphorylates a threonine residue located in the C-terminal kinase domain. Then this activated C-terminal kinase domain phosphorylates a serine in the N-terminal kinase domain, which at the end is responsible for the phosphorylation of MSK1 substrates.

After activation by the steroid hormone progesterin, phosphorylated Erk translocates to the nucleus and forms a complex with nuclear PR homodimers. Then Erk binds and phosphorylates MSK1⁵⁰ leading to its activation⁶ (Fig. 2 and Fig. 3, left). Non-steroid hormones such as RA and Vitamin D also activate MSK1 downstream of p38MAPK^{5,39,43} (Fig. 2), in line with the fact that MSK1 can be activated through both Erks and p38MAPK. Whether VDR and RAR form with p38MAPK and MSK-1 trimeric complexes has not been elucidated yet and will require further investigations.

In conclusion, it appears that steroid and non-steroid NRs are able to activate the MAPK/MSK1 pathway in response to their cognate hormone. However whether this mechanism is general has not been demonstrated yet. Indeed, ER and estrogens do not activate⁵¹ or rather inactivate⁵² MSK1. It is interesting to note that p90 ribosomal S6 kinase (RSK), which is another member of the subfamily of MAPK-activated protein kinases downstream of Erk⁴⁷ and which is overexpressed in several cancers including breast cancers,⁵³ has been shown to bind and phosphorylate ER.^{12,54} Whether ER and estrogens activate RSK instead of MSK1, will require further investigations (Fig. 2).

Concerning AR and androgens, there are still no data concerning MSK1. However, as for ER, RSK would be an interesting candidate^{53,55,56} (Fig. 2). Similarly, whether GR and glucocorticoids activate MSKs or not has not been reported yet. Note however that an activation of the Erk/MSK1 pathway has been observed in neurons upon concomitant activation of GR and the N-methyl-D-aspartate receptor (NMDA-R) in stress processes^{57,58} (Fig. 2).

RAR α Is Phosphorylated by MSK1 While the Other NRs Are Targets for the Upstream MAPK

MSK1 was originally shown to phosphorylate several transcription factors including CREB, ATF1 and Nuclear Factor- κ B p65 (NF- κ B).^{48,49} Similarly, MSK1 phosphorylates rapidly RAR α at a serine residue (S369) located in loop L9–10 within the LBD⁵⁷ (Fig. 1). This serine is an exposed residue located in a flexible loop and belongs to an Arginine-Lysine-rich motif that corresponds to a consensus phosphorylation motif for several kinases including MSK1. The interesting point is that phosphorylation of this serine initiates a coordinated phosphorylation cascade (Fig. 3, right). Indeed, our laboratory recently demonstrated that phosphorylation of S369 by MSK1 increases the dynamics/flexibility of the nearby loop L8–9,⁵⁹ which corresponds to the docking site of cyclin H⁶⁰ (Fig. 1) that forms with cdk7 and MAT1, the CAK subcomplex of the general transcription factor TFIIF. Consequently, the binding efficiency of cyclin H is increased, allowing the right positioning of the cdk7 kinase and the phosphorylation of serine 77 located in the NTD by this kinase.²¹ To our knowledge, it was the first example of cooperation between the N- and C-terminal domains of RARs through a kinase complex. The serine in L9–10 and the docking site of cyclin H are conserved between RARs but not in other NRs indicating that this kinase cascade would be RAR specific.⁵⁹

Note that in contrast to RAR, PR within the trimeric PR/Erk/MSK1 complex is phosphorylated by Erk and not by MSK1.⁶ However, concerning VDR, there are no data showing whether it is phosphorylated by MSK1 or by the upstream p38MAPK. Finally, concerning the other NRs such as ER, AR and GR, which were not found to activate MSK1 in response to the hormone, they are phosphorylated by MAPKs.^{11,12,61}

MSK1 Participates in the Activation of NR-Target Genes and Is Recruited at the Promoters of NR-Target Genes

Steroid and non-steroid hormones are well known to activate the expression of several target genes.^{1,3,4,62,63} Traditionally, this genomic action has been considered as independent of the non-genomic effects. However, it now emerges that the two pathways converge in the modification

of structural components of the chromatin. Indeed MSKs are well known to facilitate gene relaxation^{47,49} and a number of studies indicated that inhibition of MSK1 abolished the induction of progesterin-, RA- or Vitamin D-target genes.^{5,6,43}

One of the well characterized example of transcriptional control by progestins is the promoter of the mouse mammary tumor virus (MMTV), which is organized into positioned nucleosomes with one nucleosome (nucleosome B) covering the hormone response element (HRE) and which is induced upon hormone treatment.^{50,64,65} Though progesterin activation of the MMTV promoter is sensitive to Erk and MSK1 inhibition, this behavior does not represent an exception, as about 25% of the hormonally-regulated genes are also sensitive to Erk inhibition in microarrays analysis.⁶⁵ Series of chromatin immunoprecipitation experiments indicated that phosphorylated PR complexed with Erk and MSK1 is rapidly recruited to the MMTV promoter nucleosome containing the HRE⁶ (Fig. 3, left).

A similar strategy has been followed for RA-target genes and it has been demonstrated that phosphorylated RAR α and MSK1 are also rapidly recruited to RA response elements⁵ (Fig. 3, right). However, MSK1 was not associated with RAR α , in contrast to what was reported for PR. In fact, TFIIH, the second kinase complex of the MSK-1 initiated kinase cascade, was found associated with RAR α at the promoters.⁵ Unfortunately, there is no data indicating whether MSK1 is also recruited to the promoters of VDR-target genes.

MSK 1 Regulates the Chromatin Environment of NR-Target Promoters

Once recruited to target promoters, liganded NRs are known to induce an ordered and cyclical recruitment of coactivator complexes with enzymatic activities, which modify histones and remodel chromatin in an ATP-dependent manner.^{66,67} Given that MSK1 is also recruited to NRs-target promoters, the question was whether the kinase also contributes to histone phosphorylation and chromatin remodeling at these promoters, as previously described for genes implicated in cell transformation.^{49,68}

It has been found that, concomitantly to the recruitment of the ternary PR/Erk/MSK1 complex to nucleosome B of the MMTV promoter, histone H3 becomes phosphorylated at serine 10 by MSK1 (Fig. 3, left), an event coupled to acetylation of lysine 14 by pCAF and displacement of the repressive complex containing HP1 γ .^{6,64,69} BAF complexes (SWI/SNF ATP-dependent chromatin remodeling complexes) are also recruited to the promoter (Fig. 3, left) through a direct interaction with the activated PR and H3K14 acetylation participate in anchoring the complex to the promoter.⁶⁹ Unfortunately no precise order of the different events can be proposed up to now.⁶⁹ Nevertheless, BAF uses the energy of ATP hydrolysis to initiate nucleosome remodeling and to remove H2A/H2B dimers from nucleosome B, allowing binding of further PR molecules, coactivators and the transcriptional machinery including RNA polymerase II.⁶⁴

Figure 3, viewed on following page. Left) Progesterins bind a subpopulation of membrane-anchored PR complexes, and activate the Src/Ras/Erk pathway, leading to accumulation of activated Erk in the nucleus. Then a nuclear population of PR becomes phosphorylated by activated pErk, which also phosphorylates MSK1. A "PR-activated complex" composed of pPR, pErk and pMSK1 is recruited to the promoter, followed by histone H3 phosphorylation and acetylation. The BAF complex is also recruited through direct interaction with PR and is anchored to chromatin through the histone marks. Due to a lack of kinetic experiments, a precise order of events cannot be proposed. Right) Upon RA binding, a subpopulation of membrane RAR activates the p38MAPK/MSK1 pathway. Activated MSK1 phosphorylates RAR α at S369 located in the LBD, subsequently facilitating the docking of cyclin H, which forms with cdk7 and MAT1 the CAK subcomplex of the general transcription factor TFIIH. Within the RAR α -TFIIH complex, cdk7 phosphorylates RAR α at S77 located in the N-terminal domain. Finally, the phosphorylated RAR α /TFIIH complex is recruited to response elements located in the promoter of target genes. MSK1 is also recruited, but separately of the RAR α -TFIIH complex, and phosphorylates histones H3.

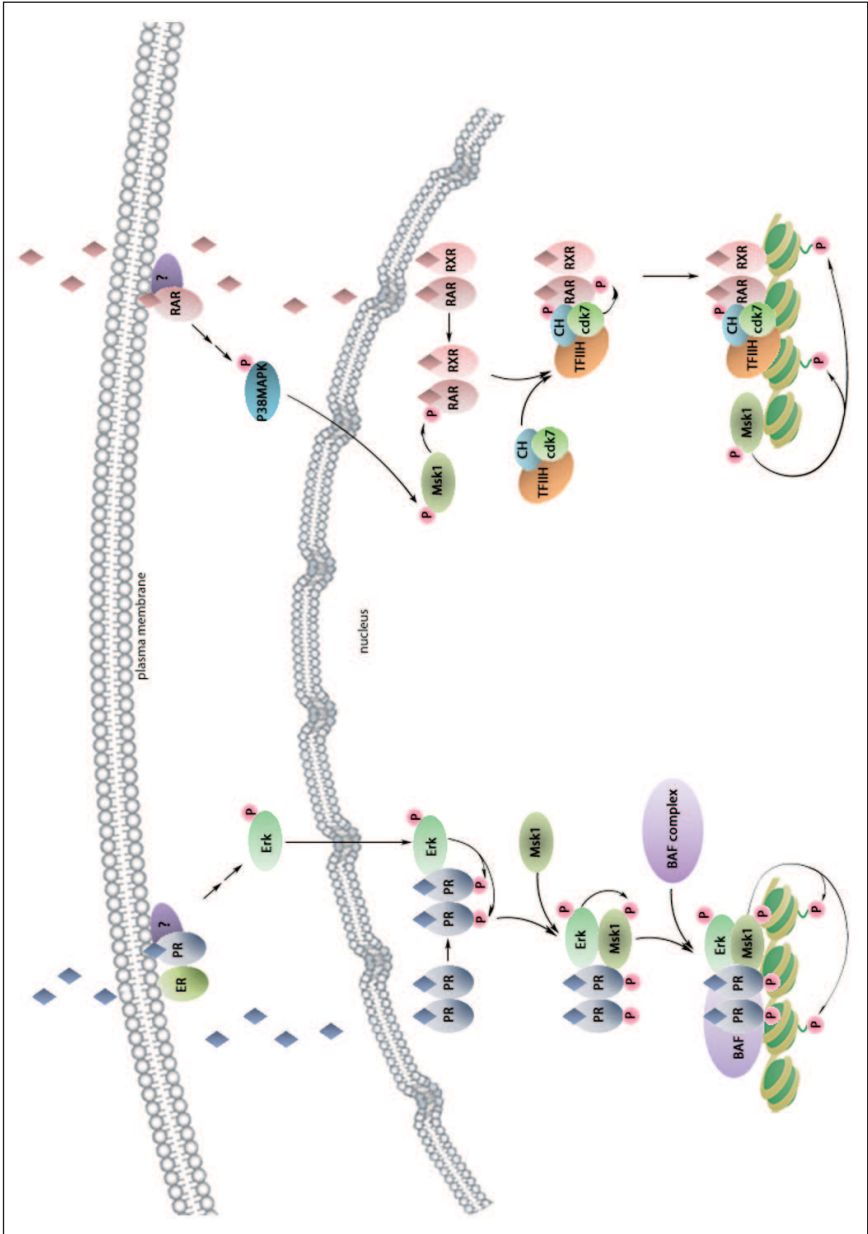


Figure 3. Please see legend on previous page.

Most interestingly, there are similarities between PR and RAR α . Indeed the recruitment of RAR α to target promoters was also concomitant with histone phosphorylation and acetylation and the subsequent recruitment of the transcriptional machinery⁵ (Fig. 3, right). However, whether MSK1 also controls the recruitment/dissociation of other complexes will require further investigations. Of note is that histone H3 phosphorylation-acetylation was also observed in response to concomitant activation of GR and NMDA-R.⁵⁷

MSK1: a Novel Regulator of NR-Target Genes?

MSK1 is well known to be activated by many physiological and pathological stimuli and to regulate gene transcription at multiple levels.⁴⁹ Indeed, MSK1 targets directly several transcription factors such as CREB, ATF-1 and NF- κ B and induces histone phosphorylation, chromatin relaxation and facilitated recruitment of other coregulators at the cognate target promoters.⁷⁰

The present review points out that MSK1 is also activated by several steroid and non-steroid hormones and regulates the expression of the cognate NR-target genes by regulating the transcriptional activity of NRs and by interfering with chromatin environment. Indeed MSK1-mediated phosphorylation of H3 contributes to several NR-target genes induction, very probably as a chromatin mark accounting in cooperation with other histones modifications for the dissociation of repressive complexes and/or the recruitment of chromatin-remodeling complexes.^{5,6,69} Thus one can propose that MSK1-mediated phosphorylation events might act as a “transcriptional clock” fine-tuning the dynamics of chromatin so that at the end the correct proteins are present with the right activity, at the right place and at the right time.

Then the question is whether all NR-target genes promoters are modified and remodeled through H3 phosphorylation by MSK1. Another question is whether MSK1 is also involved in the phosphorylation of NRs coregulators, given that most coactivators and corepressors are known to be also targets for phosphorylation processes.⁷

Future Applications

NRs and Cancer: a Versatile Role of MSK1

Steroid hormone receptors are well established in the etiology of many cancers including classical hormone-dependent cancers like breast and prostate cancer. MSKs are also well known to play a role in cell proliferation and malignant transformation through transcription regulation of the immediate early genes *c-fos* and *junB*,^{68,70} ER81⁷¹ and the Nur77, Nurr1 and Nor1 orphan nuclear receptors,⁷² coupled with histone H3 phosphorylation at specific loci and AP-1 activation.

In line with this, the non-genomic progestin signaling to MSK1 has been correlated with tumor proliferation.⁶ In addition, given that MAPK signaling is hyperactivated in several cancers such as breast and prostate cancer,^{47,73} one can speculate that signaling to MSK is also increased, potentiating the proliferative effects of ER, PR and AR. Knowing this, MSK-specific drugs would have therapeutic effect in such cancers where MSK deregulation is clearly involved. Note however, that in other cancer types such as colon cancer, the p38MAPK/MSK1 pathway rather cooperates with vitamin D and VDR for the expression of genes involved in tumor suppression.³⁹ Thus, depending on the type of cancer and on the NR, the MAPK/MSK1 pathway can have opposite effects on cell growth, restricting the use of MSK specific drugs in cancer therapy.

NRs and MSK1 Inhibition

Evidence has accumulated over the past few years that the action of NRs is not restricted to the regulation of cognate target gene expression, but also concerns several other gene programs by interfering with other transcription factors. A well-known example is the anti-inflammatory action of GR and glucocorticoids of which the action mechanism is mainly based on interference with the activity of the transcription factor NF- κ B. Indeed, in response to inflammatory cytokines, the classical NF- κ B activation pathway determines the expression of various pro-inflammatory genes. The transactivation of NF- κ B is fine-tuned by MSK1, which phosphorylates NF- κ B p65 and histone H3 S10 at inflammatory genes promoters.^{49,74} All these events participate in

the establishment of a transcription-prone chromatin environment. Recent research by Beck et al.⁷⁵ demonstrated a completely new aspect of the anti-inflammatory action of glucocorticoids. Indeed, they found that glucocorticoids counteract MSK1 recruitment at inflammatory gene promoters, through the formation of a complex between activated MSK1 and GR, followed by a subcellular relocalization of activated MSK1 to the cytoplasm. The subsequent absence of MSK1 at inflammatory gene promoters leads to impaired phosphorylation of histone and transcription factor components, resulting in a lack of activation of MSK1-dependent NF- κ B-driven promoters.

Another well known example is the inhibition of AP-1 by certain NRs such as GR, ER and RARs.¹⁷ AP-1 complexes (heterodimers of the proto-oncogene products c-Fos and c-Jun) regulate the expression of several genes involved in oncogenesis and cell transformation. Most interestingly, a network of phosphorylation processes involving MSK1 controls the activity of AP-1 complexes.⁶⁸ Though the molecular basis of the anti-AP-1 activity of GR and RARs has remained elusive,¹⁷ one cannot exclude a nucleocytoplasmic shuttling of MSK1 as above. Nevertheless, nucleocytoplasmic shuttling of MSK appears to be another new action mechanism for certain NRs, opening perspectives for novel therapeutic strategies.⁷⁶

Conclusion

It is clear that MSK-mediated chromatin remodeling plays a role in many physiological and pathological processes and the list of the agents that can activate the MAPK/MSK signaling pathway is still growing. In this context, hormones and their cognate NRs can activate this pathway, which then contributes to the activation of target genes. However, depending on the NR, MSK1 activation has been related to cell growth⁶ or differentiation.³⁹ Moreover, under certain conditions, NRs do not activate but inhibit MSK1 and thereby the activity of several genes regulated by this kinase. Therefore it does not appear to be a general rule for the cross talk between NRs and MSKs and MSK-specific drugs should have therapeutic benefits only in specific NR-related cancers or diseases.

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References

1. Germain P, Altucci L, Bourguet W, Rochette-Egly C, Gronemeyer H. Nuclear receptor superfamily: principles of signaling. *Pure Appl Chem* 2003; 75:1619-64; <http://dx.doi.org/10.1351/pac200375111619>.
2. Germain P, Staels B, Dacquet C, Spedding M, Laudet V. Overview of nomenclature of nuclear receptors. *Pharmacol Rev* 2006; 58:685-704; PMID:17132848; <http://dx.doi.org/10.1124/pr.58.4.2>.
3. Gronemeyer H, Gustafsson JA, Laudet V. Principles for modulation of the nuclear receptor superfamily. *Nat Rev Drug Discov* 2004; 3:950-64; PMID:15520817; <http://dx.doi.org/10.1038/nrd1551>.
4. Laudet V, Gronemeyer H. *Nuclear Receptor Factsbook*. London: Academic Press, 2001.
5. Bruck N, Vitoux D, Ferry C, Duong V, Bauer A, de Thé H, et al. A coordinated phosphorylation cascade initiated by p38MAPK/MSK1 directs RARalpha to target promoters. *EMBO J* 2009; 28:34-47; PMID:19078967; <http://dx.doi.org/10.1038/emboj.2008.256>.
6. Vicent GP, Ballare C, Nacht AS, Clausell J, Subtil-Rodríguez A, Quiles I, et al. Induction of progesterone target genes requires activation of Erk and Msk kinases and phosphorylation of histone H3. *Mol Cell* 2006; 24:367-81; PMID:17081988; <http://dx.doi.org/10.1016/j.molcel.2006.10.011>.
7. Rochette-Egly C, Germain P. Dynamic and combinatorial control of gene expression by nuclear retinoic acid receptors. *Nucl Recept Signal* 2009; 7:e005; PMID:19471584.
8. Rochette-Egly C. Dynamic combinatorial networks in nuclear receptor-mediated transcription. *J Biol Chem* 2005; 280:32565-8; PMID:16076839; <http://dx.doi.org/10.1074/jbc.R500008200>.
9. Lefebvre P, Martin PJ, Flajollet S, Dedieu S, Billaut X, Lefebvre B. Transcriptional activities of retinoic acid receptors. *Vitam Horm* 2005; 70:199-264; PMID:15727806; [http://dx.doi.org/10.1016/S0083-6729\(05\)70007-8](http://dx.doi.org/10.1016/S0083-6729(05)70007-8).

10. Rochette-Egly C. Nuclear receptors: integration of multiple signalling pathways through phosphorylation. *Cell Signal* 2003; 15:355-66; PMID:12618210; [http://dx.doi.org/10.1016/S0898-6568\(02\)00115-8](http://dx.doi.org/10.1016/S0898-6568(02)00115-8).
11. Chen W, Dang T, Blind RD, Wang Z, Cavasotto CN, Hittelman AB, et al. Glucocorticoid receptor phosphorylation differentially affects target gene expression. *Mol Endocrinol* 2008; 22:1754-66; PMID:18483179; <http://dx.doi.org/10.1210/me.2007-0219>.
12. Lannigan DA. Estrogen receptor phosphorylation. *Steroids* 2003; 68:1-9; PMID:12475718; [http://dx.doi.org/10.1016/S0039-128X\(02\)00110-1](http://dx.doi.org/10.1016/S0039-128X(02)00110-1).
13. Wang Z, Chen W, Kono E, Dang T, Garabedian MJ. Modulation of glucocorticoid receptor phosphorylation and transcriptional activity by a C-terminal-associated protein phosphatase. *Mol Endocrinol* 2007; 21:625-34; PMID:17185395; <http://dx.doi.org/10.1210/me.2005-0338>.
14. Weigel NL, Moore NL. Steroid receptor phosphorylation: a key modulator of multiple receptor functions. *Mol Endocrinol* 2007; 21:2311-9; PMID:17536004; <http://dx.doi.org/10.1210/me.2007-0101>.
15. Weigel NL, Moore NL. Kinases and protein phosphorylation as regulators of steroid hormone action. *Nucl Recept Signal* 2007; 5:e005; PMID:17525795.
16. Weigel NL, Moore NL. Cyclins, cyclin dependent kinases, and regulation of steroid receptor action. *Mol Cell Endocrinol* 2007; 265-266:157-61; PMID:17207919; <http://dx.doi.org/10.1016/j.mce.2006.12.013>.
17. Lavery DN, McEwan IJ. Structure and function of steroid receptor AF1 transactivation domains: induction of active conformations. *Biochem J* 2005; 391:449-64; PMID:16238547; <http://dx.doi.org/10.1042/BJ20050872>.
18. Wärnmark A, Treuter E, Wright AP, Gustafsson JA. Activation functions 1 and 2 of nuclear receptors: molecular strategies for transcriptional activation. *Mol Endocrinol* 2003; 17:1901-9; PMID:12893880; <http://dx.doi.org/10.1210/me.2002-0384>.
19. Dyson HJ, Wright PE. Intrinsically unstructured proteins and their functions. *Nat Rev Mol Cell Biol* 2005; 6:197-208; PMID:15738986; <http://dx.doi.org/10.1038/nrml589>.
20. Lalevéé S, Bour G, Quinternet M, Samarut E, Kessler P, Vitorino M, et al. Vinexin{beta}, an atypical "sensor" of retinoic acid receptor α signaling: union and sequestration, separation, and phosphorylation. *FASEB J* 2010; 24:4523-34; PMID:20634350; <http://dx.doi.org/10.1096/fj.10-160572>.
21. Gaillard E, Bruck N, Brelivet Y, Bour G, Lalevéé S, Bauer A, et al. Phosphorylation by PKA potentiates retinoic acid receptor α activity by means of increasing interaction with and phosphorylation by cyclin H/cdk7. *Proc Natl Acad Sci USA* 2006; 103:9548-53; PMID:16769902; <http://dx.doi.org/10.1073/pnas.0509717103>.
22. Norman AW, Mizwicki MT, Norman DP. Steroid-hormone rapid actions, membrane receptors and a conformational ensemble model. *Nat Rev Drug Discov* 2004; 3:27-41; PMID:14708019; <http://dx.doi.org/10.1038/nrd1283>.
23. Márquez DC, Chen HW, Curran EM, Welshons WV, Pietras RJ. Estrogen receptors in membrane lipid rafts and signal transduction in breast cancer. *Mol Cell Endocrinol* 2006; 246:91-100; PMID:16388889; <http://dx.doi.org/10.1016/j.mce.2005.11.020>.
24. Matthews L, Berry A, Ohanian V, Ohanian J, Garside H, Ray D. Caveolin mediates rapid glucocorticoid effects and couples glucocorticoid action to the antiproliferative program. *Mol Endocrinol* 2008; 22:1320-30; PMID:18308897; <http://dx.doi.org/10.1210/me.2007-0154>.
25. Luoma JI, Boulware MI, Mermelstein PG. Caveolin proteins and estrogen signaling in the brain. *Mol Cell Endocrinol* 2008; 290:8-13; PMID:18502030; <http://dx.doi.org/10.1016/j.mce.2008.04.005>.
26. de Laurentis A, Donovan L, Arcaro A. Lipid rafts and caveolae in signaling by growth factor receptors. *Open Biochem J* 2007; 1:12-32; PMID:18949068.
27. Pedram A, Razandi M, Sainson RC, Kim JK, Hughes CC, Levin ER. A conserved mechanism for steroid receptor translocation to the plasma membrane. *J Biol Chem* 2007; 282:22278-88; PMID:17535799; <http://dx.doi.org/10.1074/jbc.M611877200>.
28. Kim KH, Bender JR. Membrane-initiated actions of estrogen on the endothelium. *Mol Cell Endocrinol* 2009; 308:3-8; PMID:19549586; <http://dx.doi.org/10.1016/j.mce.2009.03.025>.
29. Vasudevan N, Pfaff DW. Non-genomic actions of estrogens and their interaction with genomic actions in the brain. *Front Neuroendocrinol* 2008; 29:238-57; PMID:18083219; <http://dx.doi.org/10.1016/j.yfrne.2007.08.003>.
30. Castoria G, Lombardi M, Barone MV, Bilancio A, Di Domenico M, Bottero D, et al. Androgen-stimulated DNA synthesis and cytoskeletal changes in fibroblasts by a nontranscriptional receptor action. *J Cell Biol* 2003; 161:547-56; PMID:12743104; <http://dx.doi.org/10.1083/jcb.200211099>.
31. Migliaccio A, Castoria G, Di Domenico M, de Falco A, Bilancio A, Lombardi M, et al. Steroid-induced androgen receptor-oestradiol receptor beta-*Src* complex triggers prostate cancer cell proliferation. *EMBO J* 2000; 19:5406-17; PMID:11032808; <http://dx.doi.org/10.1093/emboj/19.20.5406>.
32. Migliaccio A, Piccolo D, Castoria G, Di Domenico M, Bilancio A, Lombardi M, et al. Activation of the *Src/p21ras/Erk* pathway by progesterone receptor via cross-talk with estrogen receptor. *EMBO J* 1998; 17:2008-18; PMID:9524123; <http://dx.doi.org/10.1093/emboj/17.7.2008>.

33. Hagan CR, Faivre EJ, Lange CA. Scaffolding actions of membrane-associated progesterone receptors. *Steroids* 2009; 74:568-72; PMID:19135465; <http://dx.doi.org/10.1016/j.steroids.2008.12.004>.
34. Miller AL, Webb MS, Copik AJ, Wang Y, Johnson BH, Kumar R, et al. p38 Mitogen-activated protein kinase (MAPK) is a key mediator in glucocorticoid-induced apoptosis of lymphoid cells: correlation between p38 MAPK activation and site-specific phosphorylation of the human glucocorticoid receptor at serine 211. *Mol Endocrinol* 2005; 19:1569-83; PMID:15817653; <http://dx.doi.org/10.1210/me.2004-0528>.
35. Huhtakangas JA, Olivera CJ, Bishop JE, Zanello LP, Norman AW. The vitamin D receptor is present in caveolae-enriched plasma membranes and binds 1 alpha,25(OH)2-vitamin D3 in vivo and in vitro. *Mol Endocrinol* 2004; 18:2660-71; PMID:15272054; <http://dx.doi.org/10.1210/me.2004-0116>.
36. Masiá S, Alvarez S, de Lera AR, Baretino D. Rapid, nongenomic actions of retinoic acid on phosphatidylinositol-3-kinase signaling pathway mediated by the retinoic acid receptor. *Mol Endocrinol* 2007; 21:2391-402; PMID:17595318; <http://dx.doi.org/10.1210/me.2007-0062>.
37. Dey N, De PK, Wang M, Zhang H, Dobrota EA, Robertson KA, et al. CSK controls retinoic acid receptor (RAR) signaling: a RAR-c-SRC signaling axis is required for neurogenic differentiation. *Mol Cell Biol* 2007; 27:4179-97; PMID:17325034; <http://dx.doi.org/10.1128/MCB.01352-06>.
38. Piskunov A, Rochette-Egly C. A retinoic acid receptor RAR α pool present in membrane lipid rafts forms complexes with G protein α Q to activate p38MAPK. *Oncogene* 2011; [Epub ahead of print] PMID:22056876; <http://dx.doi.org/10.1038/onc.2011.499>.
39. Ordoñez-Morán P, Alvarez-Diaz S, Valle N, Larriba MJ, Bonilla F, Muñoz A. The effects of 1,25-dihydrovitaminD3 on colon cancer cells depend on RhoA-ROCK-p38MAPK-MSK signaling. *J Steroid Biochem Mol Biol* 2010; 121:355-61; PMID:20223287; <http://dx.doi.org/10.1016/j.jsbmb.2010.02.031>.
40. Alsayed Y, Uddin S, Mahmud N, Lekmine F, Kalvakolanu DV, Minucci S, et al. Activation of Rac1 and the p38 mitogen-activated protein kinase pathway in response to all-trans-retinoic acid. *J Biol Chem* 2001; 276:4012-9; PMID:11060298; <http://dx.doi.org/10.1074/jbc.M007431200>.
41. Gianni M, Bauer A, Garattini E, Chambon P, Rochette-Egly C. Phosphorylation by p38MAPK and recruitment of SUG-1 are required for RA-induced RAR α degradation and transactivation. *EMBO J* 2002; 21:3760-9; PMID:12110588; <http://dx.doi.org/10.1093/emboj/cdf374>.
42. Gianni M, Parrella E, Raska I, Gaillard E, Nigro EA, Gaudon C, et al. P38MAPK-dependent phosphorylation and degradation of SRC-3/AIB1 and RAR α -mediated transcription. *EMBO J* 2006; 25:739-51; PMID:16456540; <http://dx.doi.org/10.1038/sj.emboj.7600981>.
43. Ordóñez-Morán P, Larriba MJ, Palmer HG, Valero RA, Barbáchano A, Duñach M, et al. RhoA-ROCK and p38MAPK-MSK1 mediate vitamin D effects on gene expression, phenotype, and Wnt pathway in colon cancer cells. *J Cell Biol* 2008; 183:697-710; PMID:19015318; <http://dx.doi.org/10.1083/jcb.200803020>.
44. Chen N, Napoli JL. All-trans-retinoic acid stimulates translation and induces spine formation in hippocampal neurons through a membrane-associated RAR α . *FASEB J* 2008; 22:236-45; PMID:17712061; <http://dx.doi.org/10.1096/fj.07-8739com>.
45. Gupta P, Ho P, Huq MD, Ha SG, Park SW, Khan AA, et al. Retinoic acid-stimulated sequential phosphorylation, PML recruitment, and SUMOylation of nuclear receptor TR2 to suppress Oct4 expression. *Proc Natl Acad Sci USA* 2008; 105:11424-9; PMID:18682553; <http://dx.doi.org/10.1073/pnas.0710561105>.
46. Pan J, Kao YL, Joshi S, Jeetendran S, Dipette D, Singh US. Activation of Rac1 by phosphatidylinositol 3-kinase in vivo: role in activation of mitogen-activated protein kinase (MAPK) pathways and retinoic acid-induced neuronal differentiation of SH-SY5Y cells. *J Neurochem* 2005; 93:571-83; PMID:15836616; <http://dx.doi.org/10.1111/j.1471-4159.2005.03106.x>.
47. Dunn KL, Espino PS, Drobic B, He S, Davie JR. The Ras-MAPK signal transduction pathway, cancer and chromatin remodeling. *Biochem Cell Biol* 2005; 83:1-14; PMID:15746962; <http://dx.doi.org/10.1139/o04-121>.
48. Lazou A, Markou T. MSK1. *UCSD Nature Molecule Pages* 2010; In press; <http://dx.doi.org/10.1038/mp.a001562.01>.
49. Vermeulen L, Berghe WV, Beck IM, De Bosscher K, Haegeman G. The versatile role of MSKs in transcriptional regulation. *Trends Biochem Sci* 2009; 34:311-8; PMID:19464896; <http://dx.doi.org/10.1016/j.tibs.2009.02.007>.
50. Vicent GP, Ballare C, Zaurin R, Saragueta P, Beato M. Chromatin remodeling and control of cell proliferation by progestins via cross talk of progesterone receptor with the estrogen receptors and kinase signaling pathways. *Ann N Y Acad Sci* 2006; 1089:59-72; PMID:17261755; <http://dx.doi.org/10.1196/annals.1386.025>.

51. Espino PS, Li L, He S, Yu J, Davie JR. Chromatin modification of the trefoil factor 1 gene in human breast cancer cells by the Ras/mitogen-activated protein kinase pathway. *Cancer Res* 2006; 66:4610-6; PMID:16651411; <http://dx.doi.org/10.1158/0008-5472.CAN-05-4251>.
52. Titolo D, Mayer CM, Dhillon SS, Cai F, Belsham DD. Estrogen facilitates both phosphatidylinositol 3-kinase/Akt and ERK1/2 mitogen-activated protein kinase membrane signaling required for long-term neuropeptide Y transcriptional regulation in clonal, immortalized neurons. *J Neurosci* 2008; 28:6473-82; PMID:18562618; <http://dx.doi.org/10.1523/JNEUROSCI.0514-08.2008>.
53. Eisinger-Mathason TS, Andrade J, Lannigan DA. RSK in tumorigenesis: connections to steroid signaling. *Steroids* 2010; 75:191-202; PMID:20045011; <http://dx.doi.org/10.1016/j.steroids.2009.12.010>.
54. Clark DE, Poteet-Smith CE, Smith JA, Lannigan DA. Rsk2 allosterically activates estrogen receptor alpha by docking to the hormone-binding domain. *EMBO J* 2001; 20:3484-94; PMID:11432835; <http://dx.doi.org/10.1093/emboj/20.13.3484>.
55. Clark DE, Errington TM, Smith JA, Frierson HF Jr., Weber MJ, Lannigan DA. The serine/threonine protein kinase, p90 ribosomal S6 kinase, is an important regulator of prostate cancer cell proliferation. *Cancer Res* 2005; 65:3108-16; PMID:15833840.
56. Nguyen TV, Yao M, Pike CJ. Androgens activate mitogen-activated protein kinase signaling: role in neuroprotection. *J Neurochem* 2005; 94:1639-51; PMID:16011741; <http://dx.doi.org/10.1111/j.1471-4159.2005.03318.x>.
57. Reul JM, Chandramohan Y. Epigenetic mechanisms in stress-related memory formation. *Psychoneuroendocrinology* 2007; 32:S21-5; PMID:17644269; <http://dx.doi.org/10.1016/j.psyneuen.2007.03.016>.
58. Chandramohan Y, Droste SK, Reul JM. Novelty stress induces phospho-acetylation of histone H3 in rat dentate gyrus granule neurons through coincident signalling via the N-methyl-D-aspartate receptor and the glucocorticoid receptor: relevance for c-fos induction. *J Neurochem* 2007; 101:815-28; PMID:17250652; <http://dx.doi.org/10.1111/j.1471-4159.2006.04396.x>.
59. Samarut E, Amal I, Markov GV, Stote R, Dejaegere A, Laudet V, Rochette-Egly C. Evolution of nuclear retinoic acid receptor alpha (RAR α) phosphorylation sites. Serine gain provides fine-tuned regulation. *Mol Biol Evol* 2011; 28:2125-37. PMID:21297158.
60. Bour G, Gaillard E, Bruck N, Lalevée S, Plassat JL, Busso D, et al. Cyclin H binding to the RAR{alpha} activation function (AF)-2 domain directs phosphorylation of the AF-1 domain by cyclin-dependent kinase 7. *Proc Natl Acad Sci USA* 2005; 102:16608-13; PMID:16275922; <http://dx.doi.org/10.1073/pnas.0505556102>.
61. Faus H, Haendler B. Post-translational modifications of steroid receptors. *Biomed Pharmacother* 2006; 60:520-8; PMID:16949786; <http://dx.doi.org/10.1016/j.biopha.2006.07.082>.
62. Su D, Gudas LJ. Gene expression profiling elucidates a specific role for RARgamma in the retinoic acid-induced differentiation of F9 teratocarcinoma stem cells. *Biochem Pharmacol* 2008; 75:1129-60; PMID:18164278; <http://dx.doi.org/10.1016/j.bcp.2007.11.006>.
63. Bour G, Taneja R, Rochette-Egly C. Mouse embryocarcinoma F9 cells and retinoic acid. A model to study the molecular mechanisms of endodermal differentiation. In: Taneja R, ed. *Nuclear Receptors in Development*, Vol. 16. San Diego: Elsevier Press, 2006: 211-253.
64. Vicent GP, Nacht AS, Zaurin R, Ballare C, Clausell J, Beato M. Minireview: role of kinases and chromatin remodeling in progesterone signaling to chromatin. *Mol Endocrinol* 2010; 24:2088-98; PMID:20484412; <http://dx.doi.org/10.1210/me.2010-0027>.
65. Vicent GP, Zaurin R, Ballare C, Nacht AS, Beato M. Erk signaling and chromatin remodeling in MMTV promoter activation by progestins. *Nucl Recept Signal* 2009; 7:e008; PMID:20087429.
66. Perissi V, Rosenfeld MG. Controlling nuclear receptors: the circular logic of cofactor cycles. *Nat Rev Mol Cell Biol* 2005; 6:542-54; PMID:15957004; <http://dx.doi.org/10.1038/nrm1680>.
67. Rosenfeld MG, Lunyak VV, Glass CK. Sensors and signals: a coactivator/corepressor/epigenetic code for integrating signal-dependent programs of transcriptional response. *Genes Dev* 2006; 20:1405-28; PMID:16751179; <http://dx.doi.org/10.1101/gad.1424806>.
68. Kim HG, Lee KW, Cho YY, Kang NJ, Oh SM, Bode AM, et al. Mitogen- and stress-activated kinase 1-mediated histone H3 phosphorylation is crucial for cell transformation. *Cancer Res* 2008; 68:2538-47; PMID:18381464; <http://dx.doi.org/10.1158/0008-5472.CAN-07-6597>.
69. Vicent GP, Zaurin R, Nacht AS, Li A, Font-Mateu J, Le Dily F, et al. Two chromatin remodeling activities cooperate during activation of hormone responsive promoters. *PLoS Genet* 2009; 5:e1000567; PMID:19609353; <http://dx.doi.org/10.1371/journal.pgen.1000567>.
70. Drobic B, Perez-Cadahia B, Yu J, Kung SK, Davie JR. Promoter chromatin remodeling of immediate-early genes is mediated through H3 phosphorylation at either serine 28 or 10 by the MSK1 multi-protein complex. *Nucleic Acids Res* 2010; 38:3196-208; PMID:20129940; <http://dx.doi.org/10.1093/nar/gkq030>.

71. Janknecht R. Regulation of the ER81 transcription factor and its coactivators by mitogen- and stress-activated protein kinase 1 (MSK1). *Oncogene* 2003; 22:746-55; PMID:12569367; <http://dx.doi.org/10.1038/sj.onc.1206185>.
72. Darragh J, Soloaga A, Beardmore VA, Wingate AD, Wiggin GR, Peggie M, et al. MSKs are required for the transcription of the nuclear orphan receptors Nur77, Nurr1 and Nor1 downstream of MAPK signalling. *Biochem J* 2005; 390:749-59; PMID:15910281; <http://dx.doi.org/10.1042/BJ20050196>.
73. Yamnik RL, Holz MK. mTOR/S6K1 and MAPK/RSK signaling pathways coordinately regulate estrogen receptor alpha serine 167 phosphorylation. *FEBS Lett* 2010; 584:124-8; PMID:19925796; <http://dx.doi.org/10.1016/j.febslet.2009.11.041>.
74. Vermeulen L, De Wilde G, Van Damme P, Vanden Berghe W, Haegeman G. Transcriptional activation of the NF-kappaB p65 subunit by mitogen- and stress-activated protein kinase-1 (MSK1). *EMBO J* 2003; 22:1313-24; PMID:12628924; <http://dx.doi.org/10.1093/emboj/cdg139>.
75. Beck IM, Vanden Berghe W, Vermeulen L, Bougarne N, Vander Cruyssen B, Haegeman G, et al. Altered subcellular distribution of MSK1 induced by glucocorticoids contributes to NF-kappaB inhibition. *EMBO J* 2008; 27:1682-93; PMID:18511904; <http://dx.doi.org/10.1038/emboj.2008.95>.
76. Beck IM, Berghe WV, Gerlo S, Bougarne N, Vermeulen L, De Bosscher K, et al. Glucocorticoids and mitogen- and stress-activated protein kinase 1 inhibitors: possible partners in the combat against inflammation. *Biochem Pharmacol* 2009; 77:1194-205; PMID:19150610; <http://dx.doi.org/10.1016/j.bcp.2008.12.008>.
77. Rastinejad F, Wagner T, Zhao Q, Khorasanizadeh S. Structure of the RXR-RAR DNA-binding complex on the retinoic acid response element DR1. *EMBO J* 2000; 19:1045-54; PMID:10698945; <http://dx.doi.org/10.1093/emboj/19.5.1045>.
78. Bourguet W, Ruff M, Chambon P, Gronemeyer H, Moras D. Crystal structure of the ligand-binding domain of the human nuclear receptor RXR-alpha. *Nature* 1995; 375:377-82; PMID:7760929; <http://dx.doi.org/10.1038/375377a0>.

RESUME

Les récepteurs nucléaires de l'acide rétinoïque (AR) appelés RAR, se comportent comme des facteurs de transcription inductibles par le ligand. La transcription des gènes cibles induite par l'AR, nécessite la fixation des RAR au niveau de séquences spécifiques des promoteurs et met en jeu des changements conformationnels des récepteurs qui contrôlent l'association/dissociation de toute une panoplie de corégulateurs. Cependant, en plus de ce modèle génomique et nucléaire bien établi, l'équipe du Dr Cécile Rochette-Egly a montré récemment que l'AR a aussi des effets non-génomiques et induit rapidement la voie de signalisation p38MAPK/MSK1 qui ensuite cible les RAR pour des cascades de phosphorylations et module la transcription des gènes cibles.

Pendant mon travail de thèse, j'ai mis en exergue trois nouveaux concepts originaux du mécanisme d'action du sous-type RAR α .

J'ai montré qu'une sous-population de RAR α est présente dans des microdomaines membranaires, les radeaux lipiques ou "lipid rafts" où elle interagit avec les protéines G α q. Cette interaction est le signal des effets non génomiques de l'AR, l'activation de la voie de la p38MAPK. Ces effets ont été corrélés à l'activité des gènes cibles de l'AR, prouvant ainsi leur nécessité.

J'ai identifié un nouveau partenaire de RAR α , la profiline IIA. J'ai analysé le mécanisme moléculaire de l'interaction et démontré qu'elle a lieu dans le noyau. La profiline IIA s'est révélée être un régulateur des effets génomiques de RAR α et est recrutée avec RAR α au niveau des promoteurs des gènes cibles.

Finalement j'ai mis en évidence une nouvelle fonction de RAR α dans le contrôle de l'adhésion et de l'étalement des cellules. D'où l'hypothèse de nouveaux effets génomiques de RAR α avec la profiline IIA dans le contrôle de l'expression des protéines d'adhésion. Cependant, de manière inattendue, j'ai identifié une nouvelle population de RAR α dans le cytoplasme de ces cellules. D'où l'hypothèse de nouveaux effets non génomiques dans le cytoplasme, via l'interaction de RAR α avec des protéines d'adhésion.

SUMMARY

Nuclear retinoic acid (RA) receptors (RARs) are ligand-dependent regulators of transcription. Their transcriptional activity relies mainly on their recruitment to specific DNA response elements and on their interactions with several coregulators at the ligand-binding domain. In addition to these classical genomic effects, the team of C. Rochette-Egly demonstrated that RA also induces the rapid activation of the p38MAPK/MSK1 pathway with characteristic downstream consequences on the phosphorylation of RARs and the expression of their target genes.

Here I highlighted three novel paradigms in the field of the RAR α subtype.

I found that a fraction of the cellular RAR α pool is present in membrane lipid rafts, where it interacts with G protein alpha Q in response to RA. This interaction is the signal for nongenomic effects, i.e. the activation of p38MAPK and of the downstream kinase MSK1. These effects have been correlated to the activation of RA-target genes, highlighting its physiological relevance.

I identified a new binding partner of RAR α , profilin IIA. I deciphered the mechanism of the interaction and found that it occurs in nuclei. Remarkably, profilin IIA modulates positively the genomic effects of RAR α and is recruited with RAR α to target genes promoters.

Finally, in an attempt to decipher the relevance of the RAR α interaction with profilin IIA, I found that RAR α controls cell adhesion and spreading. This might suggest a novel genomic function of RAR α and profiling in the control of the expression of genes involved in adhesion. However, preliminary experiments indicate that a pool of RAR α is present in the cytosol, suggesting also novel nongenomic effects. Whether RAR α controls adhesion via its interaction in the cytosol proteins involved in adhesion will require further investigations.