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Optimisation des paramètres d'acquisition et de reconstruction pour une réduction de dose en tomодensitométrie dans le bilan diagnostique de douleurs thoraciques aux urgences

Francesco Macri

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THÈSE

Pour obtenir le grade de Docteur

Délivré par **Université de Montpellier en cotutelle
avec l'Université Sapienza de Rome**

Préparée au sein de l'école doctorale
Information Structures Systèmes (I2S)
Et de l'unité de recherche **EA 2415**

Spécialité : **Biostatistique**

Présentée par **Francesco Macri**

**Optimisation des paramètres d'acquisition et de
reconstruction pour une réduction de dose en
tomodensitométrie dans le bilan diagnostique de
douleurs thoraciques aux urgences**

Soutenue le 22 novembre 2016 devant le jury composé de

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Mr Guillaume GORINCOUR, Professeur Hôpital La Timone, Université de Aix-Marseille	Rapporteur
Mr Gregorino Paone, Professeur Hôpital Umberto I, Université Sapienza Rome	Examineur
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PRESENTATION ET DOCUMENTS REGISSANT LA PRESENTE COTUTELLE DE DOCTORAT

LA COTUTELLE INTERNATIONALE DE THESE

L'internationalisation, désormais incontournable des formations de l'enseignement supérieur, contribue ainsi au développement par les Écoles doctorales françaises et les structures équivalentes à l'étranger des cotutelles internationales de thèse. Elles permettent une coopération scientifique bilatérale où l'expertise de deux directeurs de recherche permet la réalisation d'un travail original par le futur docteur.

La cotutelle internationale constitue une forme spécifique de codirection. Elle s'inscrit dans les limites d'une convention qui encadre l'ensemble des modalités du Doctorat, de l'inscription à la soutenance et à la délivrance d'un ou de plusieurs diplômes.

La cotutelle de thèse est un dispositif qui favorise la mobilité des doctorants en développant la coopération scientifique entre des équipes de recherche française et étrangère. L'étudiant en cotutelle effectue son travail sous le contrôle d'un directeur de thèse dans chacun des deux pays concernés. Les deux directeurs de thèse s'engagent à exercer pleinement la fonction de tuteur auprès du doctorant ; leurs compétences sont donc exercées conjointement.

Le doctorant doit effectuer ses recherches dans les deux pays de la cotutelle selon des modalités établies par une convention.

Un accord-cadre ou un accord spécifique entre les établissements peut venir assouplir les conditions du bon déroulement de la thèse.



SAPIENZA
UNIVERSITÀ DI ROMA

AVENANT A LA CONVENTION DE COTUTELLE DE THESE
M Francesco MACRI
entre l'Université de Montpellier
et
l'Université de Rome La Sapienza
signée le 07/06/2013

Préambule

Considérant le décret n° 2014-1038 du 11 septembre 2014 portant création de l'Université de Montpellier au 1er janvier 2015, l'Université de Montpellier se substitue aux universités de Montpellier 1 et 2 regroupées au sein de ce nouvel établissement.

La convention de cotutelle de thèse pour M Francesco Macri entre l'Université de Montpellier et l'Université de La Sapienza est modifiée comme suit :

Titre de la thèse : « Optimisation des paramètres d'acquisition et reconstruction pour une réduction de dose en TDM thoracique dans le bilan diagnostique des douleurs thoraciques aux urgences »

Titre I : Modalités administratives

Article 1 : Durée de la thèse

La durée des travaux de recherche est prolongée d'une année : **année universitaire 2015/2016**.
La thèse est préparée par périodes alternées de 6 mois dans chacun des deux laboratoires.

Article 2 : Inscription :

Le doctorant prend une inscription annuelle dans les deux établissements partenaires pour chaque année de préparation de la thèse. Il règle le montant annuel des droits de scolarité dans un seul des établissements.

Le doctorant paiera ses droits de scolarité pour la 4ème année à l'Université de Montpellier et bénéficiera de l'exonération des droits par l'autre établissement partenaire.

Titre I : Modalités administratives

La thèse donne lieu à une soutenance unique reconnue par les deux universités.

Conformément à l'article 18 de l'arrêté du 7 août 2006, elle n'a lieu qu'après avis favorable des rapporteurs. Les rapporteurs sont des personnes extérieures aux universités partenaires et à leurs écoles doctorales. Ils doivent être au nombre de deux au moins, et sont désignés conjointement par les universités.

- Lieu de soutenance de la thèse (université - ville - pays) : Université La Sapienza, Rome, Italie
- Langue dans laquelle la thèse est rédigée: Italien
- Langue dans laquelle la thèse est soutenue : Anglais
- Langue du résumé oral et écrit (lorsque la langue n'est pas le français, la rédaction est complétée par un résumé substantiel en langue française) : Français

Conformément à l'article 7 de l'arrêté du 6 janvier 2005 relatif à la cotutelle internationale de thèse et à l'article 19 de l'arrêté du 7 août 2006 relatif à la formation doctorale, le nombre des membres du jury est compris entre 4 et 8.

Le jury doit représenter, à parité, les Universités partenaires.

Il comprend en outre des membres extérieurs aux Établissements et aux Écoles Doctorales d'inscription du doctorant.

La moitié, au moins, de l'ensemble des membres du jury, doit être composée de Professeurs ou assimilés.

Les présidents des deux universités désignent conjointement le jury ainsi constitué.

Les membres du jury désignent parmi eux un président et, le cas échéant, un rapporteur de soutenance. Le président doit être un professeur ou assimilé ou un enseignant de rang équivalent au sens de l'alinéa précédent. Les directeurs de thèse, s'ils participent au jury, ne peuvent être choisis ni comme rapporteurs de soutenance, ni comme président du jury. Le président du jury établit un rapport de soutenance contresigné par les membres du jury.

Fait en cinq exemplaires originaux, le ...27.06.2016

Le doctorant,

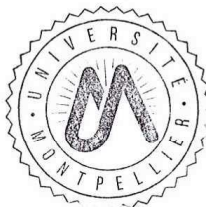
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Le Président de l'Université
La Sapienza de Rome,

Eugenio Gaudio
Eugenio GAUDIO



CLAUSOLA AGGIUNTIVA DELLA CONVENZIONE DI COTUTELA DI TESI

Dr. Francesco Macri

**tra l'Università di Roma Sapienza
e
l'Università di Montpellier
Stipulata il 07/06/2013**

La convenzione di cotutela di tesi per il Dr. Francesco Macri tra l'università Sapienza di Roma e l'università di Montpellier é modificata come segue:

Titolo della tesi: "Ottimizzazione dei parametri di acquisizione e ricostruzione per una riduzione della dose in TAC torace nella valutazione diagnostica del dolore toracico in urgenza"

Parte 1: Modalità amministrative

Articolo 1: durata della tesi

La durata dei lavori di ricerca é prolungata di un anno: anno universitario 2015/2016.

La tesi é preparata in periodi alterni di almeno 6 mesi in ognuno dei laboratori.

Articolo 2: Iscrizione

Il dottorando si iscrive ogni anno nei 2 stabilimenti partner per ogni anno di preparazione della tesi. Il dottorando pagherà il montante annuale dei suoi diritti di scolarità in un solo stabilimento.

Il dottorando pagherà i suoi diritti di scolarità per il IV anno all'università di Montpellier e beneficerà dei diritti di esonero dal pagamento dell'iscrizione nello stabilimento partner.

Parte 2: Modalità Amministrative

La tesi da luogo a una discussione unica e riconosciuta da entrambe le università.

Il giudizio positivo di entrambi i Direttori di Tesi è condizione necessaria per l'ammissione all'esame finale.

La discussione della tesi, unica, avrà luogo presso l'Università di Roma "La Sapienza"

Lingua nella quale la tesi sarà redatta: Italiano

Lingua nella quale la tesi sarà sostenuta: Inglese

Lingua del riassunto del manoscritto orale e scritta: Francese

La Commissione giudicatrice, nominata dai Rettori delle due Università, sarà composta da studiosi espressi dalle due Istituzioni e dovrà comprendere dai quattro agli otto membri.

La metà almeno dell'insieme dei membri della commissione deve essere composta da Professori o assimilati.

I Direttori di tesi possono far parte della commissione e partecipare alla discussione della tesi, ma non alla valutazione. Inoltre I direttori di tesi non possono essere nominati presidente della commissione.

Il presidente della commissione deve essere un professore o assimilato.

Il presidente della commissione redige un rapporto di discussione della tesi controfirmato dai membri della commissione.

Il dottorando



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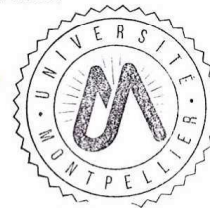
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27/06/2010

LISTE DES ACRONYMES

Nous avons listé la majorité des acronymes en anglais, à l'instar des articles de ce travail de thèse pour en faciliter la lecture.

ALARA : as low as reasonably achievable (aussi bas que raisonnablement atteignable)

ASN: autorité de sûreté nucléaire

BMI : index de masse corporel

CNR: rapport contraste sur bruit

CTDIvol: volume computed tomography dose index (index de scanographie volumique)

DCL : niveau de confiance diagnostique

DLP ou PDL : Dose length product ou Produit dose longueur

DRL : niveaux de référence diagnostiques

DRL: niveaux de référence diagnostiques

E : Dose efficace

EURATOM: Communauté Européenne de l'Energie Atomique

FBP: rétroprojection filtrée

IQI : index de qualité d'image

IR: reconstruction itérative

LD-CT : low-dose-computed-tomography (TDM basse dose)

LSF : line spread function

MTF : fonction de transfert de modulation

NPS : noise power spectrum

PSF : point spread function

S: niveau d'itération

SAFIRE : Sinogram AFfirmed Iterative REconstruction

SNR : rapport contraste sur bruit

TCM : modulation du courant du tube

ULD-CT : ultra-low-dose-computed-tomography (TDM ultra basse dose)

PUBLICATIONS ET PRESENTATIONS SCIENTIFIQUES

Publications dans des revues scientifiques

Macri F, Greffier J, Pereira FR et al (2016) Ultra-low-dose chest CT with iterative reconstruction does not alter anatomical image quality. *Diagn Interv Imaging*. 10.1016/j.diii.2016.06.009

Macri F, Greffier J, Pereira F et al (2016) Value of ultra-low-dose chest CT with iterative reconstruction for selected emergency room patients with acute dyspnea. *Eur J Radiol* 85:1637-1644

Macri F, Khasanova E, Greffier J et al (2016) Facing radiologists' reluctance of a degraded although diagnostic image quality of low/ultra-low-dose CT: our experience. *OMICS Journal of Radiology* vol. 5 Issue 3 doi:10.4172/2167-7964.1000224

Greffier J, Pereira F, **Macri F**, Beregi JP, Larbi A (2016) CT dose reduction using Automatic Exposure Control and iterative reconstruction: A chest paediatric phantoms study. *Phys Med* 32:582-589

Greffier J, **Macri F**, Larbi A et al (2016) Dose reduction with iterative reconstruction in multi-detector CT: What is the impact on deformation of circular structures in phantom study? *Diagn Interv Imaging* 97:187-196

Greffier J, **Macri F**, Larbi A et al (2015) Dose reduction with iterative reconstruction: Optimization of CT protocols in clinical practice. *Diagn Interv Imaging* 96:477-486

Greffier J, Fernandez A, **Macri F**, Freitag C, Metge L, Beregi JP (2013) Which dose for what image? Iterative reconstruction for CT scan. *Diagn Interv Imaging* 94:1117-1121

Présentations scientifiques

Journées Françaises de Radiologie (2016)

Reconstruction itérative en scanographie : le thorax (séance pédagogique)

Radiologic society of North America (2015)

Ultra-low-dose chest CT with iterative reconstructions vs chest X-ray in emergency settings. Is it the beginning of a new era? Preliminary observations

Journées Françaises de Radiologie (2015)

Comparaison d'une tomodensitométrie ultra-low-dose thoracique avec reconstruction itératives versus la radiographie thoracique pour des indications d'urgence

Société Française de Radiologie Languedoc-Roussillon (2015)

Comment et pourquoi réduire la dose d'une TDM Thoracique à une radiographie du thorax?

Journées Françaises de Radiologie (2014)

- Ultra-low dose en Tomodensitométrie thoracique avec reconstructions itératives : Expérimentation pour suspicion de pathologies thoraciques aux urgences
- Réduction de dose avec reconstructions itératives pour protocole «triple rule out » en urgence

American Society of Emergency Radiology (2014)

- Comparison between chest X-ray and very ultra-low-dose chest CT in emergency settings. Preliminary experience.
- Dose reduction with iterative reconstruction for a triple rule out study

INTRODUCTION ET ETAT DE L'ART

Tomodensitométrie comme méthode d'amélioration de la prise en charge, s'accompagnant du désavantage du risque de cancer radio-induit.

Le scanner a complètement révolutionné la prise en charge des patients depuis le début de son utilisation [1]. Depuis ce début de nombreuses améliorations technologiques se sont ajoutées ou substituées, et ont renforcé cet instrument de diagnostic [2].

De plus en plus les différentes branches de la médecine deviennent dépendantes de la tomodensitométrie (TDM) pour le diagnostic et le suivi pathologique [1].

L'imagerie produite par la TDM est générée par les rayons X, malgré tous les avantages obtenus, il y a le désavantage des effets nocifs sur l'ADN avec carcinogenèse radio-induite [3-11]. Des estimations soulignent que dans les 20 prochaines années 3% de cancers humains seront dus aux rayonnements ionisants d'origine médicale [12]. L'EURATOM (Communauté Européenne de l'Energie Atomique) a promulgué une directive pour tous les états membres de la Communauté Européenne, afin de conjurer le risque de cancer radio-induit d'origine médicale [13].

Cette directive vise l'optimisation des doses de rayonnement. Suite à cette directive le gouvernement français a publié un arrêté (JORF 24 octobre 2011) réglementant les niveaux de référence diagnostiques (DRL) pour des examens d'imagerie utilisant les radiations ionisantes [14]. En outre l'Autorité de Sûreté Nucléaire (ASN) oblige à l'observation de deux principes fondamentaux pour les patients, pour toute pratique incluant l'utilisation de rayonnements ionisants :

- **La justification** des activités comportant un risque d'exposition à des rayonnements ionisants ;
- **L'optimisation** des expositions à ces rayonnements au niveau le plus faible possible ;

Le principe d'optimisation découle d'un concept fondamental de précaution résumable comme ALARA [15].

La réduction de la dose de rayonnement détermine une augmentation du bruit de l'image, se traduisant par une altération de la qualité d'image qui apparaît plus granitée ce qui est gênant pour le radiologue [16]. Depuis quelques années des méthodes de reconstruction de l'image dites reconstruction itérative (IR), alternatives à la plus classique rétroprojection filtrée (FBP), ont été mises au point et assurent une qualité d'image diagnostique en scanner, même avec une dose abaissée [17-19]. A ce jour nous pouvons compter sur des protocoles scanner à faible dose ou plus, en général à dose significativement réduite par rapport aux DRL grâce aussi à l'implémentation de la IR [20-22].

La TDM du thorax en urgence

Dans la plupart des services des urgences la TDM est puissamment employée pour tenter de répondre de manière détaillée aux questions cliniques. Le nombre croissant

des examens TDM est lié à l'augmentation pertinente des indications cliniques (modalité répandue, rapide dans sa réalisation), mais aussi pour les demandeurs d'examen à la hantise de répercussions médico-légales de la prise en charge des patients [23]. Il se peut aussi qu'un certain nombre de TDM aux urgences soient redondant (après une étude radiographique par exemple) et peut-être dans certains cas, a posteriori, superflues (lorsqu'une échographie ou IRM auraient pu répondre alternativement à la demande) [12]. Tout cela se traduit par un grand nombre de TDM et d'irradiation des patients adressés aux urgences, avec également augmentation du risque de cancer radio-induits [23].

Les effets cumulatifs du rayonnement ionisant, sont à garder en mémoire, en particulier chez les jeunes patients (qui au cours de leur vie devront bénéficier de plusieurs examens ionisants), en raison du risque élevé du développement de tumeurs solides, selon les régions anatomiques irradiées [12].

C'est pourquoi l'optimisation de la dose est impérative vue la constante et progressive imposition de la TDM notamment dans des situations d'urgence ; en particulier les organes du thorax qui sont parmi les plus radiosensibles dans le corps humain [24; 25].

Plusieurs publications ont démontré l'efficacité diagnostique d'une TDM réalisée avec une dose équivalente à celle d'une radiographie du thorax de face et une de profil et reconstruite avec la IR [26-29]. Ce type de TDM à très faible dose a été testé pour des indications « froides » non-urgentes comme le dépistage des nodules pulmonaires, l'emphysème, les pneumoconioses, les pneumopathies obstructives ou restrictives [26; 27]. Jamais son emploi n'a été analysé pour des indications de douleurs thoraciques en urgence comme examen complémentaire ou remplaçant de la radiographie thoracique.

IRRADIATION EN TOMODENSITOMETRIE

Depuis le 24 mars 2003 en France, l'article R 1333-66 du code de la Santé Publique oblige le médecin réalisateur de l'acte radiologique à bien marquer sur le compte-rendu toutes les informations justifiant l'acte et permettant le calcul de la dose reçue par le patient.

Il est donc fondamental d'avoir une bonne connaissance des indicateurs dosimétriques les plus couramment utilisés.

CTDI volume (CTDIvol)

Cet index représente la dose moyenne délivrée pour le volume exposé de chaque coupe, selon les paramètres d'acquisition. Cette grandeur est mesurée en milliGray (mGy) (1).

Produit dose longueur (PDL ou DLP)

Cet index informe sur la dose délivrée au volume total exposé du patient. Elle est égale au produit du CTDIvol par la longueur du volume irradié, donc le nombre de coupes obtenues. Cette grandeur est exprimée en milliGray.cm (mGy.cm) (2).

Cette mesure est calculée automatiquement par le scanner et elle apparaît dans le rapport de dose de chaque patient en fin d'examen TDM.

$$CTDI_{vol} = \frac{CTDI_w}{pitch} \quad (1) \quad \text{et} \quad PDL = CTDI_{vol} \times \text{Longueur explorée} \quad (2)$$

Le CTDI_{vol} et le PDL sont calculés à partir de mesures sur fantômes et ne tiennent pas compte de la sensibilité des différents tissus et donc du risque biologique. Il s'agit d'une simple estimation de la dose délivrée au patient. De plus le CTDI_{vol} ne tient pas compte de la corpulence du patient et ne correspond pas à une estimation précise de la dose délivrée au patient dans la coupe.

Dose Efficace (E)

La E qui s'exprime en milliSievert (mSv) tient compte du risque biologique. Elle est calculée en multipliant le PDL par un coefficient de conversion, typique de chaque région anatomique irradiée (3).

Pour le thorax chez l'adulte ce coefficient est de 0.014 mSv/mGy.cm pour les deux sexes [30].

La E est la seule évaluation cohérente du niveau d'exposition globale du patient irradié considérant les différentes régions irradiées.

$$E = e_{PDL} \times PDL \quad (3)$$

NIVEAUX DE REFERENCE DIAGNOSTIQUES (DRL)

Les DRL sont des limites d'irradiation propres à chaque pays. En Europe ils sont similaires, rendant plus ou moins uniformes l'optimisation des pratiques. En France ils ont été établis par l'IRSN (Institut de Radioprotection et Sûreté Nucléaire) selon l'exposition constatée en pratique clinique (**Tableau 1**). Les DRL ne devraient pas être dépassés sans justification pour des actes routiniers chez des patients à corpulence normale. En France le DRL pour une TDM thoracique ramène à une E maximale de 6.65 mSv.

Tableau 1. Niveaux de Référence Diagnostiques en scanographie

	Adulte		1 an (10 kg)		5 ans (20 kg)		10 ans (30 kg)	
	CTDIvol	DLP	CTDIvol	DLP	CTDIvol	DLP	CTDIvol	DLP
	(mGy)	(mGy.cm)	(mGy)	(mGy.cm)	(mGy)	(mGy.cm)	(mGy)	(mGy.cm)
Crâne	65	1050	30	420	40	600	50	900
Thorax	15	475	3	30	4	65	5	140
TAP	20	1000	-	-	-	-	-	-
Abdomen	17	800	4	80	5	120	7	245
Rachis Lombaire	45	700	-	-	-	-	-	-

QUALITE D'IMAGE OBJECTIVE ET SUBJECTIVE EN TDM

En scanographie, différents indices de qualité d'image objective sont utilisés dans le domaine spatial et fréquentiel [31; 32].

Domaine spatial

- Signal, Bruit, Contraste

Les indices de qualité image (IQI) essentiels dans l'évaluation de la qualité objective de l'image sont le signal et le bruit. Dans le cas idéal, le signal de l'image serait directement lié au nombre de photons détectés et le bruit correspondrait à la fluctuation de ce nombre. En pratique, le signal correspond à l'atténuation moyenne des pixels mesurés dans une région d'intérêt (ROI) et le bruit à l'écart type de l'atténuation des pixels.

Le contraste absolu est défini comme la différence de signal entre deux structures (Contraste = Signal1- Signal2). Ce dernier ne doit pas être confondu avec le contraste apparent/subjectif qui dépend du bruit de l'image.

À partir des valeurs du bruit et du signal, les rapports signal-sur-bruit (SNR) et contraste-sur bruit (CNR) peuvent être obtenus (5 - 6). Différentes méthodes existent pour calculer le CNR (6.a - 6.b) [31; 33]:

$$\text{CNR} = \frac{\text{Signal}_{\text{ROI}}}{\text{Bruit}_{\text{ROI}}} \quad (5)$$
$$\text{CNR} = \frac{|\text{Signal}_{\text{ROI}} - \text{Signal}_{\text{Ref}}|}{\sqrt{\frac{(\text{Bruit}_{\text{ROI}}^2 + \text{Bruit}_{\text{Ref}}^2)}{2}}} \quad (6.b)$$
$$\text{CNR} = \frac{\text{Signal}_{\text{ROI}} - \text{Signal}_{\text{Ref}}}{\text{Bruit}_{\text{Ref}}} \quad (6.a) \quad \text{ou}$$

où Ref correspond à une structure de référence définie par l'utilisateur.

Domaine fréquentiel

- Résolution spatiale transverse : Résolution à haut contraste

La résolution spatiale peut être définie comme la capacité du système à différencier deux objets distincts. La résolution spatiale transverse, matérialisée par la Fonction de Transfert de Modulation (MTF), peut être obtenue de différentes manières.

La MTF est calculée en mesurant la fonction de réponse impulsionnelle du système à partir de l'image d'un point (Point Spread Function [PSF], d'une ligne (Line Spread Function [LSF]) ou d'un bord (Edge Spread Function) [34-36].

Une méthode simplifiée proposée par Droege et al. [37] estimant la MTF à partir de paires de lignes est également utilisée (7).

$$\text{MTF} = \frac{\pi}{\sqrt{2}} \times \frac{\sqrt{\text{Bruit}_{\text{Groupe}} - \text{Bruit}_{\text{Fond}}}}{|\text{Signal}_{\text{Groupe}} - \text{Signal}_{\text{Fond}}|} \quad (7)$$

La MTF montre la dégradation du contraste en fonction de la fréquence spatiale.

- Pouvoir spectral du bruit : Noise Power Spectrum (NPS 2D)

Comme défini par Verdun et al. [31], le NPS est une estimation du bruit dans le domaine fréquentiel. En supposant que le bruit est stationnaire, le NPS donne une description complète du bruit en fournissant son amplitude sur toute la plage de fréquence de l'image.

Le NPS 2D est calculé sur une image (f_x, f_y) d'un objet homogène à partir de ROI de petite taille (8) :

$$\text{NPS}_{2D}(f_x, f_y) = \frac{\Delta_x \Delta_y}{L_x L_y} \frac{1}{N_{\text{ROI}}} \sum_{i=1}^{N_{\text{ROI}}} |\text{FT}_{2D}\{\text{ROI}_i(x, y) - \overline{\text{ROI}_i}\}|^2 \quad (8)$$

où Δ_x, Δ_y sont les tailles des pixels dans la dimension x et y; L_x, L_y sont les longueurs des ROI (en pixel) pour les deux dimensions; N_{ROI} le nombre de ROI utilisé; $\overline{\text{ROI}_i}$ la valeur moyenne des pixels de la $i^{\text{ème}}$ ROI. Le NPS caractérise la texture du bruit, donnant ainsi une description plus complète que le bruit utilisé dans le domaine spatial [31; 38; 39]

Métriques quantitatives

La mesure des diamètres des différentes structures anatomiques ou le calcul d'un rapport défini entre deux ou plus structures anatomiques (p. e. l'index cardio-thoracique) peuvent être considérés comme des paramètres quantitatifs (**Figure 1**) [28].

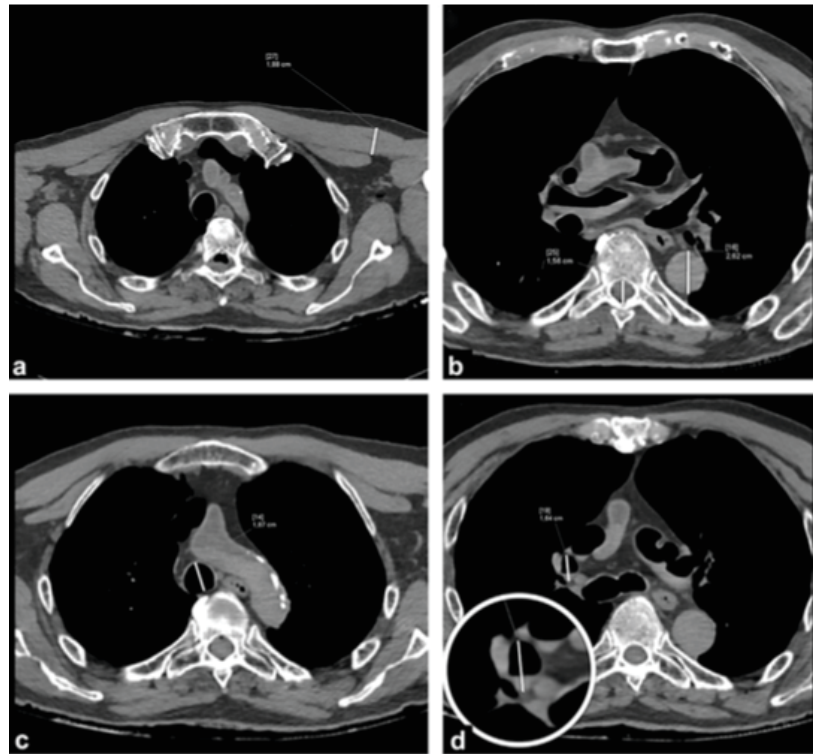


Fig. 1. Exemples de paramètres quantitatifs: diamètre maximal du muscle grand pectoral (a), diamètre maximal de l'aorte descendante et canal vertébral (b), diamètre antéro-postérieur de la trachée (c) et diamètre antéro-postérieur de l'artère pulmonaire supérieure droite (d).

Métriques subjectives

La qualité d'image subjective est généralement évaluée visuellement par des radiologues. Les métriques subjectives fréquemment utilisées sont la qualité d'image anatomique et diagnostique. Il s'agit d'une évaluation globale de la qualité d'image basée sur une échelle de Likert [26]. L'échelle de Likert utilisée pour les travaux de cette thèse était à 5 points (**Figure 2**) :

1. Excellente
2. Bonne
3. Modérée
4. Pauvre
5. Inacceptable ou non vu

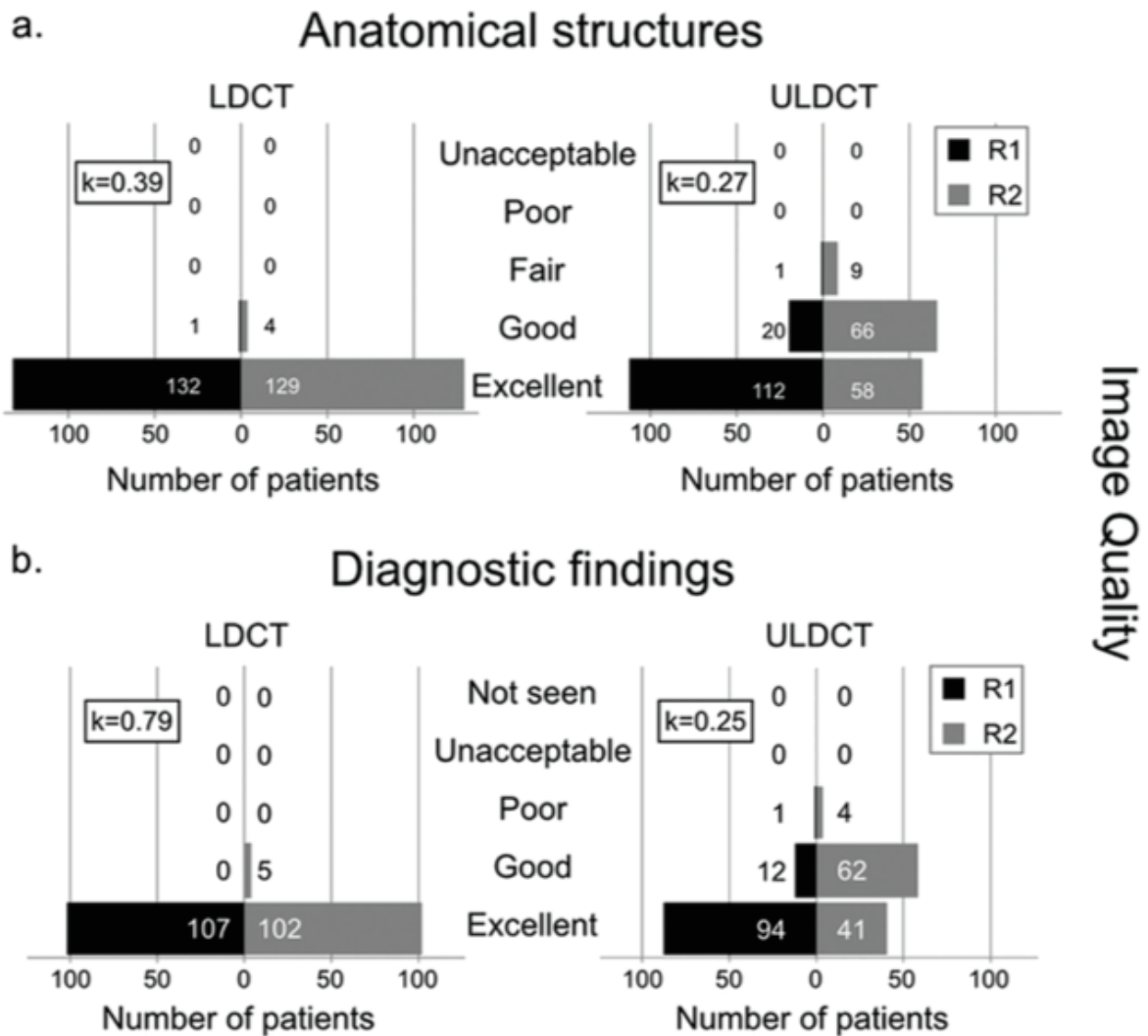


Fig. 2. Exemples d'échelles de Likert à 5 points avec valeurs relatives pour évaluation de la qualité d'image subjective : évaluation de la qualité d'image des structures anatomiques (a) et des lésions (b).

Niveau de confiance diagnostique (DCL)

En outre l'objectif final de toute image radiologique est de pouvoir confirmer ou infirmer un diagnostic et à cette fin les radiologues peuvent aussi exprimer un niveau de confiance diagnostique dans les études. Pour évaluer la confiance diagnostique pour les travaux de cette thèse il a été choisi un jugement très simple : diagnostic « certain » et diagnostic « incertain » [40].

PRINCIPALE EVOLUTION TECHNOLOGIQUES: APPARITION DES METHODES DE RECONSTRUCTION ITERATIVE (IR)

Ces dernières années, de nombreuses évolutions sont apparues sur les TDM pour permettre l'application du principe d'optimisation.

PRINCIPALE EVOLUTIONS

La modulation du courant du tube (TCM) correspond à une évolution technologique majeure. Ce système adapte les mAs tout au long de la rotation en fonction de l'atténuation du patient [41-46]. Les nouveaux systèmes TCM fonctionnent avec une double modulation : longitudinale et angulaire. La première adapte les mAs en fonction de l'atténuation du patient obtenue sur les images topographiques et la deuxième pendant l'émission (avec une $\frac{1}{2}$ rotation de retard). Ce système permet de réduire la dose délivrée jusqu'à 70% tout en maintenant une qualité d'image équivalente tout au long de l'exploration.

Les outils d'ajustement de la tension appliquée au tube permettent d'adapter les kV en fonction du type d'examen (non injecté, injecté, angiographique...) afin d'améliorer le rapport CNR. Cet outil réduit faiblement la dose. Seuls les examens angiographiques où l'on privilégie une basse tension pour favoriser l'effet photoélectrique (matériaux à Z élevés) ont des doses réduites [47].

Les constructeurs ont également fait évoluer les systèmes de détection en proposant des détecteurs plus sensibles (Gemstone GE, Stellar Siemens, PureVision Toshiba) et des systèmes de collimation permettant de diminuer l'overbeaming [48].

Mais l'évolution technologique la plus importante reste l'adaptation à la TDM des méthodes de IR déjà utilisées en médecine nucléaire. Cette avancée majeure a permis d'obtenir des images avec des doses réduites et une qualité d'image diagnostique pour le radiologue [18; 20; 49-55].

METHODE DE RECONSTRUCTION ITERATIVES

Depuis sa création, la méthode de référence en scanographie pour la reconstruction des coupes tomographiques axiales est la rétroprojection filtrée (FBP). Cette méthode rapide utilise différents filtres pour corriger les projections mesurées (**Figure 3**).

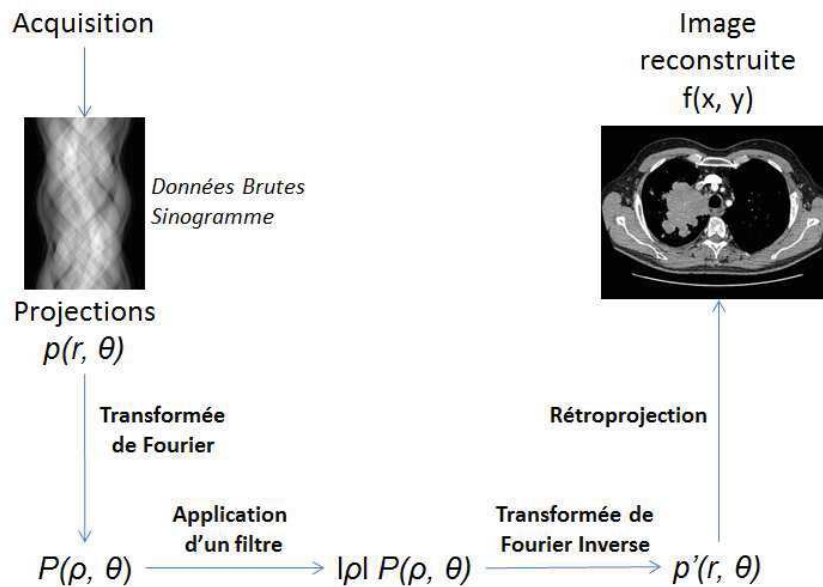


Fig. 3. Principe de la rétroprojection filtrée

Avec cette méthode, de nombreuses approximations sont non vérifiées en pratique, dues à l'absence de prise en compte des fluctuations statistiques et des perturbations physiques. Les données obtenues sont bruitées et sous-échantillonnées. Afin de pallier à certaines de ces limites, les méthodes de IR ont été adaptées aux données brutes des TDM.

Les méthodes IR sont de deux types : algébriques ou statistiques. Trop coûteuses en temps, les méthodes algébriques ne sont pas utilisées en TDM. Les méthodes statistiques utilisent les projections mesurées pour définir l'image « la plus probable » [56]. On distingue deux sous types de méthodes statistiques : « Hybrides » et « Totalement Statistiques » (Fully Statistical). Les méthodes « Hybrides » qui combinent la FBP et IR, consistent :

- soit à reconstruire les données brutes par FBP dans l'espace des sinogrammes puis à améliorer les performances de l'image avec les IR dans l'espace des images,
- soit à réduire le bruit avec les IR dans l'espace des sinogrammes avant de reconstruire l'image par FBP.

Les méthodes IR « Hybrides » sont actuellement utilisées en TDM. L'utilisation préalable de la FBP et l'amélioration des outils informatiques permettent de reconstruire les images avec IR dans un temps adapté à la routine clinique

Les algorithmes itératifs permettent une meilleure estimation quantitative. Ils fonctionnent par approximations successives pour déterminer la solution qui se rapproche au plus près de l'objet réel. À chaque itération, une nouvelle estimation de la coupe est réalisée (**Figure 4**).

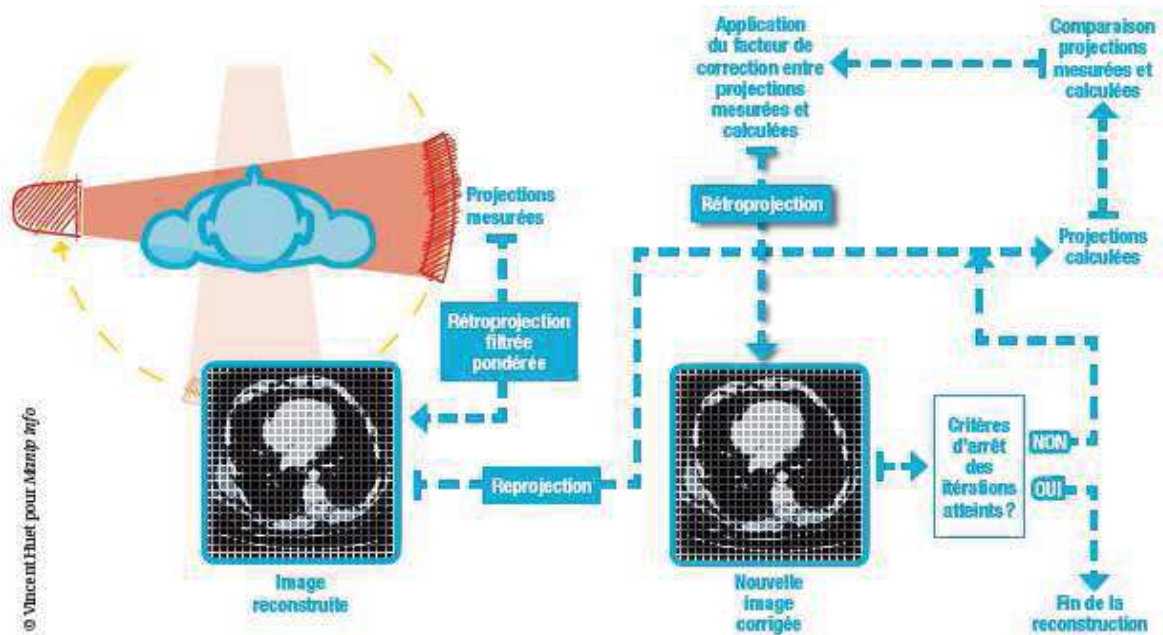


Fig. 4. Exemple du principe de fonctionnement des méthodes IR [57]

Chaque constructeur propose des algorithmes variant par leur utilisation. Ils peuvent se présenter sous la forme de niveaux d'itération (SAFIRE, Siemens; AIDR, Toshiba ; iDose4, Philips) ou de pourcentage de la méthode itérative par rapport à la RPF (ASIR, GE). Actuellement, des méthodes IR « totalement statistiques » (Model Based Iterative Reconstruction (MBIR)) sont également disponibles sur les installations (ADMIRE, Siemens ; ASIR-V, GE ; IMR, Philips).

Reconstruction itérative en routine

L'utilisation des IR présente un fort potentiel dans la réduction de la dose mais présente également des contraintes. De nombreuses publications ont mis en évidence, dans différentes localisations anatomiques, des réductions de dose importantes avec ces méthodes [18; 20; 49-55; 58]. Les utilisateurs, sont maintenant capables de réaliser des acquisitions à très basses doses avec une qualité diagnostique de l'image préservée [17; 59; 60]. Par ailleurs, l'image résultante est considérée par les radiologues comme « modifiée ». On parle de lissage de l'image et de modification de la composition et de la texture de l'image [31; 38]. Enfin, la réalisation d'acquisition avec réductions importantes de la dose peut affecter la détection des structures à faible contraste [56].

L'évaluation de la qualité des images reconstruites avec les IR est différente des images avec FBP. De nombreuses publications ont mis en évidence les propriétés « non-linéaires » et « non-stationnaires » des IR [31; 38; 61-63]. La « non-linéarité » de IR se traduit par une dépendance en contraste de la résolution spatiale [61; 63]. Ott *et al.*[38] et Vaishnav *et al.* [62] ont mis en évidence l'influence des IR sur les métriques dans le domaine de Fourier. Avec les IR, le NPS est influencé par le niveau de dose et la résolution par le contraste

et le niveau de dose. Pour qu'une MTF soit fiable, l'hypothèse de linéarité doit être remplie. Comme définie par Verdun *et al.* [31], une adaptation des métriques objectives dans le domaine de Fourier doit être réalisée pour les IR.

TDM THORACIQUE

TDM Thoracique standard

Les doses moyennes d'une TDM thoracique standard à « pleine dose » dans la littérature sont très variables et comprises entre 230 et 1600 mGy.cm (E= 4-27 mSv). Le DRL d'une TDM thoracique équivaut à 475 mGy.cm soit 6.65 mSv.

TDM thoracique à faible dose (low-dose-computed-tomography_LD-CT)

Les améliorations technologiques récentes permettent d'abaisser de façon significative la dose tout en gardant une qualité d'image satisfaisante d'un point de vue diagnostique. Il n'existe pas un niveau précis de dose pouvant définir l'appellation de TDM basse dose, mais il est consensuellement reconnu que les doses à ne pas dépasser sont celles de l'étude du National Lung Screening Trial Research Team (NLST) ou la E maximale était >1 mSv <1.5 mSv [64]. La TDM thoracique peut donc être réalisée en routine avec des doses réduites de plus de la moitié pour des examens sans injection.

TDM thoracique à très faible dose (ultra-low-dose-CT_ULD-CT)

L'ULD-CT trouve son emploi pour des indications sans nécessité d'injection. Il n'existe pas non plus une dose de référence précise pour la définition de TDM ULD-CT mais la radiographie du thorax de face et profil qui normalement délivre globalement une dose entre 0.1 et 0.3 mSv peut être considérée comme référence à cet effet [65].

INFLUENCE DES PARAMÈTRES SUR LA DOSE ET SUR LA QUALITÉ IMAGE

Compromis dose/qualité image

L'influence croisée des paramètres d'acquisition et de reconstruction sur la dose et les IQI est présentée dans le Tableau 2. Toute modification de la dose entraîne une modification de la qualité image nécessitant une réflexion permanente sur la recherche d'un compromis. La dose n'est influencée que par les paramètres d'acquisition qui modifient le faisceau primaire.

Tableau 2: Influence des paramètres d'acquisition sur la dose et la qualité image

	Dose	Indices de Qualité Image (IQI)	Recommandations
Paramètres d'acquisition	kV ↑	$\propto kV^2$ Contraste diminue pour les matériaux à Z élevés (iode, os ...)	Travailler avec kV aussi faible que possible et adapter en fonction de la morphologie du patient
	mAs ↓	$\sim mAs$ Détectabilité dégradée pour les structures à bas contraste (risque perte informations)	Structures à fort contraste réduction importante possible
		Bruit augmente	Structures à faible contraste réduction limitée
Pitch* ↑	$\sim \frac{1}{pitch}$	Bruit augmente Résolution spatiale est dégradée	Fonction de l'examen

	Epaisseur (e_c) ↓	$\text{si } \frac{e_c}{n} \text{ alors } \text{Dose} \sim \sqrt{n}$	Bruit augmente Résolution spatiale est améliorée	Fonction de l'examen (+ e_c est fine + reconstructions multi-planaires seront de bonne qualité)
Paramètres de reconstruction	Kernel ↑	-	Bruit augmente Résolution spatiale est améliorée	Fonction de la localisation anatomique
	Epaisseur (e_r) ↑	-	Bruit diminue Résolution spatiale est dégradée	Fonction de l'examen
	FOV ↑	-	Bruit diminue Résolution spatiale est dégradée	Fonction de la localisation anatomique

* Selon le TDM utilisé. L'influence de chaque paramètre s'entend pour tout autre paramètre constant

REALISATION D'UN ULD-CT THORACIQUE SANS INJECTION DE PRODUIT DE CONTRASTE AVEC RECONSTRUCTION ITERATIVE

Toute réduction de dose s'accompagne d'une augmentation inversement proportionnelle du bruit et d'une altération de la résolution spatiale, affectant la qualité d'image finale [22]. Pour la ULD-CT le compromis recherché est celui de la dose d'irradiation la plus faible possible, en contrepartie d'une qualité d'image dégradée [16]. Ce compromis est plus accessible en scanographie thoracique, puisqu'en particulier l'air du parenchyme pulmonaire représente un haut contraste naturel car il n'y a pas beaucoup des structures atténuantes adjacentes [66].

Une image interprétable pour ces doses n'a été rendue possible que par l'introduction de la IR en remplacement de la classique rétroprojection filtrée (FBP) [20]. La IR, disponible sur l'ensemble des scanners depuis 2010, permet une diminution drastique du bruit, d'un certain nombre d'artefacts, engendrant soit une amélioration des IQI à dose équivalente, soit une réduction très significative de la dose à IQI conservés ou modérément abaissés [65]. Chez les patients avec index de masse corporel élevé (BMI>25) par contre la performance diagnostique de ce protocole s'affaiblit dans les régions apicales et basales du thorax, où l'on retrouve une atténuation plus importante [28; 40]. Il faut souligner qu'une ULD-CT pour qu'elle ait une utilité diagnostique nécessite une reconstruction avec des hauts niveaux de IR (dans notre cas SAFIRE \geq S3). L'association d'une image dégradée, en raison de l'augmentation du bruit liée à la très faible dose, avec des niveaux d'itérations élevés restitue une image qui pourrait perturber l'interprétation du radiologue non aguerri à ce type d'imagerie [22; 28; 40].

Modification des constantes d'acquisition pour obtenir un ULD-CT

L'ULD-CT non injecté a été optimisé. Il existe deux choix pour réaliser ce type d'examen : soit un protocole avec basse tension/haute intensité (\downarrow kVp/ \uparrow mAs) soit un protocole haute tension-basse intensité (\uparrow kVp/ \downarrow mAs) [65]. De plus, plusieurs niveaux d'itération peuvent être appliqués et les images reconstruites avec différents kernels. Il est donc fondamental de trouver la bonne combinaison entre les paramètres d'acquisition, le type de méthode de reconstruction de l'image et les kernels à associer [65].

OBJECTIFS DE LA THESE

La directive 97/43 de la Communauté Européenne de l'Energie Atomique (EURATOM) et le concept ALARA (*as low as reasonably achievable*) obligent à l'optimisation des doses des radiations ionisantes en médecine tout en gardant une qualité d'image diagnostique afin de réduire le risque de cancer radio-induit [13]. Selon différentes études ce risque a été estimé élevé à cause d'un emploi toujours plus prédominant du scanner en médecine, notamment au niveau du thorax qui est la région anatomique la plus radiosensible [24]. En particulier en urgence, l'exposition aux radiations ionisantes est fréquemment plus élevée qu'en routine [67]. Dans le but d'explorer un patient présentant des douleurs thoraciques l'irradiation est quasiment certaine, car la radiographie et le scanner sont les modalités de choix pour l'étude du thorax et souvent réalisées en première et seconde intentions sur le même patient lors du même passage aux urgences.

Dans le cadre des douleurs thoraciques il faut considérer celles d'origine cardiovasculaire (filière injectée des protocoles TDM) et celles non cardiovasculaires d'origine non traumatique ou traumatique mineurs (**filière non injectée** des protocoles TDM). Cette thèse a visé uniquement l'optimisation de protocoles TDM pour l'exploration de la filière non injectée, ayant comme indications plus fréquentes pour les douleurs thoraciques non traumatiques la pneumopathie infectieuse, l'exacerbation de pneumopathie interstitielle et pleurésie. Pour celles d'origine traumatique l'indication était un traumatisme thoracique mineur fermé.

L'objectif de ce travail de thèse était de développer un protocole TDM thoracique délivrant une dose inférieure à celle du DRL national pour une radiographie du thorax de face et une de profil (0.225 mSv) [14], puis de le valider en terme de performance diagnostique. Son périmètre était l'exploration en urgence des douleurs thoraciques ne relevant pas d'une injection de contraste iodé chez les adultes. Comme objectif secondaire, étant donné que l'image ULD-CT est modifiée par rapport à l'image habituelle, la confiance d'interprétation des lecteurs non habitués à ce type d'imagerie a été évaluée.

DEROULEMENT DE LA THESE

Afin d'établir un protocole scanner du thorax délivrant une dose inférieure aux DRL d'une radiographie du thorax et qui maintienne une fiabilité diagnostique, trois phases ont été réalisées (**figure 5**).

1ère phase. Essais sur fantômes. Plusieurs protocoles scanner avec dose décroissante (140 kVp/350 mAs → 80 kVp/50 mAs) ont été testés sur des fantômes qualité d'image et anthropomorphiques, pour constater l'influence des modifications des paramètres d'acquisition et des paramètres de reconstruction sur la qualité d'image objective.

2nde phase. Essais sur thorax de cadavres humains. Un protocole standard (120kVp/200mAs), LD-CT (120 kVp/40 mAs) et ULD-CT (100 kVp/10 mAs) ont été testés sur le thorax de cadavres humains en évaluant la qualité d'image objective, la qualité anatomique subjective et les paramètres quantitatifs.

3ème phase. Essais (Accords CNIL et IRB obtenus) et validation finale sur patients en urgence.

- Analyse de la qualité (objective et subjective) et de la performance diagnostique du protocole ULD-CT (100 kVp/10 mAs) versus le protocole institutionnel du thorax (100kVp/60 mAs avec TCM activé) en urgence chez des patients dyspnéiques sans notion de traumatisme.
- Analyse de la qualité subjective et de la performance diagnostique du protocole ULD-CT (100 kVp/10 mAs) versus la radiographie conventionnelle en urgence chez des patients ayant subi un traumatisme thoracique mineur fermé.

Les études sur fantômes, cadavres humains et patients ont été conduites sur deux scanners Somatom Definition AS+ (Siemens) équipés des IR : SAFIRE (Sinogram Affirmed Iterative Reconstruction).

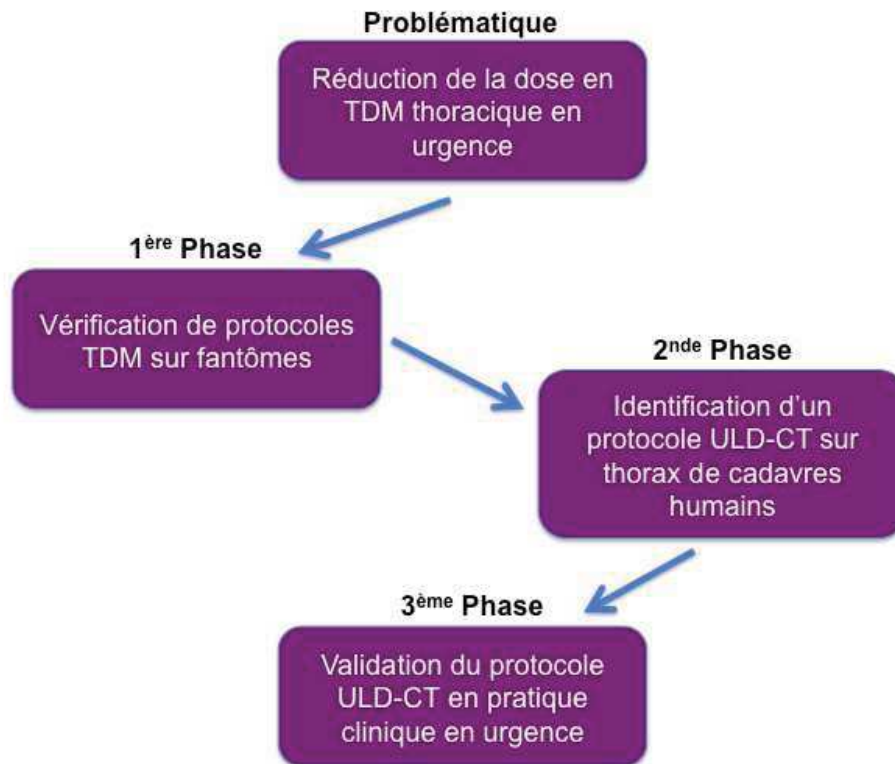


Fig. 5 Problematique et plan de thèse

1ère PHASE. Démarche initiale pour le développement d'un protocole ULD-CT

La création d'une méthode globale pour choisir un protocole scanographique à dose abaissée visant l'optimisation s'imposait pour cette phase, afin d'établir un protocole apte à satisfaire les essais des phases successives.

Une étude a été conduite pour analyser l'effet de la réduction de la dose et l'influence de SAFIRE sur la qualité d'image pour plusieurs protocoles sur les différentes régions anatomiques. Les protocoles TDM étaient réalisés avec différentes valeurs de kVp, mAs et pitch avec une collimation fixe sur un fantôme qualité image (Catphan 500). Ensuite la qualité des images des protocoles TDM jugés satisfaisants a été vérifiée sur un fantôme anthropomorphique adulte (Atom Dosimetry phantoms). Les données brutes ont été reconstruites avec la FBP et avec différents niveaux de SAFIRE.

Le fantôme Catphan 500 présentait trois sections, dont chacune composée d'un matériel différent ayant une densité se rapprochant de l'air, du tissu adipeux, de l'eau, etc. En particulier une section unique (CTP 528a) était utilisée seulement pour évaluer la résolution transverse spatiale en calculant la fonction de transfert de modulation Modulation Transfer Function (MTF). Pour évaluer la qualité objective de l'image, le signal et le bruit ont été relevés dans des régions d'intérêts (ROI) positionnées dans les inserts des sections du fantôme Catphan 500. Ensuite le rapport signal sur bruit (SNR) et contraste sur bruit (CNR) ont été calculés. Pour choisir les protocoles TDM à tester ensuite sur le fantôme anthropomorphique un logiciel sur Excel (macro) a été développé. Enfin la qualité des images des protocoles suggérés par celui-ci a été validés sur le fantôme anthropomorphique. Le bruit, le SNR and CNR ont été mesurés à partir des ROI dans des structures du fantôme anthropomorphique similaires à celles du Catphan 500 et comparés.

Enfin des radiologues ont visualisé les images du fantôme anthropomorphique et validé certains protocoles en fonction d'une qualité d'image satisfaisante.

Une variation significative du signal a été observée, en général s'il y avait une modification des kVp tandis que cet effet n'avait pas lieu si les mAs ou les niveaux de SAFIRE changeaient. Une augmentation du bruit était retrouvée lors d'une réduction des kVp et des mAs par rapport à l'acquisition de référence (120 vVp/200 mAs/FBP). Par contre une réduction du bruit de l'image a été remarquée lors de l'application de hauts niveaux de SAFIRE, se traduisant par une augmentation du SNR et CNR. Le logiciel développé avait proposé 5 possibilités de protocoles TDM avec une réduction de la dose entre 25% et 70%. Il avait en outre suggéré de reconstruire avec les niveaux d'itération S3, S4, S5. Le niveau S5 était le seul apte à une réduction de la dose de 70%. Donc en réalisant ces protocoles TDM avec les niveaux de SAFIRE suggérés sur le fantôme anthropomorphique, le bruit, le SNR et le CNR par rapport à l'acquisition de référence étaient maintenus ou améliorés et la MTF ne variait pas.

Les protocoles validés par les radiologues ont permis une réduction de la dose significative dans la pratique clinique de notre institution par rapport aux DRL nationaux pour les différentes régions anatomiques et en particulier pour le thorax de 83% correspondant à un LD-CT.

En conclusion cette première étude a permis l'identification d'une méthode pour choisir des protocoles TDM à faible dose avec des niveaux de SAFIRE appropriés pour garder un niveau de qualité d'image satisfaisant et pouvoir donc optimiser les protocoles dans la pratique clinique.



ORIGINAL ARTICLE / *Research and innovation*

Dose reduction with iterative reconstruction: Optimization of CT protocols in clinical practice



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KEYWORDS

Multidetector CT;
Iterative reconstruction;
Dose reduction;
Image quality;
Patient safety

Abstract

Objectives: To create an adaptable and global approach for optimizing MDCT protocols by evaluating the influence of acquisition parameters and Iterative Reconstruction (IR) on dose reduction and image quality.

Materials and methods: MDCT acquisitions were performed on quality image phantom by varying kVp, mAs, and pitch for the same collimation. The raw data were reconstructed by FBP and Sinogram Affirmed Iterative Reconstruction (SAFIRE) with different reconstruction kernel and thickness. A total of 4032 combinations of parameters were obtained. Indices of quality image (image noise, NCT, CNR, SNR, NPS and MTF) were analyzed. We developed a software in order to facilitate the optimization between dose reduction and image quality. Its outcomes were verified on an adult anthropomorphic phantom.

Results: Dose reduction resulted in the increase of image noise and the decrease of SNR and CNR. The use of IR improved these indices for the same dose without affecting NCT and MTF.

Abbreviations: CNR, Contrast-to-Noise Ratio; CTDI, Computed Tomography Dose Index; DRL, Diagnostic Reference Levels; FBP, Filtered Back Projection; FOV, Field-Of-View; IR, Iterative Reconstruction; LDPE, Low-Density PolyEthylene; LSF, Line Spread Function; MDCT, Multi-Detector Computed Tomography; MTF, Modulation Transfer Function; NCT, CT Number; NPS, Noise Power Spectrum; PSF, Point Spread Function; ROI, Region Of Interest; SAFIRE, Sinogram Affirmed Iterative Reconstruction; SNR, Signal-to-Noise Ratio; VBA, Visual Basic Application.

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The image validation was performed by the anthropomorphic phantom. The software proposed combinations of parameters to reduce doses while keeping indices of the image quality adequate. We observed a CTDIvol reduction between -44% and -83% as compared to the French diagnostic reference levels (DRL) for different anatomical localization.

Conclusion: The software developed in this study may help radiologists in selecting adequate combinations of parameters that allows to obtain an appropriate image with dose reduction.

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Introduction

Due to a growing demand of computed tomography (CT) examinations, patients are being exposed more frequently to ionizing radiation [1]. To address this increasing medical/clinical requirement, health care professionals are asked to strengthen the rationale for examinations and to optimize practices and procedures. The optimization is achieved by simultaneously managing the dose level and the image quality [2,3]. Changes in the parameters of the image acquisitions can be arranged to reduce the dose delivered to patients but this causes a deterioration of the image quality [4].

Recent advances in iterative reconstruction (IR) methods of MDCT images have provided a reliable and alternative method for optimizing the ratio between the dose and the image quality. These methods consist in post-processing mathematical approaches that allow us to correct raw data by reducing image noise without changing the transverse spatial resolution [5,6]. Several studies have demonstrated that it is possible to maintain satisfactory image quality with dose reduction [7-19]. However, the dose reduction is usually a medical judgment and the gain in the image quality obtained by IR needs to be quantified. Those studies evaluated intra-group comparison with optionally chosen acquisition and reconstruction parameters. Moreover, dosimetric and qualitative analyses were made a posteriori.

The purpose of this work was to define an adaptable and global approach for optimizing MDCT protocols by evaluating the influence of acquisition parameters, SAFIRE on dose reduction and image quality by using the phantom Catphan 500 and an anthropomorphic phantom. We developed a software in order to facilitate the optimization between dose reduction and image quality.

Materials and methods

MDCT protocol

Images were acquired on a MDCT SOMATOM Definition AS+ (Siemens, Erlangen, Germany) with floating diaphragm on the 3 axes allowing to obtain a collimation of 128×0.6 mm from an array of 64 detectors 0.6 mm. Raw data were reconstructed using two procedures: Filtered Back Projection (FBP) and Sinogram Affirmed Iterative

Reconstruction (SAFIRE). The latter uses two corrections loops, which are applied on the raw data and on the image data with five iteration levels (S1 to S5) respectively [16,20].

Phantom Quality Image

A Catphan 500 phantom (The Phantom Laboratory, Salem, USA) was used to assess the quality of image based on the acquisition parameter and the levels of SAFIRE. Three sections of the phantom (CTP 401, CTP 486 and CTP 528a) were studied. The CTP 401 section is composed of four inserts of distinct densities. Each section aims to assess both signal (CT Number (NCT)) and image noise in the Air (-1000 HU), in Low-Density PolyEthylene (LDPE, -100 HU), in Acrylic (120 HU) and in Teflon (950 HU).

The CTP 486 section consists of a uniform section for measuring NCT and image noise of a material that owns density close to the water, (20 HU). Finally, the CTP 528a section is used to assess the transverse spatial resolution by the computing the Modulation Transfer Function (MTF).

Standardized method for acquisition and reconstruction parameters

Raw data were collected and reconstructed according to the parameters presented in Table 1. These parameters are available on the MDCT and include five levels of iteration in SAFIRE (S1 to S5). Overall, 4032 combinations of parameters were obtained.

Dosimetry

For each acquisition Computerized Tomography Dose Index volume (CTDIvol) was measured with the dosimetry phantom body (The Phantom Laboratory, Salem, USA) with 32 cm of diameter and a pencil ionization chamber of 10 cm. The ionization chamber and the multimeter were calibrated according to an accredited laboratory (Swedish Board for Conformity Assessment and Accreditation 2035 ISO/IEC/17025).

Physical metrics

Except for Noise Power Spectrum (NSP), data were analyzed with the CTP module software Qualimagiq (QUALIFORMED,

Table 1 Parameter of Acquisition and Reconstruction studied: in total, 4032 combinations of parameters are available.

	Parameters used in the software	Parameters presented in the paper
kVp	80, 100, 120, 140	80, 100, 120
mAs	50, 100, 150, 200, 250, 300, 350	50, 100, 150, 200
Pitch	0.8, 1.2	0,8
Kernel	B/130f, B/140f, B/150f, B/170f	B/130f
Thickness/Overlap	1 mm/0.7 mm; 2 mm/ 1 mm; 3 mm/ 1 mm	1 mm/0.7 mm
Reconstruction Type	FBP, S1, S2, S3, S4, S5	FBP, S1, S2, S3, S4, S5

La Roche sur Yon, France). NCT (mean of pixel values in regions of interest) and image noise (standard Deviation of pixel values in regions of interest) were estimated on the CTP 401 sensitometric section and on the CTP 486 uniform section. Measurements on the CTP 401 section were carried out in the center of the four inserts (Air, LDPE, Acrylic and Teflon) with regions of interest (ROI) of 420 pixels (0.785 cm²). The NCT and the image noise of the water on the CTP 486 section were assessed by placing a ROI of 14,400 pixels (36 cm²) in the center of the phantom representing 40% of its diameter. In order to obtain accurate results, the NCT and image noise were assessed out on 10 consecutive sections and described as average with a standard deviation from the mean.

From the values on these two sections, the signal-to-noise ratio (SNR) and the contrast-to-noise ratio (CNR) [21] were calculated according the Equation (1) and (2) respectively. The CNR was obtained by considering the image noise values and the water NCT as a reference in the Equation (2).

$$SNR = \frac{|HU_{ROI}|}{\sigma_{ROI}} \quad (1)$$

$$CNR = \frac{|HU_{ROI} - HU_{Water}|}{\frac{(\sigma_{ROI} + \sigma_{Water})}{2}} \quad (2)$$

The transverse spatial resolution, characterized by the MTF [22–24], was calculated by measuring the impulse response function of the imaging system represented by the spreading function of a point also known as "Point Spread Function (PSF)". This function was estimated in the 528 bis CTP section, composed of a small ball of Tungsten Carbide with diameter of 0.28 mm, which is less than one pixel in size. A square area of 32 pixels was centered on the middle of the PSF (maximum intensity pixel) and the background signal was subtracted therein.

To reduce the influence of noise, two spread functions of a line source (Line Spread Function: LSF) were calculated by projecting the different PSF profiles depending on vertical and horizontal directions of the image. At the end, the MTF was obtained from the average of 2 modules of the Fourier transform of 2 LSFs. Image noise properties can be characterized by the noise power spectrum (NPS). It measures, depending on the frequency, the noise component and the image smoothing with the dose reduction and the use of SAFIRE. NPS were calculated with a home-made Matlab® routine (The MathWorks, Natick, USA) based on 60 image slices of the homogeneous water section (CTP 486) containing ROIs of 128 × 128 pixels. NPS were determined by averages in the frequency domain along the fx and fy directions [21, 25–28].

Proposal of software for data analysis

We developed a macro in Excel (Microsoft, Redmont, USA) using Visual Basic for Applications (VBA) from the 4032 available parameters. This software was applied on the database with distinct acquisition and reconstruction parameters in combination with values of CTDIvol, MTF10%, image noise, SNR and CNR.

The usage of the software is done within three steps. First, the operator chooses acquisition and reconstruction parameters present on the workstation (Table 1). Second, the operator elects the distinct parameters to be kept for the output; for example, the same kVp, the same reconstruction type or the same reconstruction kernel used in the first step. As a final step, the operator defines the minimum percentage of dose reduction and maximum variation of image quality indices (image noise, SNR, CNR, MTF10%). Only the combination of parameters with the image quality indices that were not reduced more than 5% compared to the reference acquisition was retained. In this study, a standard sequence was chosen to illustrate the optimization possibilities offered by this software. As first step, the sequence studied was performed with 120 kVp, 200 mAs and FBP as reference. Pitch 0.8 and for collimation was in 128 × 0.6 mm. The raw data were reconstructed with slice thickness of 1 mm every 0.7 mm, by Filtered Back Projection with a reconstruction kernel "Medium Smooth" B30f. Then, the same kVp, pitch, collimation, slice thickness and reconstruction kernel were entered in addition to levels of SAFIRE (S1, S2, S3, S4, S5). Finally, we choose a minimal dose reduction of 20% that did not impair image quality indices.

Data verification on anthropomorphic phantom

Post-process data were verified on an adult anthropomorphic phantom "ATOM Dosimetry Phantoms" (CIRS, Norfolk, USA). Comparisons of image noise, CNR and SNR were performed by positioning ROI in structures having densities similar to those of the phantom Catphan 500 inserts: Air (0.004*10²³ cm⁻³) vs. Lung tissue (0.681*10²³ cm⁻³); Water (3.343 *10²³ cm⁻³) vs. Soft tissue (3.434 *10²³ cm⁻³) and Teflon (6.243*10²³ cm⁻³) vs. Bone tissue (5.028*10²³ cm⁻³). No comparison was possible between the two phantoms for LDPE and acrylic.

Optimization in clinical practice

The MDCT protocols were optimized by using the parameters combinations proposed by the software and after validation

with anthropomorphic phantom. Several combinations of parameters were offered according anatomical location: Head, Abdomen-Pelvic, Chest, Chest-Abdomen-Pelvic and Lumbar Spine. The quality of the phantom images for each proposed combinations were accepted by radiologists of our department.

The impact of the aforementioned technique was assessed by means of the comparison of news CTDIvol with the French Diagnostic Reference Levels (DRL) [29] and CTDIvol before optimization. These CTDIvol corresponded to the mean of CTDIvol obtained during one year on all CT exams on two CT scan (same brand) in our department.

Statistics

Statistical analysis was performed using 'Biostatgv' (<http://marne.u707.jussieu.fr/biostatgv>). The comparison for Catphan 500 phantom between the reference acquisition and other acquisitions was obtained using the paired Mann Whitney-Wilcoxon test. A P -value < 0.005 (adjusted for multiple comparisons) was considered significant.

Results

Physical metrics

Changes in kVp resulted in significant variation ($P < 0.005$) of the NCT as shown in Table 2a, independently of the inserts location. For example, the water NCT were 12.1 HU

for 120kVp, 2.6 HU for 100 kVp and -13.2 HU for 80 kVp. Unlikely, reduction of the number of mAs or the increases of the level of SAFIRE did not cause significant ($P > 0.005$) changes on the NCT. Compared to the reference (120 kVp, 200 mAs and FBP), reduction in kVp or in mAs values were associated with increasing noise in the image (Table 2b). Compared to the reference acquisition with 80 kVp and 200 mAs water image noise was increased by 78% and 31% with 120kVp and 100 mAs, respectively. Significant noise reduction ($P < 0.005$) was observed when higher levels of SAFIRE were applied. Compared to the reference acquisition water image noise was decreased by -19% with S1, -37% with S3 and -55% with S5. Regarding the FBP, the image noise reduction was more pronounced in LDPE, Water and Acrylic (-50% to -60% between FBP and S5) than Air or Teflon (-19% to -21% between FBP and S5).

The degradation of CNR due to reductions of kVp was observed according to the variation of NCT and to the increment of image noise (Table 2c). For example, the Acrylic CNR were 11.5 for 120kVp, 9.8 for 100 kVp and 6.2 for 80 kVp. The degradation of CNR due to mAs reduction was also noticed with significant increase in image noise ($P < 0.005$). The acrylic CNR for 120 kVp was 11.5, 8.2 and 5.8 with 200, 100 and 50 mAs, respectively. Along with application of higher level of SAFIRE, the CNR was improved for all inserts. Compared to the reference acquisition, the acrylic CNR was increased by 18% with S1, 57% with S3 and 133% with S5. Regarding the FBP, improvement of CNR was more pronounced in LDPE and Acrylic (51% to 53% between FBP and S5) than in air or Teflon (112% to 133% between FBP and S5).

Table 2a Effects of kVp, mAs and reconstruction type on CT number.

	CT Number (HU)				
	Air	LDPE	Water	Acrylic	Teflon
120 kVp 200 mAs FBP B30f	-1000.9	-90.7	12.1	122.0	940.5
100 kVp 200 mAs FBP B30f	-1000.8*	-100.6*	2.6*	115.3*	953.8*
80 kVp 200 mAs FBP B30f	-995.2*	-117.8*	-13.2*	101.3*	984.9*
120 kVp 150 mAs FBP B30f	-999.5	-87.5	12.0	123.3	940.2
120 kVp 100 mAs FBP B30f	-1000.1	-88.7	11.9	120.4	935.6
120 kVp 50 mAs FBP B30f	-995.4*	-91.3	11.8	122.6	936.2
120 kVp 200 mAs SAFIRE I30f S1	-1001.0	-90.7	12.1	122.1	940.6
120 kVp 200 mAs SAFIRE I30f S3	-1001.3	-91.0	12.1	122.0	941.0
120 kVp 200 mAs SAFIRE I30f S5	-1001.6	-91.1	12.1	122.0	941.3

Table 2b Effects of kVp, mAs and reconstruction type on Image Noise.

	Image Noise				
	Air	LDPE	Water	Acrylic	Teflon
120 kVp 200 mAs FBP B30f	14.1	8.0	9.9	9.2	14.4
100 kVp 200 mAs FBP B30f	14.9	10.9*	11.7*	11.4*	20.8*
80 kVp 200 mAs FBP B30f	19.0*	14.5*	17.6*	19.7*	22.5*
120 kVp 150 mAs FBP B30f	15.5	9.3*	10.6*	10.7*	15.9
120 kVp 100 mAs FBP B30f	16.0*	13.0*	13.0*	13.3*	17.4*
120 kVp 50 mAs FBP B30f	18.0*	18.2*	18.0*	20.4*	28.3*
120 kVp 200 mAs SAFIRE I30f S1	13.5 + (-4.3%)	7.1 + (-11.1%)	8.0 + (-19.1%)	8.1 + (-11.6%)	13.8 + (-3.9%)
120 kVp 200 mAs SAFIRE I30f S3	12.3 + (-12.6%)	5.4 + (-32.7%)	6.2 + (-37.2%)	5.9 + (-35.6%)	12.7 + (-11.5%)
120 kVp 200 mAs SAFIRE I30f S5	11.2 + (-20.7%)	4.0 + (-50.4%)	4.5 + (-54.5%)	3.7 + (-59.9%)	11.6 + (-19.1%)

Table 2c Effect of kVp, mAs and reconstruction type on CNR.

	Contrast-to-Noise Ratio			
	Air	LDPE	Acrylic	Teflon
120 kVp 200 mAs FBP B30f	84.2	11.4	11.5	76.4
100 kVp 200 mAs FBP B30f	75.6*	9.2*	9.8*	58.6*
80 kVp 200 mAs FBP B30f	53.7*	6.5*	6.2*	49.8*
120 kVp 150 mAs FBP B30f	77.6*	10.0*	10.5	70.1
120 kVp 100 mAs FBP B30f	69.8*	7.7	8.2	60.7*
120 kVp 50 mAs FBP B30f	56.0*	5.7	5.8*	39.9*
120 kVp 200 mAs SAFIRE I30f S1	94.0+ (11.6%)	13.6+ (18.5%)	13.6+ (18.4%)	85.0+ (11.3%)
120 kVp 200 mAs SAFIRE I30f S3	109.2+ (29.6%)	17.7+ (54.8%)	18.1+ (57.4%)	98.0+ (28.3%)
120 kVp 200 mAs SAFIRE I30f S5	129.1+ (52.3%)	24.3+ (112.3%)	26.8+ (133.3%)	115.1+ (50.7%)

Changes in kVp, mAs or SAFIRE's level did not alter the transverse spatial resolution, which is expressed in the MTF curves and shown in Table 2d.

The Frequency Distribution of Noise (expressed by NPS) indicated that the image noise was increased in two situations: (i) for decreasing values of kVp but conserving the mAs (Fig. 1a) and (ii), for reducing values of mAs at the same kVp (Fig. 1b).

Compared to FBP, higher levels of SAFIRE decreased NPS. Moreover, the peaks of the NPS curves were shifted to lower frequencies when SAFIRE was applied (Fig. 1c).

Verification on anthropomorphic phantom of the combinations parameters proposed by the software

Table 3 shows the combination of parameters of acquisition and reconstruction. Regarding such output combinations, the variations of dose, image noise and CNR are entered, the software taking into account the definition made by the operator. The SAFIRE level 5 was the only one proposed over 50% of dose reduction.

The software proposed five possibilities of dose reduction ranging from 25% to 50%. It also suggested three possible

SAFIRE levels: S3, S4 and S5. Values of image noise, SNR and CNR were maintained or improved and the transverse spatial resolution (MTF10%) was not changed. Table 4 shows the values of image noise, SNR and CNR for images acquired on the anthropomorphic phantom from parameters combinations suggested by the software. These values for the three structures had the same magnitude as those of the air, Water and Teflon on the phantom Catphan 500. Variation of image noise, SNR and CNR of combinations proposed with respect to the acquisition reference were, with the exception of the bone, more marked on the anthropomorphic phantom than phantom Catphan 500. Similar to phantom Catphan 500, the effect of SAFIRE was greater for the Water than for the bone and air.

Fig. 2 shows the position of the three ROI placed in the anthropomorphic phantom according to the selected tissues at distinct levels doses; for instance, the dose reduction with FBP (2a) 25% with S3 (2b) and 50% with S5 (2c).

Optimization on clinical practice

Table 5 shows CTDIvol values obtained in 2012 and 2013, before and after optimization of the parameters for different anatomical locations. This table also includes a

Table 2d Effect of kVp, mAs and reconstruction type on MTF.

	Modulation Transfer Function	
	MTF50%	MTF10%
120 kVp 200 mAs FBP B30f	3.56	6.11
100 kVp 200 mAs FBP B30f	3.56	6.13
80 kVp 200 mAs FBP B30f	3.51	6.05
120 kVp 150 mAs FBP B30f	3.55	6.11
120 kVp 100 mAs FBP B30f	3.59	6.18
120 kVp 50 mAs FBP B30f	3.59	6.18
120 kVp 200 mAs SAFIRE I30f S1	3.56	6.12
120 kVp 200 mAs SAFIRE I30f S3	3.57	6.14
120 kVp 200 mAs SAFIRE I30f S5	3.57	6.15

Values express the effects of kVp, mAs and reconstruction type on CT number (2a), image noise (2b), CNR (2c) and MTF (2d). Comparisons with the reference acquisition defined as: 120 kVp, 200 mAs with FBP. Noise and NCT water is used to calculate the CNR, CNR water is not presented in the Table 2c. (FBP: Filtered Back Projection, LDPE: Low-Density PolyEthylene). Significance compared to the reference acquisition * $P < 0.005$ and + $P < 0.005$ (when value was improved).

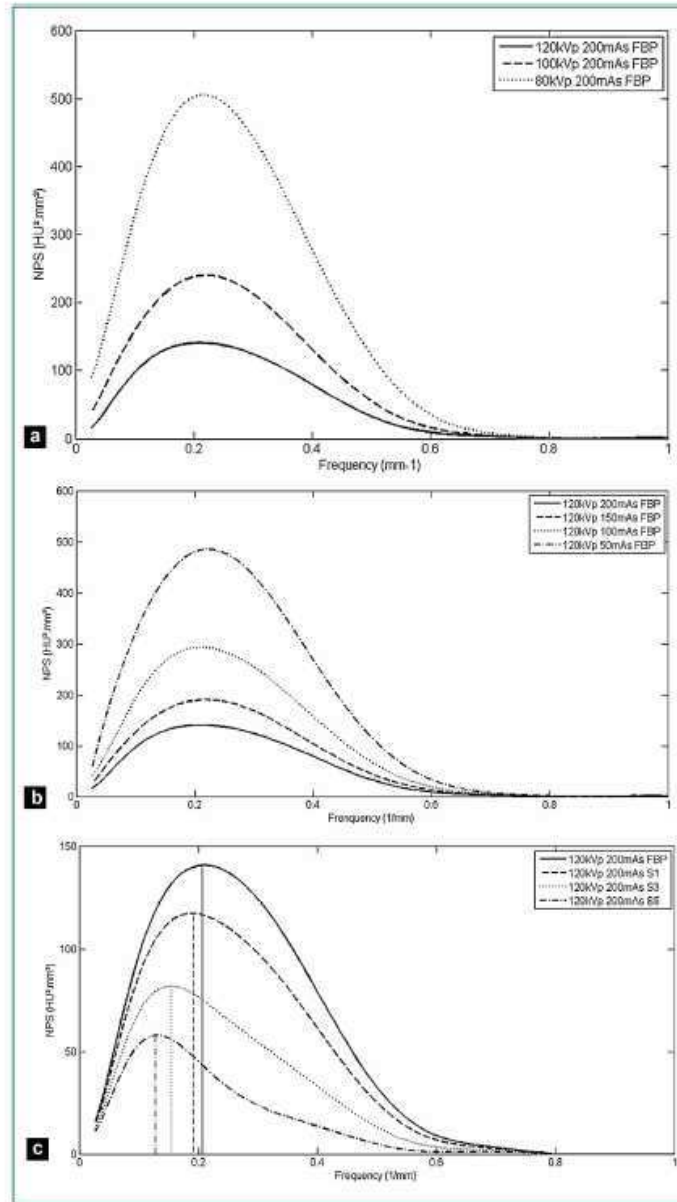


Figure 1. Noise Power Spectrum (NPS) curve for distinct kVp, mAs and reconstruction type. a. FBP (B30f), different kVp and 200 mAs. b. FBP (B30f) 120 kVp and different mAs. c. for 120 kVp and 200 mAs and FBP (B30f), S1, S3, S5 (I30f).

Table 3 Combinations of the parameters of acquisition and reconstruction.

CTDIvol (mGy)	mAs ref	Recon Type	Air (El. density 0.004 10^{23} cm^{-3})			Water (El. density 3.343 10^{23} cm^{-3})			Teflon (El. density 6.243 10^{23} cm^{-3})		
			Image Noise	SNR	CNR	Image Noise	SNR		Image Noise	SNR	CNR
13.4	200	FBP	14.1	70.9	84.2	8.9	1.4		14.4	65.4	76.4
10.1	150	S3	12.8	78.1	91.8+	7.4+	1.6		12.9	72.8	83.7+
10.1	150	S4	12.0+	83.3+	107.5+	6.4+	1.9+		12.0	77.9	100.4+
10.1	150	S5	11.0+	90.8	113.2	5.3+	2.2		11.2+	83.4+	102.3+
6.7	100	S4	13.6+	73.5+	93.4+	8.1+	1.5+		15.2	62.1	80.0
6.7	100	S5	12.9+	77.3	110.8+	6.9+	1.7		14.6	64.6	93.4+

The software works on 150 mAs (25% dose reduction) and uses levels SAFIRE S3 to S5 or 100 mAs (50% dose reduction) and S4 to S5. For 3 inserts (air, water, Teflon) values of noise, SNR and CNR, proposed by the tool combinations are close to or better than the values of the reference acquisition. (FBP: Filtered Back Projection, El: Electron, SNR: Signal-to-Noise Ratio, CNR: Contrast-to-Noise Ratio). Significance compared to the reference acquisition * $P < 0.005$ and + $P < 0.005$ (when value was improved).

Table 4 Verification with anthropomorphic phantom of combinations proposed by software.

CTDIvol (mGy)	mAs ref	Recon Type	Lung tissue (El. density 0.681 10^{23} cm^{-3})			Soft tissue (El. density 3.434 10^{23} cm^{-3})			Bone tissue (El. density 5.028 10^{23} cm^{-3})		
			Image Noise	SNR	CNR	Image Noise	SNR		Image Noise	SNR	CNR
13.4	200	FBP	11.0	72.2	81.6	9.0	2.4		14.0	57.9	68.5
10.1	150	S3	10.0	79.9	96.6	7.0	3.1		13.0	62.2	78.7
10.1	150	S4	9.0	88.8	109.5	6.0	3.7		12.0	67.4	87.4
10.1	150	S5	8.0	99.9	136.8	4.0	5.5		12.0	67.4	98.4
6.7	100	S4	10.0	79.7	96.5	7.0	3.3		15.0	54.1	71.7
6.7	100	S5	9.0	88.6	109.3	6.0	3.8		14.0	58.0	78.9

Noise, SNR and CNR were measured in Lung tissue, Soft tissue and Bone tissue on the anthropomorphic phantom for combinations proposed by the software. (FBP: Filtered Back Projection, El: Electron, SNR: Signal-to-Noise Ratio, CNR: Contrast-to-Noise Ratio). Significance compared to the reference acquisition * $P < 0.005$ and + $P < 0.005$ (when value was improved).



Figure 2. Images obtained from the three combinations defined, with values of SNR and CNR close to dose reductions of 25% and 50%. The same image settings were used for images a, b and c. a. 120 kVp; 200 mAs; FBP; CTDIvol: 13.5 mGy. b. 120 kVp; 150 mAs; S3; CTDIvol: 10.1 mGy. c. 120 kVp; 100 mAs; S5; CTDIvol: 6.7 mGy.

comparison with French DRL. After optimization, CTDIvol were reduced by 26% for the head, 32% for abdomen-pelvic, chest 40%, 35% for the chest-abdomen-pelvic and 55% for the lumbar spine. The same values measured in 2013 were between -44% and -83% below the French DRL.

Discussion

This experimental study used the phantom image quality Catphan 500 that allowed one to establish a database of 4032 combinations of acquisition and reconstruction

Table 5 CTDIvol values before and after implementation of an optimization approach, compared to French NRD.

CTDIvol (mGy)	Head	Abdomen-Pelvic	Chest	Chest Abdomen-Pelvic	Lumbar Spine
Nîmes 2012	48.8	7.5	4.2	10.2	36.3
Nîmes 2013	36.3	5.1	2.5	6.6	16.5
French NRD	65	17	15	20	45
% Difference (2013 vs. NRD)	-44	-70	-83	-67	-63
% Difference (2013 vs. 2012)	-26	-32	-40	-35	-55

The values expressed the CTDIvol obtained for five sequences before and after the implementation of an optimization and use of it tools approach. A comparison was made with the French NRD. The percentage difference between the values obtained in 2013 and 2012 or NRD was presented.

parameters with values CTDIvol, image noise, SNR, CNR and MTF10%.

The present software considered the influence of acquisition and reconstruction parameters on the dose and on image quality and allowed users to reduce the dose without impairing the image quality. Several studies [21,24,27] have focused on iterative reconstructions with the dose reduction associated to image quality by means of image quality phantoms. Decreases in mAs and kVp resulted in deterioration of the image quality indices together with increases in image noise and NPS, as well as deterioration of the SNR and CNR [21,24,27]. Thus, changes of kVp caused change in the NCT of distinct structures.

The present study supports previous literature [21,24,27] and confirms that SAFIRE change neither the transverse spatial resolution nor the NCT, independently of the inserts densities. Decreases of the image noise were observed when the levels of SAFIRE were increased as opposed to FBP. The impact of SAFIRE was less pronounced in structures with a high NCT e.g. air or Teflon. The values of image noise reduction from one level to another for Water were the same as those described in the literature [21,24,27]. This reduction of image noise resulted in increased SNR and CNR independently of the insert used.

The study of NPS between the FBP and the different levels of SAFIRE confirmed the noise reduction but exposed a shift of the curves peak toward to lower frequencies with increasing levels SAFIRE. In addition, the increase of levels of SAFIRE determined an increase of image smoothing [24,28].

Taking into account the influence of distinct acquisition and reconstruction parameters, we choose to reduce the doses by decreasing the mAs reference without changing the kVp. Compensation of degradation of image quality indices, especially those due to noise increase, was mainly assured by increasing levels of SAFIRE.

With the present study we were able to provide a rigorous and reproducible approach aiming to optimise the image quality settings from the established database. The ad-hoc implementation of the software gave the choice to operator to reduce the dose while keeping satisfactory quality image indices from the acquisition and reconstruction parameters. Given the large number of parameters analysed, this software has the advantage that it can be applied to the majority of the available protocols in the MDCT. As much as the dose reduction was defined by the operator, fewer combinations of parameters are available in the software.

Compensation was initially provided by SAFIRE. From the image quality point of view of, the use of increased levels of SAFIRE amplified the smoothing effect of the image with alteration of its texture. The shape of the NPS curves was modified and the peaks left-shifted toward the lower frequencies. The texture and quality of the phantom images were accepted by radiologists in our department for implementation in clinical routine. The verifications that were done on the anthropomorphic phantom for the combinations parameters proposed confirmed the efficacy of this software especially for soft tissues. Only the combination of parameters with the image quality indices that were not reduced more than 5% compared to the reference acquisition was retained.

The implementation of this tool in routine practice also seemed complex. With no direct synchronization of acquisition and reconstruction parameters on the MDCT workstation, the operator was obligated to manually enter the input and output parameters, the variations of the dose reduction and quality image indices. These last two points were physician-dependent and not always available at the workstation at same time.

Moreover, the software proposed here may be very useful for medical physicists for optimization approach of the parameters, because it constitutes a fair and substantial instrument of measures that takes into account all the parameters available on MDCT. In practice, all MDCT protocols of our reference center were optimized without deteriorating image quality. Reductions doses were obtained for the different anatomical locations with values well below French DRL [29]. The quality of images obtained with lower doses for all protocols was evaluated and considered as satisfactory by a radiologist and is conducted by a radiologist to evaluate satisfaction and efficacy.

This study has nevertheless some limitations. First, the Catphan device 500, used as reference to quantify the physical measures, was a quick and simple approach for the evaluation of certain properties of reconstruction methods and it was limited especially for MTF measurements with non-linear reconstruction. Second, even if the software database is composed of several values of pitch, reconstruction thickness and reconstruction kernels, the results presented in this study targeted the effect of SAFIRE, kVp and mAs on dose reduction and image quality. Third, the subjective quality criteria has not been studied. Finally, the impact of SAFIRE on the spatial resolution in the Z-axis was not studied either.

Conclusion

To conclude, the present work confirmed that the use of SAFIRE allows us to increase the quality of images with same dose or to keep adequate image quality with dose reduction. Also, using the software we developed helps to choose the dose reduction delivered to the patients in clinical practice.

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Disclosure of interest

The authors declare that they have no conflicts of interest concerning this article.

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2ème PHASE. Test du protocole ULD-CT sur le thorax humain.

Dans cette partie des travaux de thèse on a évalué les effets obtenus de protocoles TDM à dose abaissée reconstruits avec SAFIRE sur la qualité d'image de structures anatomiques réelles du thorax. De plus on a comparé la capacité de reconnaissance des structures anatomiques entre un radiologue familier et un radiologue inexpérimenté à la lecture des images à dose réduite.

On a conduit une étude sur 18 cadavres humains relevant d'une autopsie virtuelle avec un intervalle post mortem dans les 48H et en bon état de conservation, sans dommage au niveau du thorax. Trois protocoles TDM thoracique ont été testés : un protocole standard « pleine dose » (120 kVp/200 mAs) ayant fonction de référence, un à « basse dose (Low-dose_LD; 120kVp/80 mAs) et un à « très basse dose » (ULD_120kVp/). Les séries obtenues ont été reconstruites avec FBP et SAFIRE S3, S4 and S5 comme niveaux d'itération. La qualité d'image objective a été évaluée en relevant le signal et le bruit des 9 régions d'intérêts (ROIs) positionnées sur les images thoraciques médiastinales, et parenchymateuses pulmonaires (**Figure 6**). Six ROIs étaient placées au niveau du parenchyme pulmonaire antérieur, moyen et postérieur de chaque poumon en fenêtre parenchymateuse. Trois autres ROIs respectivement au niveau de la graisse axillaire, du muscle pectoral majeur et dans le corps d'une vertèbre thoracique.

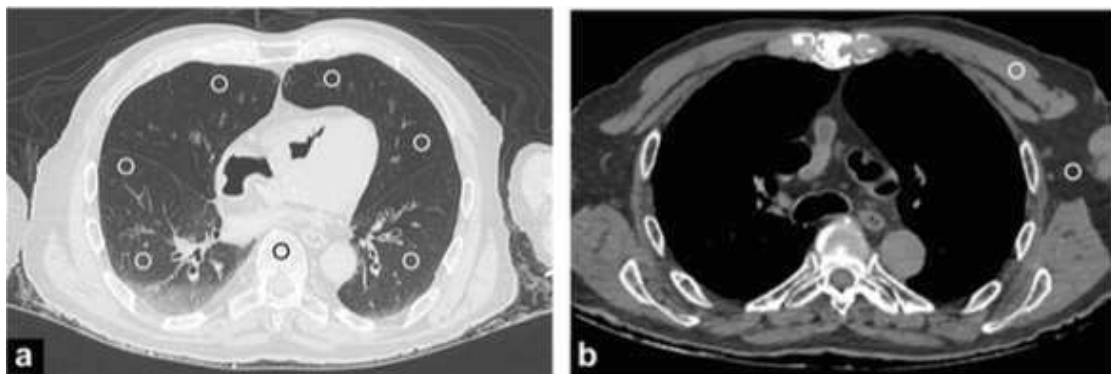


Fig. 6. Positions de différents ROI pour obtention des valeurs de signal, bruit et calcul du SNR et CNR pour évaluation de la qualité d'image objective (a) image pulmonaire (b) image médiastinale.

Le rapport signal sur bruit (SNR) et le rapport contraste sur bruit (CNR) ont été calculés.

En considération de la modification connue de l'image du fait de la réduction de la dose et de l'emploi de SAFIRE, deux radiologues indépendants ont analysé en aveugle la qualité d'image subjective des structures anatomiques selon une échelle de Likert à 5 points : 1 excellente, 2 bonne, 3 correcte, 4 pauvre, 5 inacceptable. En outre les radiologues ont même exprimé un grade de confiance représentant la capacité de reconnaissance d'une certaine structure anatomique

(50% et 95 % de certitude). L'analyse quantitative a été conduite en traçant la plus grande épaisseur du muscle pectoral majeur, les plus grands diamètres de l'aorte thoracique descendante, du canal spinal, de la trachée et de l'artère pulmonaire supérieure. De plus l'index cardio-thoracique a été calculé. Les valeurs dosimétriques ont été relevées à partir du rapport de dose de chaque TDM effectuée.

L'analyse des index de qualité de l'image (signal, SNR et CNR) a montré une réduction du bruit du 20 % et une augmentation du 26 % pour le SNR et du 24% pour le CNR pour le LD-CT et le ULD-CT reconstruit avec des hauts niveaux d'itération (LD-CT/S3 et ULD-CT/S5). La qualité d'image subjective n'a jamais été considérée pauvre ou inacceptable, ni pour le protocole LD-CT ni pour l'ULD-CT, avec respectivement une concordance inter observateur excellente et bonne. En particulier les radiologues n'ont jamais eu de difficultés à reconnaître les structures anatomiques du thorax avec certitude sur le protocole avec dose la plus faible (ULD-CT). Il n'y a pas eu des différences significatives pour les mesures quantitatives parmi les différents protocoles.

Les E moyennes étaient pour le protocole standard de référence 5.3 mSv, pour le LD-CT 1.1 mSv et pour le ULD-CT 0.27 mSv.

Finalement on a constaté que SAFIRE sur des protocoles LD-CT et ULD-CT permet d'améliorer la qualité d'image et que les radiologues reconnaissent aisément les structures anatomiques.

En considération le fait que le protocole ULD-CT a délivré une dose similaire à celle d'une radio de thorax de face et une de profil sans altération des paramètres quantitatifs et de qualité subjective, des études supplémentaires se sont imposées pour vérifier l'efficacité diagnostique, et qui sont discutées dans la dernière phase de cette thèse.



ORIGINAL ARTICLE/RESEARCH AND NEW DEVELOPMENTS

Ultra-low-dose chest CT with iterative reconstruction does not alter anatomical image quality

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KEYWORDS

Ultra-low-dose chest CT;
Sinogram affirmed iterative reconstruction;
Image quality;
Dose reduction;
Safire[®]

Abstract

Purpose: To evaluate the effect of dose reduction with iterative reconstruction (IR) on image quality of chest CT scan.

Materials and methods: Eighteen human cadavers had chest CT with one reference CT protocol (RP-CT; 120 kVp/200 mAs) and two protocols with dose reduction: low-dose-CT (LD-CT; 120 kVp/40 mAs) and ultra-low-dose CT (ULD-CT; 120 kVp/10 mAs). Data were reconstructed with filter-back-projection (FBP) for RP-CT and with FBP and IR (sinogram affirmed iterative reconstruction [SAFIRE[®]]) algorithm for LD-CT and ULD-CT. Volume CT dose index (CTDIvol) were recorded. The signal-to-noise (SNR), contrast-to-noise (CNR) ratios of LD-CT and ULD-CT and quantitative parameters were compared to RP-CT. Two radiologists reviewed the CT examinations assessed independently the quality of anatomical structures and expressed a confidence level using a 2-point scale (50% and 95%).

Results: CTDIvol was 2.69 mGy for LD-CT (–80%; $P < 0.01$) and 0.67 mGy for ULD-CT (–95%; $P < 0.01$) as compared to 13.42 mGy for RP-CT. SNR and CNR were significantly decreased ($P < 0.01$) for LD-CT and ULD-CT, but IR improved these values satisfactorily. No significant differences were observed for quantitative measurements. Radiologists rated excellent/good the RP-CT and LD-CT images, whereas good/fair the ULD-CT images. Confidence level for subjective anatomical analysis was 95% for all protocols.

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Conclusions: Dose reduction with a dose lower than 1 mGy, used in conjunction with IR allows performing chest CT examinations that provide a high quality of anatomical structures.
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Computed tomography (CT) of the chest plays an important role in the diagnostic and therapeutic decisions in medical practice [1,2]. A major increase of the radiation dose delivered to the patients associated with all consecutive biological hazards was observed [3]. The chest is particularly sensitive to radiation [4]. Dose reduction should be one priority for every radiologist who performs CT examination [5,6]. However, because dose reduction alters image quality, it is crucial to find a proper balance between dose reduction and diagnostic performance. This technological challenge has been addressed and solved by manufacturers with multiple new approaches [7]. Tube voltage reduction, tube current (mAs) [8–10] and iterative reconstructions (IR) [11–16] are currently effective methods. In particular, the use of sinogram affirmed iterative reconstruction (Safire[®], Siemens Healthcare, Erlangen, Germany) can improve image quality [17–30]. IR algorithms have an effect on the objective image quality represented by indices of image quality (IQ) (i. e., noise, signal-to-noise ratio [SNR], contrast-to-noise ratio [CNR]) and on the subjective visual image quality [28]. IR algorithms improve the IQ by reducing the noise for acquisitions obtained with the same dose, without altering signal parameters and transverse spatial resolution [27]. Thus, IR indirectly reduces patients radiation exposure. The use of IR algorithms counterbalances the degradation of raw data due to dose reduction so that useful applications have been developed in different clinical settings [31,32]. High strengths of IR maintain values of SNR and CNR similar to those of images obtained with high radiation doses, allowing a dose reduction from 50 to 75% [17,19]. However, by using high strengths of Safire[®], changes in the visual appearance (smoothing effect) and image texture (changes in noise power spectrum) have been reported [13]. Initially, this modification impeded a rapid and wide diffusion of these techniques.

Several studies have demonstrated the possibility to reduce radiation exposure using low dose CT (LD-CT) protocols of the chest (effective dose [ED] < 1.5 mSv) [26,33]. Recently, some researchers have proposed interesting applications of ultra-low dose CT (ULD-CT) protocols for the chest (ED < 0.5 mSv) associated with IR in clinical practice [34–36]. Some of these ULD-CT protocols result in a radiation dose similar to that of a chest X-ray while achieving good image quality. These results opened a debate on the possibility of using ULD-CT protocols rather than conventional X-ray examinations in several selected indications even in an emergency setting [37]. However, these studies did not address the issue of repeatability or reproducibility. A comparison of anatomical image quality obtained at different dose CT protocols on the same individual is currently

lacking. Such comparison is virtually impossible on living subjects because of ethical issues and unnecessary patient radiation exposure. Anthropomorphic phantoms are suitable to evaluate differences between CT scan protocols but with limitations regarding the number of evaluable tissues [15,38,39]. For this reason, human cadavers are a good alternative for this research of optimization of CT protocol.

The purpose of our study was to evaluate the image quality of anatomical structures using LD-CT and ULD-CT with Safire[®] compared to a reference chest CT protocol on the same human cadaver.

Materials and methods

Subjects

This prospective study was approved by our institutional review board and informed consent was obtained from the deceased's relatives. Adult human cadavers within a maximum post-mortem interval (PMI) of 48 hours, sent from the department of forensic pathology to the radiology department of our institution for post-mortem CT, were included from April to October 2015. A limited PMI was mandatory, in order to have tissue densities as similar as those of living subjects. Advanced tissue alterations (i. e., evident signs of putrefaction, charred or lacerated cadavers) served as exclusion criteria. Cadavers were scanned wrapped into two artifact-free body bags with the upper limbs placed along the thorax.

CT protocol and image reconstruction

CT images were acquired using a Somatom Definition AS+[®] (Siemens Healthcare). The detector acquisition configuration was 128 × 0.6 mm, which corresponds to a physical collimation of 64 × 0.6 mm. The use of z-flying focal spot technique allowed double sampling along the z-axis.

After CT acquisitions for virtual autopsy were obtained, only one chest scout view was performed and used for each cadaver prior to perform the protocols of the study. The scout view was acquired at 100 kVp and 20 mA. Consecutively, three different chest protocols were implemented on each cadaver covering from the first to the last thoracic vertebra without administration of intravenous contrast material. The first acquisition was the reference CT with a full radiation dose of 200 mAs, followed by other two at a dose reduced by 80% (40 mAs; LD-CT) and 95% (10 mAs; ULD-CT), respectively.

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Study images were obtained with the following parameters: field of view, 500 mm; tube current, 120 kVp; pitch, 1.2; rotation time, 0.33 s; beam collimation, 128 × 0.6 mm; acquisition thickness, 1 mm. A tube current of 120 kVp was employed because of the arms along the torso of the cadaver, whereas 100 kVp is usually used in clinical routine setting in our institution. Images were acquired without automatic exposure control for all three protocols. Automatic exposure control was not used in order not to consider the attenuation differences of each cadaver generated by the arms along the torso and the body bags.

All images were reconstructed in the transverse plane at 1 mm thickness and 0.7 mm overlapping. Raw data were reconstructed with the conventional filtered back projection (FBP) algorithm and with the Safire[®] algorithm. This method allows obtaining two corrections loops, one for the raw data and another for the image data with five iteration strengths (S). On a scale from S1 to S5, S1 indicates the lowest amount of noise reduction while S5 refers to the highest one [11, 12, 26–28]. The FBP algorithm was used with medium and strong sharp kernel (B30 and B70, respectively); the Safire[®] algorithm was used with the kernel that has the same sharpness than FBP algorithm (I30 and I70). Different S of iteration were performed: S3, S4 and S5 for both LD-CT and ULD-CT. The same parenchymal (–600/1600 Hounsfield Unit [HU]) and mediastinal windowing (450/50 HU) were used for both FBP and Safire[®] reconstruction modes.

Evaluation of the delivered doses

The delivered doses were directly retrieved from the review report available in the picture archiving and communication system (PACS). They corresponded to volume CT dose index (CTDI_{vol}) and dose-length product (DLP). These were recorded for each acquisition. The effective dose (ED) was estimated by multiplying the DLP by a chest-specific conversion coefficient (0.014 mSv × mGy⁻¹ × cm⁻¹) [40].

The ED of the CT acquisitions were compared to a double projection chest X-ray referring to the French diagnostic reference level (DRL) [41]. The dose area product (DAP) corresponds to 250 mGy.cm² and 1000 mGy.cm² for the postero-anterior and lateral projection respectively. The ED was estimated by multiplying the DAP by a chest-specific conversion coefficient (0.00018 mSv × mGy⁻¹ × cm⁻²) and corresponds to 0.225 mSv.

Objective image quality

The signal (mean CT number, HU) and noise (standard deviation, σ) of the images were assessed quantitatively within a region of interest (ROI) of 1 cm² ± 0.03 (SD) or 133 pixels (voxel size: 0.98 × 0.98 × 1 mm³). These ROIs were placed at the level of anterior, middle and posterior pulmonary parenchyma on each side, the axillary fat, the pectoralis major muscle and the body of a thoracic vertebra as depicted in Fig. 1. The data were measured for all cadavers in all image datasets, for every type of reconstruction (four reconstructions, three acquisition modes) and for each analyzed structure (nine ROIs). A total of 2268 measurements were performed.

The signal-to-noise ratio (SNR) and contrast-to-noise ratio (CNR) were calculated using the following formulas [42].

$$SNR = \left| \frac{HU_{ROI}}{\sigma_{ROI}} \right| \quad (1)$$

and

$$CNR = \frac{|HU_{ROI} - HU_{Axillary-fat}|}{\sqrt{\frac{\sigma_{ROI}^2 + \sigma_{Axillary-fat}^2}{2}}} \quad (2)$$

In the formula (1) and formula (2), σ corresponds to standard deviation of image noise in the ROI. In the formula (2), the CNRs were obtained by considering the axillary fat as a reference. The SNR and CNR of the pulmonary parenchyma corresponded to the average SNR and CNR measured on the level of ROI of the parenchyma on each side.

Subjective image quality

Two blinded radiologists (F.M. [Reader 1] and E.K. [Reader 2] with 9 and 5 years of experience, respectively) evaluated the quantitative parameters and image quality of the anatomical structures on Syngovia[®] workstations (Siemens Healthcare). The anatomical structures evaluated in the mediastinal window were fat, muscle, vessels, trachea and nodes, whereas in the lung window bronchi, bronchioles, fissures, ribs/sternum and vertebrae. Reader 1 had a 3-year experience in LD/ULD images, whereas Reader 2 had a specific learning program in LD/ULD images of post-mortem CT for this study. These different degrees of expertise were used to assess interobserver agreement in reading LD/ULD images. The images were assessed at 1 mm slice thickness in the transverse plane and with fixed windowing (lung images at window width of 1600 HU and window center of –600 HU and mediastinal images at window width of 450 HU and window center of 50 HU). Before the study, the two radiologists read in consensus three cases in order to define the analysis method.

A five-point Likert scale was used to subjectively evaluate images quality of anatomical structures: one point: anatomical structures visible at 100% (excellent), two points: anatomical structures visible at >75% (good), three points: anatomical structures visible between 25% and 75% (fair), four points: anatomical structures visible < 25% (poor), five points: landmarks were not visible at all (unacceptable) [34].

Finally, the two radiologists were asked to give a confidence level representative of the capability to recognize a given anatomical structure according a 2-point scale: one point for 50% of subjective certainty and two points for 95% of subjective certainty.

Quantitative analysis

Six quantitative measurements were used for each acquisition and reconstruction or 756 steps in total for the whole subject population. Fig. 2 shows the different zones where the measurements were obtained on mediastinal images in the transverse plane at the level of:

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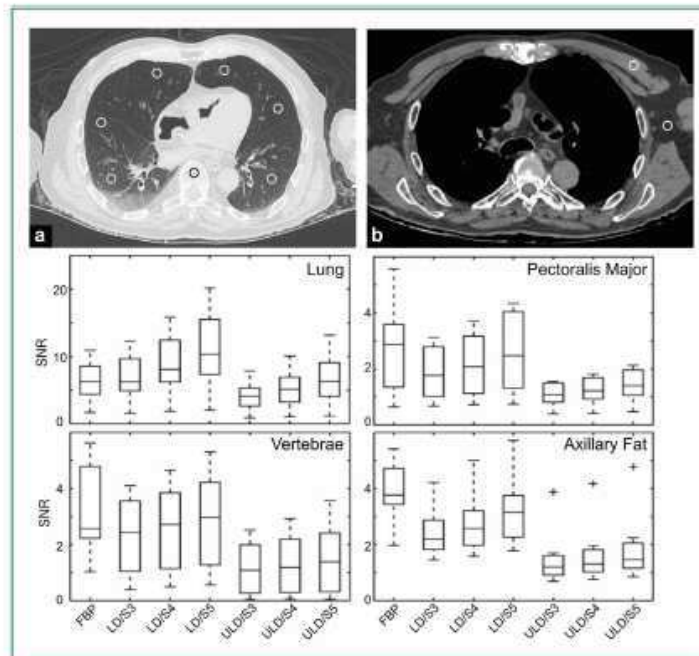


Figure 1. a: lung; b: mediastinal CT images in the transverse plane show placement of the region of interest for objective quality assessment. Box plots show the signal-to-noise ratio for lung parenchyma and vertebra on lung images and for pectoralis major muscle and axillary fat on mediastinal images.

- the maximal thickness of the pectoralis major muscle;
- the maximal diameter of the descending thoracic aorta;
- the anteroposterior diameter of the thoracic spinal canal;
- the maximal anteroposterior diameter of the trachea;
- the maximal anteroposterior diameter of upper lobar pulmonary artery.

The maximal horizontal cardiac diameter and the maximal horizontal thoracic diameter were measured on transverse images to calculate the cardiothoracic index (CTI) according to the following formula.

$$CTI = \frac{Diameter_{Heart}}{Diameter_{Thorax}} \quad (3)$$

Statistical analysis

Statistical analysis was performed using "Biostatgv" (<http://marne.u707.jussieu.fr/biostatgv>). The comparison for image quality index (IQI) and quantitative parameters between the reference acquisition and other acquisitions were obtained using the Wilcoxon rank sum test. After adjustments made for multiple comparisons, a P -value < 0.01 was considered significant. The Cohen kappa test was used to assess inter-observer agreement for each anatomical structures studied. Inter-protocol comparison between reference protocol and others acquisitions

were made with Friedman test with significance set at $P < 0.01$.

Results

Subjects

A total of 29 cadavers with a maximum PMI of 48 hours underwent post-mortem CT during the study period. The three cases read by consensus and eight deteriorated cadavers (four charred, two extremely deformed, one mangled and one with gunshot wounds at the chest) were excluded. Overall, 18 cadavers were included in the study.

Dosimetry

The scout view generated a steady dose for each cadaver of 1.5 mGy.cm that was equivalent to an ED of 0.021 mSv. The scout view dose was summed to that of each protocol.

CTDIvol of the reference CT protocol scan was 13.42 mGy compared to 2.69 mGy of LD-CT (-80% ; $P < 0.01$) and 0.67 mGy of ULD-CT (-95% ; $P < 0.01$). The EDs were 5.3 mSv, 1.1 mSv and 0.27 mSv, for RP-CT, LD-CT and ULD-CT, respectively.

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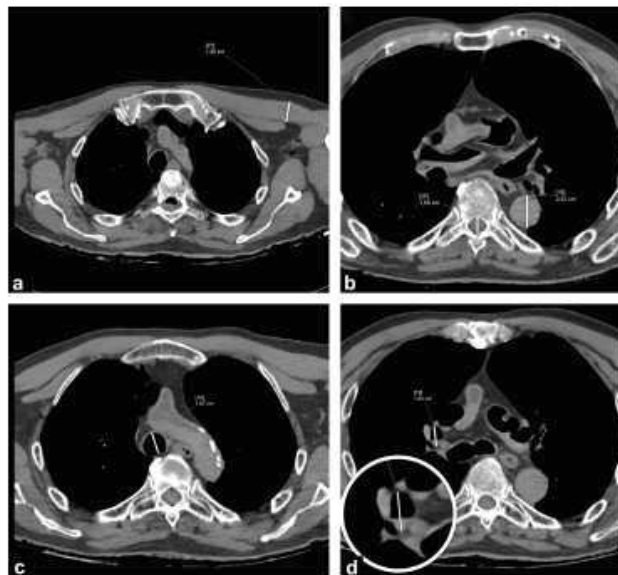


Figure 2. White grass line illustrates the quantitative measurements performed on mediastinal CT images in the transverse plane. a: the maximal thickness of the pectoralis major muscle; b: the maximal diameter of the descending thoracic aorta and the anteroposterior diameter of the thoracic spinal canal; c: the maximal anteroposterior diameter of the trachea; d: the maximal anteroposterior diameter of the right upper lobar pulmonary artery. Note that the dependent side of the lumen is filled with blood (zoom).

Objective image quality

Exposure dose reduction due to a decrease in mAs resulted in a significant increase of image noise for all type of reconstruction (Table 1A). Pulmonary parenchyma noise increased by 63% from LD-CT to ULD-CT at S3 iteration level. This increase of noise resulted in a decrease of SNR and CNR, leading to the deterioration of image quality. Safire[®] reduced noise when iteration levels increased, improving in SNR and CNR (Fig. 1, Table 1B). Indeed, for the pulmonary parenchyma LD-CT, the transition from S3 to S4 resulted in a noise reduction of 20% and SNR and CNR improvement of 26% and 24% respectively.

The analysis of IQI (noise, SNR and CNR), using LD-CT/S3 and ULD-CT/S5, showed similar values (Wilcoxon test) as compared to reference CT protocol. Therefore, the comparative analysis of the other parameters focused on these two acquisitions and reconstruction protocols.

Subjective image quality

Both radiologists rated an excellent image quality for the reference CT protocol and excellent/good for LD-CT/S3, whereas radiologists rated from fair to good image quality for ULD-CT/S5 independently of the windowing (Figs. 3 and 4). Independently of the anatomical structures, the differences between the reference CT protocol and ULD-CT/S5 were significant ($P < 0.01$). The mean confidence level for mediastinal and parenchymal windowing was 95% for all

the protocols. On average, the inter-observer agreement was excellent for both reference CT protocol ($\kappa = 1.00$) and LD-CT protocol ($\kappa = 0.88$) and good for ULD-CT protocol ($\kappa = 0.69$) (Figs. 3 and 4). The confidence level was 95% of subjective certitude for recognizing the anatomical structures for both radiologists.

Quantitative analysis

No significant differences in quantitative analysis were found between LD-CT/S3 or ULD-CT/S5 protocols and the reference CT protocol as shown in Table 2. All measurements of diameter or thickness were identical, with no significant differences for all three protocols.

Discussion

The results of our study demonstrate that a chest CT scan can be performed with a dose similar or even lower than that of the national French DRL for a postero-anterior and lateral chest X-ray (≤ 0.225 mSv), with adequate objective IQI and quantitative parameters and a good anatomical subjective image quality. Safire[®] can reduce the increased image noise due to a decrease in mAs in both LD-CT and ULD-CT protocols, in particular for pulmonary parenchyma. A significant reduction up to 95% (RP-CT vs. ULD-CT) of individual exposure was obtained for chest CT in human cadavers without inducing distortion of the measurements in the images such as diameters of solid or gas structures

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Table 1 Image noise, contrast-to-noise ratio and radiation dose according to decrease in mAs and strengths of iteration.

		RP-CT (13.4 mGy)		LD-CT (2.7 mGy)			ULD-CT (0.7 mGy)				
		FBP		FBP	S3	S4	S5	FBP	S3	S4	S5
		Image noise	Pulmonary parenchyma	116.7	224.0 ^a	119.7	95.7	80.1	326.0 ^a	194.7	159.2
	Thoracic vertebrae	32.6	59.5 ^a	42.3	38.6	35.1	94.9 ^a	78.0	72.5	65.8	
	Pectoralis major	18.0	37.2 ^a	25.8	22.6	19.1	66.7 ^a	47.0	41.4	35.8	
	Axillary fat	21.3	49.2 ^a	34.4	30.8	26.8	85.7 ^a	63.6	57.5	51.4	
Contrast-to-noise ratio	Pulmonary parenchyma	7.2	3.2 ^a	7.1	8.8	10.7	2.2 ^a	4.0	4.8	5.9	
	Thoracic vertebrae	6.2	3.9 ^a	4.8	5.2	5.6	1.9 ^a	2.4	2.6	2.9	
	Pectoralis major	5.7	3.1 ^a	4.7	5.1	5.6	2.1 ^a	3.1	3.4	3.9	

FBP indicates filtered back projection; S3-S4-S5 indicate strengths of Safire[®]; RP-CT indicates reference CT protocol (120 kVp/200 mAs); LD-CT indicates low dose CT (120 kVp/40 mAs); ULD-CT indicates ultra-low dose CT (120 kVp/10 mAs).
^a Differences were searched for by comparison with the reference CT protocol ($P < 0.01$).

[43]. RP-CT (ED: 5.3 mSv) and LD-CT (ED: 1.1 mSv) aimed to obtain an effective dose similar to those previously published and used for large cohort studies (ED: 7 mSv and ED: 1.5 mSv for RP-CT and LD-CT, respectively)

[33,44]. The use of high S of Safire[®] in LD-CT/S3 and ULD-CT/S5 protocols result in images with IQI (image noise, SNR, CNR) close to reference CT protocol in the same cadaver.

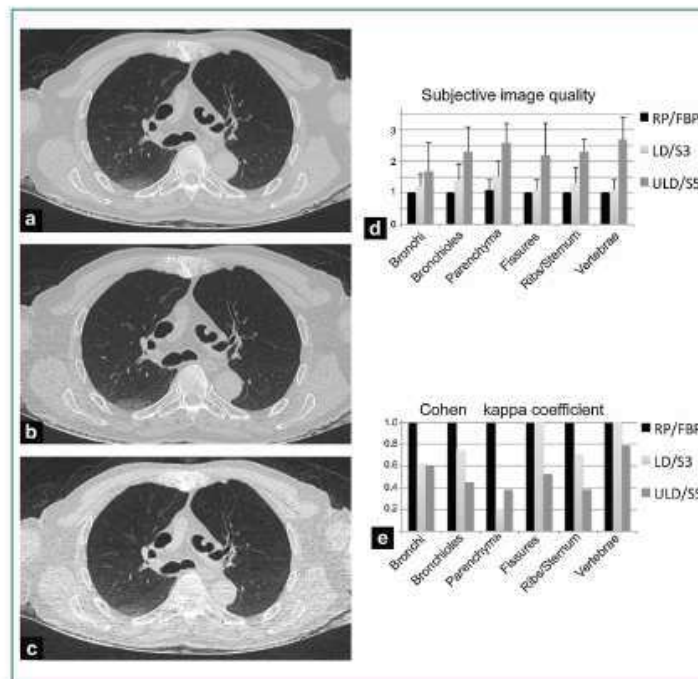


Figure 3. Subjective image quality of lung images at the level of tracheal bifurcation in axial sections. a: RP/FBP, reference CT protocol reconstructed with filtered back projection; b: LD/S3, low dose CT reconstructed with Safire[®] strength 3.; c: ULD/S5, ultra-low dose CT reconstructed with Safire[®] strength 5; d: column bars of subjective quality represent the mean score of the 5-point Likert scale (1: excellent; 2: good; 3: fair; 4: poor; 5: unacceptable) of both radiologists for each anatomical structure; e: column bars of Kappa values for inter-observer agreements of subjective quality for the assessed anatomical structures (Kappa values = 0.01–0.20 [poor]; 0.21–0.40 [fair]; 0.41–0.60 [moderate]; 0.61–0.80 [good]; > 0.81 [excellent]).

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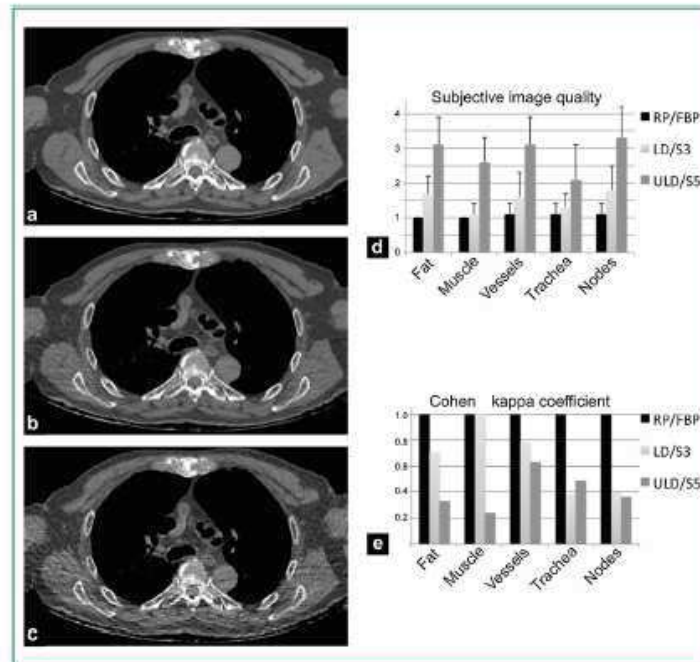


Figure 4. Subjective image quality of mediastinal images at the level of tracheal bifurcation in the transverse plane. a: RP/FBP, reference protocol CT reconstructed with filtered back projection; b: LD/S3, low dose CT reconstructed with Safire[®] strength 3; c: ULD/S5, ultra-low dose CT reconstructed with Safire[®] strength 5; d: column bars of subjective quality represent the mean score of the 5-point Likert scale (1: excellent; 2: good; 3: fair; 4: poor; 5: unacceptable) of both radiologists for each anatomical structure; e: column bars of Kappa values of inter-observer agreements of subjective quality for the assessed anatomical structures (Kappa values = 0.01–0.20 [poor]; 0.21–0.40 [fair]; 0.41–0.60 [moderate]; 0.61–0.80 [good]; > 0.81 [excellent] [e]).

In clinical practice, it is challenging to tailor the dose to the patient's body in order to decrease the radiation dose. To achieve this goal, a compromise should be found between radiation reduction and acceptable image quality

for clinical interpretation. Therefore, in order to suit patient and medical needs, knowledge of acquisition and reconstruction settings of CT scan as well patient body mass index is thus critical. Prior to develop acquisition protocols

Table 2 Quantitative parameters of anatomical structures of 18 human cadavers for the three different chest CT protocols.

	RP-CT/FBP ^a	LD-CT/S3 ^a	ULD-CT/S5 ^a
CTI	0.53	0.54	0.54
Upper pulmonary artery (mm)	15.26	15.14	15.98
Trachea (mm)	20.73	20.66	20.93
Thoracic descending aorta (mm)	27.25	26.88	26.14
Spinal canal (mm)	15.90	15.49	15.94
Pectoralis major (mm)	11.04	10.78	10.79

CTI indicates cardiothoracic index (i.e., the ratio between the largest horizontal diameter of the heart and the greatest transverse thoracic diameter). Other values are expressed in mm. FBP indicates filtered back projection; S3 and S5 indicate strengths of Safire[®]; RP-CT/FBP indicates reference CT protocol (120 kVp/200mAs) reconstructed with filtered back projection; LD-CT/S3 indicates low dose protocol (120 kVp/40 mAs) reconstructed with Safire[®] strength 3; ULD-CT/S5 indicates ultra-low dose protocol (120 kVp/10 mAs) reconstructed with Safire[®] strength 5.

No significant differences were found between the three groups.

^a Data are expressed as medians.

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with a reduced dose, some researchers have evaluated image quality on phantoms [28]. Experimental results were crucial to understand the different effects of acquisition and reconstruction parameters on the dose and image quality. However, the results obtained using the phantoms are often different from those of the human body. Importantly, in our study, CT images were performed on recently deceased subjects (PMI < 48 h) with basically the same body density than living subjects, which allows a more reliable comparison of the results and an easier generalizability of the protocols. The diagnostic quality was not investigated because of the different semiology between living and deceased subjects [45]. Several scientific publications have shown the effect of Safire® in compensation of image quality degradation caused by reduction of exposure with the voltage or tube current [17,19,20,23–28]. Safire® helps maintain satisfactory values of SNR or CNR by decreasing the noise due to dose reduction. This study demonstrated that, even with massive dose reduction for chest CT scan (ULD-CT), Safire® can improve the IQI such as image noise, SNR and CNR and allows obtaining values similar to those obtained with the reference CT protocol. The objective image quality is improved, independently of the strength of Safire® used, compared to filtered back projection for images obtained with the same dose.

In our study, regarding quantitative parameters, all measurements of length were similar between the reference acquisition and LD-CT or ULD-CT protocols. In addition, no misinterpretation of the contours of anatomical structures were observed [43].

With regard to the ULD-CT, although the objective image quality and the quantitative analysis are not significantly modified by the considerable dose reduction, the subjective image quality of the anatomical structures is decreased from excellent to fair but never to poor or unacceptable. Indeed, ULD-CT images were moderately grainy from a visual standpoint although Safire® objectively improved the IQI. The degradation of the subjective quality was more evident for mediastinal images. The inter-observer agreement values were not excellent for all assessed structures on ULD-CT and for some of LD-CT (trachea, nodes, lung parenchyma). Reader 1 frequently scored ULD images "excellent", whereas Reader 2 scored them "good/fair". This slightly mismatching classification induced lower degrees of agreement between the two readers. This presumably resulted from the difference in experiences between the two readers in LD/ULD images. Reader 2 was less experienced with grainy LD/ULD images and was more demanding for subjective quality of anatomical structures than Reader 1. Moreover, the know effect of *smoothing* of the image along with the modification of the image texture characteristic of IR may have initially disturbed Reader 2. Notwithstanding these differences, Reader 2 was able to recognize easily each anatomic structure as showed by the high level of confidence. Therefore, these results suggest that a radiologist new to LD/ULD images reconstructed with IR has a learning curve to get accustomed to this type of imaging.

It is noteworthy that ULD-CT/55 showed lower ED than other recent ULD-CT protocols performed with dual source CT systems on living subjects or on cadaveric lungs [35,36,46,47] with the only exception of the ULD-CT protocol proposed by Neroladaki et al. [34]. Neroladaki et al.

developed the ULD-CT protocol with a dual source CT as well and with 100 kVp/ 10 mAs on living patients [34]. ULD-CT protocol of our study was performed with 120 kVp/ 10 mAs to decrease beam-hardening artifacts because of the non-conventional position of the cadavers (upper limbs along the thorax). Nevertheless, the analysis of the impact of kVp reduction was not a goal of our study.

Our study has some limitations that should be mentioned. First, the small number of subjects could be questioned and therefore, the scarce number of anatomical structures available for the study. Second, the body mass index of cadavers was not calculated so that the CT protocols were not adjusted for this parameter. Postmortem CT is performed before autopsy and the weight and height of the cadavers in the first hours after death are not available. Third, acquisitions were not performed on lungs during the inspiratory apnea because in our centre, we do not inflate cadavers mechanically for virtual autopsy. Therefore, lung structures were evaluated at a different state from the one of living individuals during a chest CT examination. Fourth, beam-hardening artifacts were often present due to the upper limbs along the torso. Fifth, these acquisitions were not performed with automatic exposure control. This system normally would be used for the LDCT but not for the ULDCT, because we aimed to achieve 10 mAs per slice to be sure to obtain an ED ≤ 0.225 mSv. Lastly, motion artifacts of the subject and artifacts related to respiratory or cardiac activity, usually seen in clinical practice, were obviously absent, hence not evaluable.

In conclusion, our study confirms the already known effectiveness of the LD-CT protocol and suggests the good trade-off of the ULD-CT protocol of the chest with high S of Safire® for both anatomical image quality and dose reduction. This chest ULD-CT protocol, delivering a dose close to the national French diagnostic reference level for a chest X-ray examination, should now be tested in living subjects to investigate its diagnostic confidence level, especially for indications where chest X-ray represents the first line examination.

Disclosure of interest

The authors declare that they have no competing interest.

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3^{ème} PHASE. Comparaison de l'efficacité diagnostique du protocole ULD-CT in-vivo.

Cette phase s'est caractérisée par deux études après accords de la CNIL et de l'IRB :

- **(ULD-CT versus LD-CT)** étude visant à montrer l'équivalence du protocole ULD-CT par rapport à notre TDM thoracique institutionnelle, qui correspond à un LD-CT, dans les cas de patients dyspnéiques non traumatiques. L'objectif secondaire était d'évaluer la confiance diagnostique d'un radiologue peu expérimenté avec les images en ULD-CT.
- **(ULD-CT versus RX)** étude visant à évaluer la performance du protocole ULD-CT par rapport à la radiographie conventionnelle, dans le cas du traumatisme thoracique fermé mineur. L'objectif secondaire était d'évaluer la confiance diagnostique d'un radiologue peu expérimenté et de radiologues complètement inexpérimentés avec les images en ULD-CT.

ETUDE ULD-CT versus LD-CT

Le but de ce travail était d'évaluer la performance diagnostique du protocole ULD-CT, délivrant une dose inférieure à celle de DRL de radiographies thoraciques de face et de profil, en urgence chez des patients dyspnéiques. De plus la différence de performance diagnostique entre un radiologue aguerri et un radiologue formé pour cette étude à l'imagerie en ULD à été analysée.

Un total de 133 patients dyspnéiques, suspects de pneumopathies infectieuses, exacerbation de pneumopathies obstructives et restrictives, pneumothorax non traumatiques, épanchements pleuraux et péricardiques ont été examinés. Le protocole LD-CT était réalisé avec 100 kVp et 60 mAs de référence avec TCM activé et 100kVp/10 mAs pour l'ULD-CT. Les images étaient reconstruites uniquement avec SAFIRE S2 et S3 respectivement pour le médiastin et le poumon, tandis que pour ULD-CT c'était avec S4 et S3 respectivement pour le médiastin et le poumon. La qualité objective des structures anatomiques a été évaluée en relevant le signal, l'SNR et le CNR par des ROIs positionnées au niveau de la graisse

axillaire, du muscle souscapulaire, de la trachée, d'une vertèbre et des trois niveaux du parenchyme pulmonaire.

La qualité subjective anatomique et pathologique a été évaluée par deux radiologues indépendants par le biais d'une échelle à 5 points de Likert (1 excellent → 5 inacceptable) et qui ont également pris en compte les lésions pouvant justifier leur dyspnée. De même ils ont listé les plus petits nodules pulmonaires visibles. A souligner qu'un des radiologues travaillait déjà avec des images à dose abaissée depuis trois ans, alors que l'autre avait été formé uniquement pour l'étude. Enfin les radiologues ont exprimé un niveau de confiance diagnostique comme « certain » ou « incertain ». Les doses délivrées ont été recueillies.

SAFIRE a démontré une importante amélioration des IQI pour les images du parenchyme pulmonaire d' ULD-CT par rapport LD-CT, tandis que cet effet n'a pas été observé pour les images en fenêtre médiastinale. Pour la qualité subjective les deux radiologues ont présenté une mauvaise concordance inter observateur pour l'ULD-CT, car le radiologue moins expérimenté a été plus critique mais enfin a démontré un niveau de confiance étant certain pour la totalité de 133 dossiers comme le lecteur expérimenté. Les E moyennes étaient de 1.164 mSv pour le LD-CT et de 0.182 mSv pour l'ULD-CT.

Avec cette étude on a démontré qu'un ULD-CT non injecté délivre une dose inférieure aux DRL des clichés du thorax (0.225 mSv) et qui maintient une performance diagnostique équivalente à celle d'un LD-CT, également pour des lecteurs non habitués à ce type d'imagerie à dose faible.



Value of ultra-low-dose chest CT with iterative reconstruction for selected emergency room patients with acute dyspnea



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ABSTRACT

Objective: To compare the diagnostic confidence between low-dose computed-tomography (LDCT) and ultra-low-dose CT (ULDCT) of the chest on a single source CT system (SSCT) for patients with acute dyspnoea.

Materials and methods: One hundred thirty-three consecutive dyspnoic patients referred from the emergency room (ER) were selected to undergo two sequential non-enhanced chest CT acquisitions: LDCT first acquisition (100 kVp and 60 mAs), followed by ULDCT (100 kVp ± 20 and 10 mAs). Images were reconstructed with sinogram affirmed reconstruction (SAFIRE). Objective and subjective image quality assessments were made. Two radiologists evaluated subjective image quality and the level of diagnostic confidence as certain or uncertain.

Results: The mean effective doses (ED) were 1.164 ± 0.403 and 0.182 ± 0.028 mSv for LDCT and ULDCT, respectively. Objective image quality improved significantly on lung images of ULDCT compared with LDCT ($p < 0.05$). Subjective image quality was rated excellent/good in 90% of patients with BMI > 25 kg/m² for ULDCT. The level of diagnostic confidence was "certain" in all cases for both radiologists with excellent inter-observer agreement ($k = 1$).

Conclusion: Chest ULDCT with SAFIRE on a SSCT allows a high level diagnostic confidence for the evaluation of selected acute dyspnoic patients.

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1. Introduction

Although chest X-ray (CXR) is the most commonly used diagnostic tool in Emergency Room (ER), Computed Tomography (CT) is becoming increasingly determinant for patient's care, but with the drawback of non-negligible radiation doses [1,2]. The risk to develop radiation-induced cancer increases especially in patients of young age with a long life expectancy [3–5]. In addition, the

chest is the most radiation sensitive region compared to the other parts of the body [6,7], therefore an inappropriate irradiation of this anatomic region raises concerns.

To reduce the radiation-induced cancer risk, the European Atomic Energy Community (EURATOM) issued a directive that required the European Community member States to optimise the dose for ionizing imaging while maintaining a diagnostic quality of Image [8]. Based on this directive, the French government established the Diagnostic Reference Levels (DRLs) for chest CT imaging [9]. Such DRLs limit the dose length product (DLP) to 475 mGy cm, which is equivalent to the effective dose (ED) of 6.65 mSv (conversion factor: 0.014 mSv mGy⁻¹ cm⁻¹) [10].

Several tools were suggested to reduce the dose in CT but often resulted in a degradation of the image quality with difficulties for diagnosis [11–13].

The iterative reconstruction (IR) is a method that improves the quality of the image decreasing the image noise in comparison to filtered back projection (FBP) for a protocol with the same dose [14]. Moreover, IR permits to maintain a good image quality while

Abbreviations: BMI, Body Mass Index; CNR, contrast-to-noise ratio; CT, Computed Tomography; DLP, dose length product; DRLs, Diagnostic Reference Levels; DSCT, dual source computed tomography; ED, effective dose; ER, Emergency Room; LDCT, low dose computed tomography; ROI, region of interest; SAFIRE, Sinogram Affirmed Iterative Reconstruction; SNR, signal-to-noise ratio; SSCT, single source computed tomography; ULDCT, ultra low dose computed tomography.

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reducing the dose [15]. Sinogram Affirmed Iterative Reconstruction (SAFIRE; Siemens) is one of IR methods whose applications are widely used for clinical purposes [16,17].

Since SAFIRE is available at our institution, a routine low-dose chest CT (LDCT) protocol was established with effective dose (ED) lower than 1.5 mSv [18].

Previous studies demonstrated that ultra-low-dose chest CT (ULDCT) imaging associated with IR can provide satisfactory outcomes in clinical practice. These studies compared chest ULDCCT with IR and LDCT or standard dose protocols reconstructed either with IR or with FBP [19–22]. Such comparisons were performed using a dual-source CT system (DSCT), but no evidences of clinical application have already been published using a single-source CT system (SSCT).

With the present study we aimed to evaluate the image quality and the level of diagnostic confidence of a ULDCCT protocol, delivering a dose similar to that of a double projection CXR, in comparison with an LDCT protocol for the study of the chest in selected acute dyspnoeic patients coming from ER.

2. Materials and methods

2.1. Patients

This prospective monocentric study was approved by the Institutional Review Board. Patients were duly informed and they signed an informed consent before examinations. The study was carried out from October 1st to December 31st 2015 and the CT indication was the assessment of acute dyspnoeic patients, whom have had preliminarily a CXR and for whom a non-enhanced chest CT was requested as additional study. Specifically, as causes of acute dyspnoea were considered infectious pneumonia, non-traumatic pneumothorax and the exacerbation of known chronic obstructive pulmonary diseases (COPD) or idiopathic interstitial pneumonia (IIP). Dyspnoeic patients with suspected cardio-vascular disease (e.g. myocardial infarct, pulmonary embolism, aortic dissection), cancer, sustained a trauma or any other indications deserving an enhanced chest CT were not considered for this study.

3. CT examination

3.1. Image acquisition

Chest CT images were obtained on a 64 slices SSCT (Somatom, Definition AS+, Siemens, Erlangen, Germany) with z-flying focal spot for simultaneous acquisition with 128 overlapping and 0.6-mm thick sections with both measurement systems.

Patients lied in supine position during a non-enhanced two consecutive acquisitions CT protocol. The first acquisition was the routinely used institutional chest LDCT and the second the ULDCCT study acquisition, which was performed immediately after.

Overall, both acquisitions were conceived to do not exceed the National DRLs for chest CT for standard patient care. LDCT dataset was obtained with 0.33 s rotation time, tube voltage of 100 kVp (with activated Care kV), tube current of 60 mAs reference (with activated CareDose 4D), collimation of 128 × 0.6 mm (slice thickness 1 mm) and pitch 1.2. Subsequently, ULDCCT dataset was obtained with 0.33 s rotation time with, tube voltage of 100 kVp (no activated Care kV: 120 kVp for BMI > 25 kg/m²), tube current of 10 mAs reference (without CareDose 4D), collimation of 128 × 0.6 mm (slice thickness 1 mm) and pitch 1.5.

3.2. Image reconstruction

LDCT protocol consisted of 1-mm thick overlapped 0.7 mm images reconstructed with raw data-based iterative reconstruction (SAFIRE), as implemented on the CT scanner with a high-spatial-resolution reconstruction kernel (I70, lung images) and a soft-tissue reconstruction kernel (I30, mediastinal images). SAFIRE strength was set at 3 and 2 for lung and mediastinal images, respectively.

ULDCT protocol consisted of 1-mm-thick overlapped 0.7 mm images reconstructed with SAFIRE. ULDCCT images were reconstructed by using a high-spatial-resolution reconstruction kernel (I50, lung images) and a soft-tissue-resolution reconstruction kernel (I30, mediastinal images). SAFIRE strength was set at 4 and 3 for lung and mediastinal images, respectively.

4. Images analysis

4.1. Objective image quality

Objective assessments were obtained by measuring the mean (signal) and the standard deviation (noise) of pixel values in six regions of interest (ROI [cm²]) on mediastinal (I30) images at three anatomic levels: axillary fat (0.51 ± 0.01 cm²), in subscapular muscle (0.71 ± 0.01 cm²) and into the trachea (0.71 ± 0.01 cm²); on lung (I50 or I70) images, at three anatomic levels, in the pulmonary parenchyma (1.01 ± 0.01 cm²), in a vertebral body (0.71 ± 0.01 cm²) and into the trachea (0.71 ± 0.01 cm²). Altogether, these ROIs covered the greatest part of the chest structures.

The signal-to-noise ratio (SNR) and contrast-to-noise ratio (CNR) were calculated according the method previously described by Mieville et al. [14]. The signal and the noise measured within the ROI of trachea, both in the mediastinal and in lung images, were used as reference to calculate the CNR.

4.2. Subjective image quality

Two radiologists (F.M. [R1] and A.C.R. [R2] with nine and six years of experience, respectively) read the images on clinical workstations with Centricity PACS viewer system (General Electric, Healthcare, Wisconsin, USA). R1 had a three-year experience with ULDCCT images, whereas R2 was trained to interpret ULDCCT images only for this study. This different expertise was voluntarily sought in order to evaluate whether any interpretation difference subsisted between an experienced radiologist in ULDCCT images and a radiologist less experienced.

Radiologists viewed LDCT and ULDCCT anonymised images by using standard mediastinal (window width, 450 HU; window centre, 50 HU) and lung parenchymal (window width, 1600 HU; window centre, –600 HU) window settings.

For each patient, the clinical data and the reason of the examination were not available. Radiologists interpreted by consensus ten cases randomly chosen, which were excluded from the study. The remaining cases were read independently.

LDCT and ULDCCT images were presented in a random fashion to the readers. The image quality of anatomical structures was rated according to the five-point scale proposed by Neroladaki as follows [19]: 1 point: anatomical structures visible at 100% (excellent), 2 points: anatomical structures visible at > 75% (good), 3 points: anatomical structures visible between 25% and 75% (fair), 4 points: anatomical structures visible < 25% (poor), 5 points: landmarks were not visible at all (unacceptable).

The image quality of diagnostic findings was rated according to an other five-point Likert scale proposed by Neroladaki scale [19]: 1 point: abnormal structures clearly visible with good demarcation (Excellent), 2 points: structures visible with blurring but without

restriction for diagnosis (Good), 3 points: abnormal structures visible, with blurring and uncertainties about the evaluation (Poor), 4 points: abnormal structures barely visible with unreliable interpretation (Unacceptable), 5 points: abnormal structures not seen (Not seen).

Finally, radiologists expressed a subjective degree of diagnostic confidence as certain and uncertain.

Pathologic findings were considered as follows: infectious pneumonia and non-traumatic pneumothorax were included in *Acute A group*; exacerbation of COPD or IIP were included in *Acute B group*; coexistence of pathologies belonging to the two previous groups was classified in the *Both group*. Pleural and pericardial effusions and adenopathies were also counted independently of the clinical context. The small diameter of the smallest solid and ground glass nodules was also measured to assess the smallest nodule size visible. Moreover the size of the same nodule, independently of the conspicuity, was compared between the two CT protocols.

5. Dose evaluation

The radiation dose differences between the two CT protocols were evaluated with the volume of CT dose index (CTDIvol) and the Dose Length Product (DLP).

E was calculated for each CT examination by multiplying the DLP by the normalised effective dose conversion coefficient for the chest ($0.014 \text{ mSv mGy}^{-1} \text{ cm}^{-1}$) [10].

5.1. Statistical analysis

Statistical analysis was performed using 'Biostatgv' (<http://marne.u707.jussieu.fr/biostatgv/>). The comparisons of the CTDIvol, DLP, ED, Image Noise, SNR and CNR values between the two protocols were performed using the paired Student's t-test with a significance level of 0.05. For the same protocol, the agreement between radiologists were computed with Kappa test and classified as poor ($k=0.00-0.20$), fair ($k=0.21-0.40$), moderate ($k=0.41-0.60$), good ($k=0.61-0.80$), or excellent ($k=0.81-1.00$). For each radiologist, the inter-protocol comparisons of the scores were evaluated using the Friedman test with a significance level of 0.05.

6. Results

6.1. Patients

One hundred thirty-three consecutive ER patients (84 men and 49 women) were included, with mean age of 63 ± 20.5 years old (61.6 ± 19.9 for men and 65.3 ± 21.5 for women). The Body Mass Index (BMI) average was $23.6 \pm 5.1 \text{ kg/m}^2$ (23.9 ± 4.9 for men and 23.1 ± 5.4 for women).

7. Image analysis

7.1. Objective image quality

The results of the objective image quality measured within 1596 ROIs (12 ROIs per patient and six ROIs for each CT protocol) are shown in Table 1. Image noise, SNR and CNR of ULDCCT were significantly different from LDCT ($p < 0.05$).

For mediastinal images, the increase of SAFIRE strength between ULDCCT and LDCT protocols did not compensate the degradation of indexes of image quality. An increase of the noise and a reduction of SNR and CNR were found in all evaluated structures.

For lung images, the adaptation of the reconstruction kernel (from 170 to 150), in addition to the increase of SAFIRE strength

between the two CT protocols, resulted in an improvement of indices of image quality with a reduction of the noise and an increase of SNR and CNR.

7.2. Subjective image quality

The subjective image quality assessment of anatomical structures for the 133 patients of the study is shown in Fig. 1(a). With regard to the LDCT images, both radiologists considered the quality of anatomical structures globally excellent (99% for R1 and 97% for R2). For ULDCCT, R1 scored excellent for 84% of cases, good for 15% and fair the 1% whereas R2 ranked 44%, 50% and 7%, respectively. The inter-observer agreement was fair for LDCT ($k=0.39$) and ULDCCT ($k=0.27$). The inter-protocol comparison was significantly different for both radiologists ($p < 0.05$).

The results of image quality assessment of the diagnostic findings are illustrated in Fig. 1(b). Both radiologists found that the majority of abnormal structures of the LDCT images were clearly visible with a good demarcation and without noise (97% for R1 and 95% for R2).

For ULDCCT images, R1 found that in 88% of the cases the abnormal structures were clearly visible with a good demarcation; 11% were noisy but distinguishable; 1% were with uncertainty for the diagnosis. R2 found 38%, 58%, 4%, respectively. ULDCCT images of patients with a BMI $\leq 25 \text{ kg/m}^2$ had excellent or good diagnostic image quality in 90% of cases whereas the images of patients with a BMI $> 25 \text{ kg/m}^2$ were rated excellent or good in 76% of cases.

The inter-observer agreement was good ($k=0.79$) for LDCT images and bad ($k=0.17$) for ULDCCT images and the inter-protocol comparisons for each radiologist were significant ($p < 0.05$).

The diagnostic confidence level was certain for all cases for both radiologists with an excellent inter-observer agreement both for LDCT and ULDCCT protocols. The inter-protocol comparison for each radiologist did not differ significantly.

For 107 patients at least one pathologic finding was observed on the images of both CT protocols as shown in Fig. 2. The inter-protocol comparison was not significant (p : NS) for both radiologists, with the exception of effusion for R1 ($p < 0.05$). Independently of the CT protocols, the inter-observer agreement was excellent for each researched pathologic item.

The mean size of the smallest solid nodules recorded was $3.13 \pm 1.64 \text{ mm}$ for LDCT and of $3.41 \pm 1.75 \text{ mm}$ for ULDCCT with a significant difference between CT protocols ($p < 0.05$). The mean size of the smallest ground glass nodules was of $3.33 \pm 2.63 \text{ mm}$ for LDCT and of $4.85 \pm 4.90 \text{ mm}$ for ULDCCT but no significant difference was found. Of note, a specific nodule that was detected on LDCT images showed a bigger size with a mean of 0.8 mm on ULDCCT images.

CT image quality comparison in different clinical settings is visible in Figs. 3–5. The image quality of a chest, without detectable pathological findings, and of a nodule are shown in Supplementary Figs. S1 and S2 (on the online version at DOI: [10.1016/j.ejrad.2016.06.024](https://doi.org/10.1016/j.ejrad.2016.06.024)) respectively.

8. Dose evaluation

LDCT protocol had tube voltage of $103.7 \pm 7.8 \text{ kVp}$ and a tube current of $58.7 \pm 8.1 \text{ mAs}$. ULDCCT protocol had a tube voltage of $100.5 \pm 3.1 \text{ kVp}$ and tube current of $10.0 \pm 0.0 \text{ mAs}$. CTDIvol was $2.6 \pm 0.9 \text{ mGy}$ for LDCT and was $0.4 \pm 0.0 \text{ mGy}$ for ULDCCT. The DLP was $83.1 \pm 28.8 \text{ mGy cm}$ and the E was $1.164 \pm 0.403 \text{ mSv}$ for LDCT whereas the DLP was $13.0 \pm 2.0 \text{ mGy cm}$ and the E $0.182 \pm 0.028 \text{ mSv}$ for ULDCCT. All of these parameters were significantly different ($p < 0.05$) between the two CT protocols. The ULDCCT presented a reduction of the dose by 97% compared to the French chest

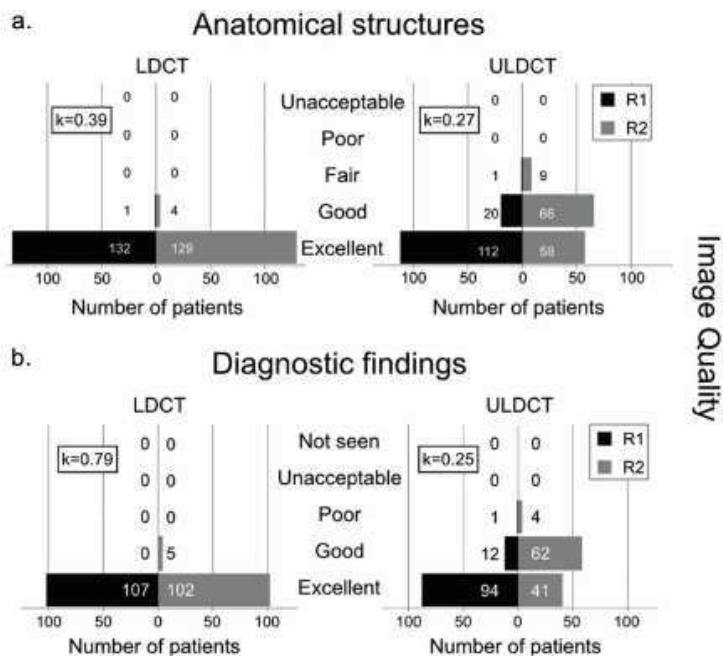


Fig. 1. Subjective image quality. Radiologists (R1 and R2) scored the majority of the cases excellent or good for low-dose CT (LDCT) and ultra-low-dose CT (ULDCCT) images, for both the image quality of anatomical structures for 133 patients (a) and of diagnostic findings for 107 patients (b). K = inter-observer agreement value.

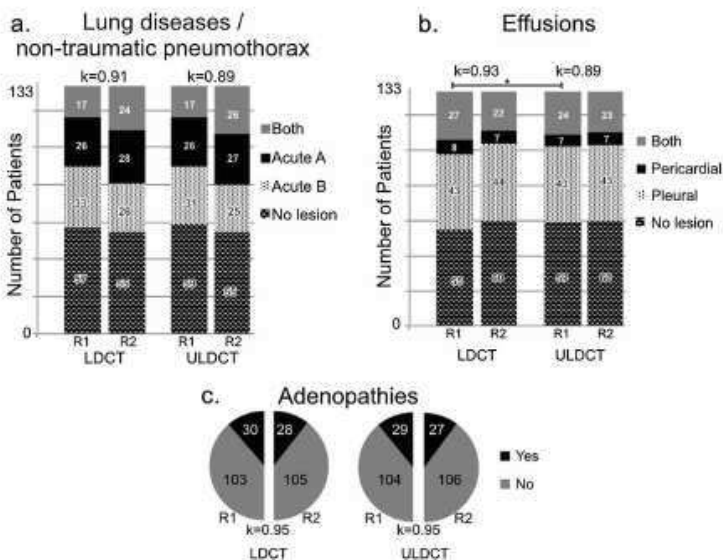


Fig. 2. Pathologic findings resulted from 107 patients on a total of 133. Only one non-traumatic pneumothorax was found from both radiologists (R1 and R2) for the same patient. There was an excellent inter-observer agreement (k) for lung diseases/non-traumatic pneumothorax (a). R1 had a significant inter-protocol difference (p < 0.05) for effusions (b). Radiologists showed an excellent inter-observer agreement for adenopathies, despite the significant inter-protocol differences of objective image quality for mediastinal images (c). LDCT low-dose CT. ULDCCT ultra-low-dose CT.

Table 1
Objective image quality for low-dose CT (LDCT) and ultra-low-dose CT (ULDCT) protocols.

			Low Dose CT	Ultra Low Dose CT	% difference
Mediastinal Images	Image Noise	Trachea	14.7 ± 12.6	23.4 ± 13.5	59%
		Muscle	14.4 ± 4.4	27.5 ± 9.1	91%
		Fat	14.1 ± 3.4	25.5 ± 8.9	81%
	SNR	Trachea	78.5 ± 20.8	48.8 ± 17.3	-38%
		Muscle	3.6 ± 1.6	2.0 ± 0.9	-45%
		Fat	7.4 ± 2.2	4.3 ± 1.4	-42%
	CNR	Muscle	108.5 ± 28.9	63.0 ± 21.7	-42%
		Fat	92.5 ± 21.5	56.0 ± 18.7	-39%
Lung Images	Image Noise	Trachea	40.6 ± 12.7	35.4 ± 16.1	-13%
		Bone	107.1 ± 24.6	96.7 ± 33.5	-10%
		Lung	59.7 ± 16.0	55.1 ± 21.6	-8%
	SNR	Trachea	24.2 ± 5.3	30.2 ± 10.6	25%
		Bone	1.9 ± 1.1	2.2 ± 1.0	16%
		Lung	15.3 ± 4.5	17.7 ± 7.2	15%
	CNR	Bone	20.5 ± 5.4	24.1 ± 7.7	18%
		Lung	2.2 ± 1.1	2.9 ± 1.2	30%

Values of image noise, signal-to-noise ratio (SNR) and contrast-to-noise ratio (CNR) between LDCT and ULDCT protocols were all significant ($p < 0.05$).

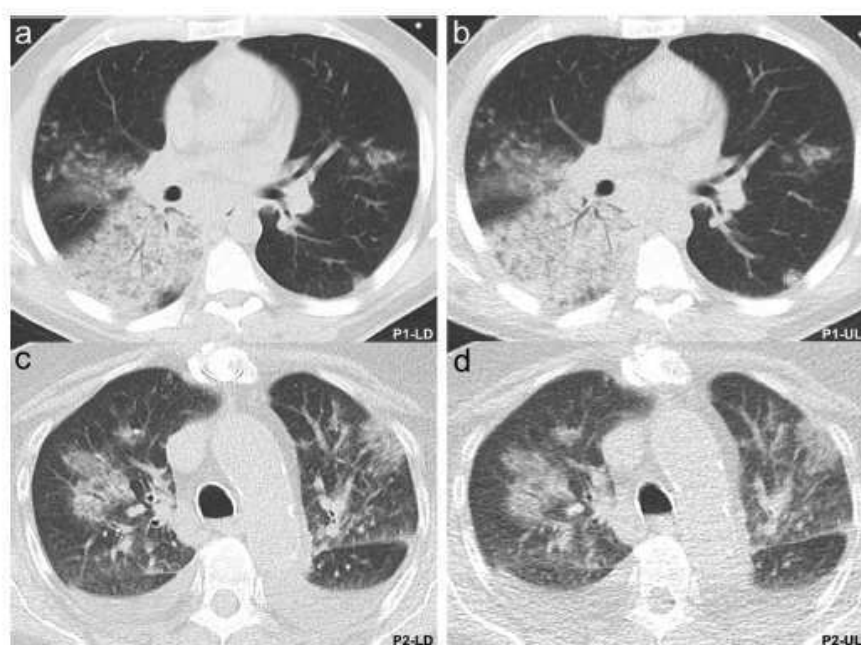


Fig. 3. Pneumonia. Patient 1 (P1), multiple pulmonary consolidations consisting with bronchopneumonia in a man of 48 year-old with a BMI of 23.2 kg/m². Image quality was diagnostic on both LD (a) and ULD (b) images. Patient 2 (P2), bronchopneumonia and pleural effusions in a man of 72 year-old with a BMI of 28.1 kg/m². Even in this case the image quality was diagnostic both on LD (c) and ULD (d) images.

CT DRLs [9]. The mean overall DLP per patient was 96.1 mGy cm with a mean overall ED of 1346 mSv, which were the 79.8% less than DRLs.

9. Discussion

Chest CT is a fast and thorough method to explore the thorax notably in emergency settings. However radiation harm hailing from CT raises concerns and particularly the irradiation of the thorax [6,7]. In ER settings, many chest CT studies follow a CXR or are

repeated in a short time frame increasing the radiation-induced risk of carcinogenesis. Also, this redundant irradiation increases the risks of radiation exposure cumulative effects [23]. Continuous calls to a strict radiation protection policy, particularly in ER, are pronounced. Worrying estimates of radiation-induced cancers in the next years encouraged medical community and manufacturers to develop deontological and technical solutions to decrease useless or redundant exposure [24–26].

The reduction of the dose entails a degradation of the image quality that is well compensated by IR [15]. The association of IR

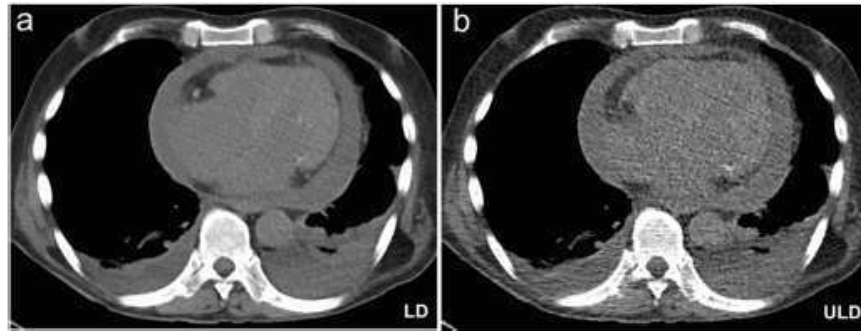


Fig. 4. Effusions. Pleural and pericardial effusions in a man of 63 year-old man with a BMI of 20.0 kg/m² clearly visible on mediastinal LD image (a). The effusions can be easily diagnosed on the ULD image (b), despite the noisier appearance.

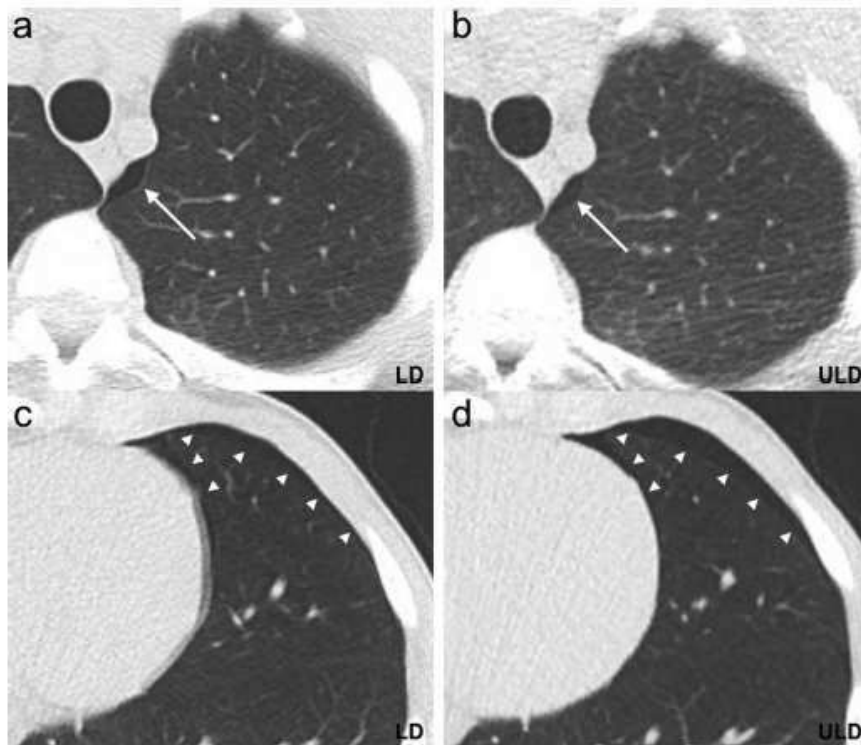


Fig. 5. Non-traumatic pneumothorax. Image quality of a left slight pneumothorax of a man of 39 year-old man with a BMI of 19.8 kg/m². Image quality was diagnostic at apical level (arrow) both on LD (a) and, in particular, on ULD (b) images despite the more prominent streak artifacts of the shoulder. The image quality was also diagnostic at the lingular level (arrow-heads) both on LD (c) and ULD (d) images.

on DSCT obtained a good trade-off between the decrease of radiation dose and diagnostic quality of image. Indeed DSCT and IR may achieve lower doses than conventional radiology studies while keeping a quality of image suitable for diagnostic purposes [27].

So far, the majority of chest ULDCT protocols associated with IR and with a diagnostic quality of image were developed on DSCT. In

contrast, the present study was implemented to test the capabilities of a chest ULDCT associated with IR on a SSCT, which is most largely used in radiology departments compared to DSCT.

Our ULDCT protocol delivered to patients a radiation dose lower than those of previously reported studies with ULDCT protocols using DSCT. Indeed, ULDCT of this study had a lower ED of 59%

and 41% compared respectively to A and B ULDCT protocols of Kim et al. [21], and of 37% compared to that of Won Lee et al. [20]. However, compared to Neroladaki's protocol the overall ED of our ULDCT protocol was slightly higher (14%) [19]. This may be due to patients > 85 kg for whom the tube voltage was adapted to 120 kVp. All these percentages resulted from the comparison with the most relevant and recent studies concerning ULDCT protocols, which were all carried out with a DSCT. In addition, the ED of ULDCT protocol of the present study was 84% lower than our institutional chest LDCT.

Compared to the data of Won Lee et al., the noise in trachea of ULDCT was 34% and 60% lower on mediastinal and lung images, respectively [20]: 54% and 65%, respectively when compared to protocols A and B of Kim's study [21]. We could not compare the noise with others authors since they did not specify the type of kernel from where the data of the ROI in trachea were measured. However, among all the studies that could be compared with, our ULDCT protocol had the lowest noise.

Improvement in the indices of image quality (Noise, SNR, CNR) for ULDCT lung images was mainly due to the modification of the reconstruction kernel (from 170 to 150) and to the SAFIRE strength (from S3 to S4). This modification of the reconstruction kernel entails a loss of spatial resolution without affecting the subjective diagnostic confidence level.

The inter-observer agreement for the image quality of the anatomical structures was fair for LDCT ($k=0.39$) and ULDCT ($k=0.27$) as well as for the image quality of diagnostic findings for ULDCT ($k=0.24$). Although low values of agreement suggested that radiologists scored the same case differently, but the majority of them were scored good or excellent as demonstrated in Fig. 1.

R2 was more critical about ULDCT image quality probably because of the relatively short experience with this type of images, whereas R1 has worked on ULDCT images for three years. This suggests that an implicit visual adjustment effect occurs to ULDCT grainy images with the experience. In addition, the distinction between good or excellent for both radiologists is highly variable, which influenced the low agreement values. The scale used in the present work, suggested in a previous study, seems not to be accurate for slight difference of image quality between the good and excellent levels. However, both radiologists showed a high certainty of diagnostic confidence for the two protocols.

In terms of lung diseases, ULDCT images revealed the same findings of the LDCT protocols, except in two cases (BMI 26.8 and 27.4) where mild emphysematous lesions were overlooked in patients with a BMI > 25, mirroring the data of the literature [20,21]. Solid nodules of small size (≤ 3 mm) were visible and this confirmed the usefulness of a ULDCT for the detection of small solid nodules. Ground glass nodules were visible in patients with BMI < 25 and with more difficulty in patients with a BMI > 25. In particular this difficulty was predominant for those nodules located in apical segments of upper lobes or in the lowest part of basal lobes. Indeed, in these anatomical regions the streak artifacts are more frequent [28]. In addition, a ground glass nodule was recorded in two patients (BMI of patients 27.6 and 28.8 respectively) on ULDCT images, but those putative nodules were not seen in LDCT images.

Also, both radiologists scored a small pleural effusion in the posterior costo-diaphragmatic recess in three cases (BMI of patients 27.7, 28, 28.8 respectively) on ULDCT images but it was disproved on LDCT images. These last two observations suggest that radiologists should be particularly careful to avoid recording inexistent ground glass nodules or slight quantity of pleural effusion when reading (ULDCT) images of patients with a BMI > 25, because of the potential low dose contours distortion [29]. The study of mediastinum was difficult if there was a shortage of mediastinal fat because of a reduction of natural contrast. Moreover, the degradation of the values of quality image indices on mediastinal

reconstructions did not support the assessment of this anatomic area.

This study had some limitations. Firstly, we did not compare the ULDCT to a reference non-low dose diagnostic protocol. Secondly, we did not take into account a possible different inspiratory apnoea between the two acquisitions. Thirdly, although the radiologists were not aware about the type of images they were viewing, the ULDCT images were easily recognisable because of their more grainy texture. Finally more than one less experienced radiologists in ULD images should have evaluated the subjective quality to strengthen the diagnostic versatility of the ULDCT protocol.

In conclusion we showed that a non-enhanced chest ULDCT with SAFIRE allows a high level of diagnostic confidence on a SSCT in selected acute dyspnoeic patients, even for radiologists new to ULD images. The ULDCT protocol of this study delivered a radiation dose in the range of that of a double projection CXR. Further studies should be carried out to compare the diagnostic performance of chest ULDCT protocol for other selected indications that are usually firstly explored with a CXR.

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ETUDE ULD-CT versus RX

L'objectif de ce travail était de tester la performance diagnostique du protocole ULD-CT versus une étude radiographique du thorax (radiographies du thorax de face et de profil et clichés costaux) chez des patients ayant eu un traumatisme thoracique fermé mineur (MBTT) en urgence. En outre l'impact d'une telle imagerie scanographique sur des radiologues non habitués a aussi été évalué.

Un total de 160 patients a été inclus, tous après avoir subi un MBTT et hémodynamiquement stables. Les patients ont bénéficié d'abord d'une étude radiographique du thorax et dans les 24 heures suivantes d'une étude scanographique sans injection de produit de contraste. L'étude scanographique comprenait deux acquisitions : la première était la TDM thoracique institutionnelle (correspondant à un LD-CT) qui fonctionnait comme référence (Ref-CT) et la seconde était l'ULD-CT, délivrant une dose similaire à celle d'une radiographie de thorax de face et profil. Deux radiologues (study radiologists_SR) dont un avec plus de trois ans d'expérience en imagerie ULD (SR1) et un autre entraîné spécialement pour cette étude (SR2) ont recherché des lésions liées au MBTT (pneumothorax, pneumomédiastin, emphysème sous cutané, contusions pulmonaires, fractures du squelette thoracique, épanchement pleural et péricardique). Ils ont coché les cases d'un compte-rendu structuré (StruRep) [items identiques pour radiographie et TDM] impérativement avant d'interpréter la Ref-CT.

Les SRs ont jugé en outre de la qualité de l'image globale et exprimé un niveau de confiance diagnostique comme « certain » et « incertain ». La sensibilité et la spécificité des deux modalités employées dans cette étude ont été calculées et comparées aux résultats des interprétations des Ref-CT, considérées comme le "gold standard".

Pour comprendre l'impact de l'ULD-CT en routine les radiologues responsables des vacations radiographiques et du scanner (RRSs), qui n'étaient pas du tout formés à l'imagerie ULD-CT, ont rempli le StruRep de la même manière que les SRs, durant la période d'acquisition de l'étude. Les StruReps des SRs et des RRSs ont été comparés.

Les doses délivrées aux patients, pour la radiographie et pour l'ULD-CT ont été relevés.

Les résultats ont démontré une supériorité de l'ULD-CT par rapport à la radiographie pour la recherche de tout type de lésion liée à un traumatisme thoracique fermé mineur. La sensibilité était de 100% vs 75% et la spécificité de 89.3% vs 85.7% entre l'ULD-CT et la radiographie. Malgré ses critiques sur la qualité d'image, SR2 (qui a été entraîné seulement pour l'occasion en imagerie ULD-CT) a eu un niveau de confiance diagnostique très élevé avec l'ULD-CT et supérieur à celui de la radiographie tout comme SR1. La comparaison des StruReps des RRS avec ceux des SRs a conduit aux mêmes résultats : l'ULD-CT permettait de retrouver plus de lésions que la radiographie. La dose efficace moyenne de l'ULD-CT (0.203 mSv) était inférieure à celle de l'étude

radiographique (0.427 mSv) et des DRL d'une radiographie thoracique (0.225 mSv).

Cette étude a démontré que l'ULD-CT est capable de mieux évaluer les patients après un traumatisme thoracique fermé mineur par rapport à une étude radiographique, en délivrant une dose de radiations ionisantes inférieure. De plus les radiologues peu expérimentés ou non expérimentés ont retrouvé plus de lésions sur l'ULD-CT que sur la radiographie standard.

Article en cours de révision chez **EUROPEAN RADIOLOGY**

Minor blunt thoracic trauma: value of an unenhanced ultra-low-dose CT versus a conventional radiographic study of the chest in emergency settings.

European Radiology

Minor blunt thoracic trauma: value of an unenhanced ultra-low-dose CT versus a conventional radiographic study of the chest in emergency settings.

--Manuscript Draft--

Manuscript Number:	
Full Title:	Minor blunt thoracic trauma: value of an unenhanced ultra-low-dose CT versus a conventional radiographic study of the chest in emergency settings.
Article Type:	Original Article
Funding Information:	
Abstract:	<p>Objectives To evaluate the diagnostic performance of a chest ultra-low-dose-computed-tomography (ULD-CT) and its impact on radiologists new to ULD-CT, compared to a chest X-ray (CXR) for minor blunt thoracic trauma (MBTT).</p> <p>Methods One hundred and sixty MBTT patients were explored firstly with a radiographic study, subsequently with a double acquisition chest CT protocol: a reference CT and immediately after a ULD-CT, reconstructed with iterative reconstruction (IR). Two study radiologists (SRs) assessed injuries, by using a structured report (StruRep), image quality and expressed a diagnostic confidence level (DCL) as certain or uncertain. The radiologists responsible of CXR and CT shifts (RRSs), who were unaccustomed to ULD-CT, also filled out the StruReps. The radiation doses were assessed.</p> <p>Results SRs and RRSs found significantly more injuries on ULD-CT than CXR ($p < 0.05$). The ULD-CT image quality was rated excellent/good for the majority of cases ($\geq 95\%$). The ULD-CT DCL was certain at least in the 95.6% (CXR 81.8%). The ULD-CT effective dose was 10% lower than the national CXR diagnostic reference level (0.225 mSv).</p> <p>Conclusion ULD-CT with IR, with dose similar to CXR, is more reliable than a radiographic study for MBTT assessment. Radiologists new to ULD are more confident on ULD-CT than on CXR.</p>
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CONCLUSIONS

Synthèse des travaux

La radioprotection du patient est devenue au cours de ces dernières années un objectif majeur du fait de l'importante irradiation médicale liée au scanner [68]. La directe relation entre le rayonnement et la carcinogenèse en particulier de tumeurs solides est connue depuis le bombardement de Hiroshima et Nagasaki qui a donné lieu à une étude encore en cours [69; 70].

En imagerie thoracique le scanner possède un rôle incontournable, étant la modalité "Gold standard" pour une étude de seconde intention du thorax en complément de la radiographie du thorax [71]. Malgré que la radiographie soit toujours indiquée comme examen de premier choix pour une étude du thorax, il y a plusieurs travaux scientifiques qui démontrent la supériorité du scanner pour la totalité des indications cliniques [26; 72; 73]. L'ASN demande d'observer le principe d'optimisation consistant à trouver le meilleur compromis entre l'obtention de la dose la plus faible possible tout en gardant une qualité d'image diagnostique.

Ce travail de thèse a mis en exergue l'utilité en urgence d'un protocole ULD-CT reconstruit avec IR, avec une approche translationnelle caractérisée par trois phases : tests sur fantômes, sur thorax de cadavres humains et en pratique clinique.

Dans la démarche d'optimisation de la TDM dans notre service, plusieurs tests avaient été faits avec différents protocoles, dont certains présentaient une dose se rapprochant de celles du domaine radiographique. Il était remarquable que ces protocoles gardaient également une bonne qualité d'image sur les fantômes en utilisant des hauts niveaux de SAFIRE. Certains des radiologues qui avaient validé les images des fantômes remarquaient une image dégradée, du fait de la forte réduction de la dose et de l'effet de lissage de SAFIRE à hauts niveaux d'itération, entraînant un ralentissement dans leur évaluation car non habitués.

Il a donc été décidé d'évaluer la qualité d'image d'une TDM, délivrant une dose similaire à celle d'une radiographie du thorax, reconstruite avec SAFIRE sur des structures thoraciques réelles de cadavres humains. La réaction d'un radiologue expérimenté et d'un autre peu expérimenté sur des images ULD-CT a été prise en compte et interprétée selon leur niveau de confiance lors de l'évaluation des structures anatomiques. Les protocoles standards « pleine dose », LD-CT et ULD-CT reconstruits avec FBP, S3, S4 et S5 ont été réalisés sur des cadavres humains. Les résultats ont été comparés au protocole TDM standard à pleine dose. Les deux radiologues ont présenté un niveau de confiance similaire, malgré un jugement significativement différent et plus critique du lecteur peu expérimenté concernant la qualité de l'image [28]. Cela a confirmé la valeur du protocole LD-CT et a établi un très bon compromis du protocole ULD-CT avec

des hauts niveaux de SAFIRE (S4 et S5), tout en délivrant une dose inférieure à celle des DRL d'une radiographie du thorax (0.225 mSv) [14]. Ceci suggérant des applications pour des indications normalement explorées en radiographie thoracique.

Plusieurs études en effet dans les quatre dernières années ont validé différents protocoles TDM à très basses doses avec IR sur des machines de différents constructeurs. Ces études ont promu l'utilisation de l'ULD-CT pour des applications « froides », c'est à dire non urgentes comme le dépistage du cancer bronchique, l'étude des pneumoconioses etc [26; 27; 29].

Fréquemment quand un patient est adressé aux urgences pour suspicion de pathologie thoracique urgente, le premier examen d'imagerie dont il bénéficie est une radiographie du thorax (uniquement la face ou face + profil selon les institutions) [12; 67]. Ensuite si la radiographie est non contributive ou montre un tableau méritant d'être approfondi, le second examen à être réalisé est la TDM thoracique, normalement dans un bref laps de temps. Cette attitude très fréquente dans la majorité des services des urgences détermine une redondance et irradiation excessive des patients, avec une augmentation théorique du risque de cancer radio-induit, outre un retard de diagnostic définitif et donc de prise en charge active [74].

Dans le but final de fournir une solution à cette attitude pernicieuse et surtout pour réduire le risque de cancer radio-induit nous avons analysé la performance diagnostique *in vivo* de l'ULD-CT. L'ULD-CT, délivrant une dose de type radiographique, a été comparé au protocole LD-CT et à la radiographie du thorax pour des situations d'urgence, ne relevant pas d'une injection de produit de contraste.

Les résultats étaient positifs pour la recherche de pneumopathie infectieuse, d'exacerbation de pneumopathie restrictive ou obstructive [40]. L'ULD-CT présentait une performance équivalente à celle du LD-CT. L'ULD-CT était par contre plus sensible et spécifique par rapport à l'étude radiographique pour l'évaluation du traumatisme thoracique fermé mineur. Nous avons également démontré que même les radiologues peu expérimentés et critiques envers la qualité d'image ont affirmé un niveau de confiance diagnostique élevé [28; 40].

Les travaux de cette thèse sont pionniers pour l'étude du thorax en urgence avec l'ULD-CT. Ils suggèrent une plus forte implication de l'ULD-CT avec IR en urgence comme première méthode d'évaluation pour des indications cliniques sélectionnées.

Perspectives

Les perspectives majeures sont représentées par une probable réduction supplémentaire de la dose en TDM thoracique, notamment avec les scanners et IR de nouvelle génération. En outre l'adoption de l'ULD-CT comme méthode potentielle de première ligne d'évaluation de certaines indications pourrait permettre une amélioration des soins, grâce à une réponse rapide, détaillée et

conclusive. Ceci pourrait se traduire par une réduction des coûts à long terme, du fait d'une réduction de la morbidité et mortalité, liées à un retard de diagnostic. Il paraît envisageable que le scanner dans le futur remplace quasi complètement la radiographie thoracique. Les nouveaux scanners générant des images avec une dose inférieure à celle de la radiographie thoracique, nous permettent d'avoir des informations morphologiques et désormais aussi, fonctionnelles, grâce à l'imagerie spectrale.

Les travaux de cette thèse ouvrent pour moi aussi un autre chapitre à explorer : l'implication de la double énergie en TDM avec des protocoles à faible dose en urgence, aboutissant à une période post-doctorale d'un an au Massachusetts General Hospital de Boston (EU).

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RESUMES

Le scanner a révolutionné la médecine permettant une accélération et une meilleure prise en charge du patient. La tomographie assistée par ordinateur (TDM) s'accompagne d'un désavantage qui est l'augmentation du risque de cancer radio-induit des patients qui en bénéficient. La question se pose notamment aux urgences où l'emploi du scanner est de plus en plus prédominant, souvent après la réalisation d'une radiographie. Cette attitude, malgré tout justifiée dans la plupart des cas, peut s'avérer délétère. De ce fait les principes de radioprotection obligent à l'optimisation de la dose délivrée aux patients. L'inquiétude principale réside dans l'irradiation du thorax qui est la région la plus radiosensible du corps humain. Cela se traduit par une recherche continue d'un compromis entre l'obtention de la dose la plus basse possible tout en gardant une qualité d'image satisfaisante pour le diagnostic. Les dernières années des innovations technologiques ont été développées pour optimiser la dose au scanner ; la plus importante et la plus récente étant la reconstruction itérative (RI). La RI permet d'améliorer les index de qualité image avec une dose abaissée ou à dose équivalente reconstruite avec la classique rétroprojection filtrée, mais restituant enfin une qualité d'image modifiée. L'objectif de cette thèse était d'établir un protocole TDM du thorax délivrant une dose similaire à celle d'une radiographie du thorax de face et une de profil (ULD-CT_Ultra-low-dose-Computed Tomography) pour des indications de douleurs thoraciques en urgence sans injection de produit de contraste. La réaction des radiologues non habitués a été investiguée pour considérer la modification de l'image liée à la réduction de la dose et de l'emploi de la RI. Pour atteindre cet objectif les travaux de cette thèse se sont déroulés selon trois phases. La première phase représente une approche globale à la RI, testée sur fantômes pour optimiser les protocoles TDM de notre département. À partir des résultats obtenus, la deuxième phase a débuté. Des protocoles TDM thorax standard, à basse dose (LD-CT_Low-dose) et à très basse dose (ULD-CT) ont été testés sur des cadavres humains. La troisième phase a été caractérisée par l'application du protocole ULD-CT en pratique clinique aux urgences. Quatre articles scientifiques ont été rédigés pour représenter les trois phases de cette thèse.

En conclusion, le protocole ULD-CT reconstruit avec des hauts niveaux de RI a délivré une dose inférieure à celle du niveau de référence diagnostique national pour une radiographie du thorax de face et une de profil. Ce type de protocole à très faible dose reconstruit avec RI est une alternative valable à la radiographie pour certaines indications sélectionnées pour l'exploration du thorax en urgence. En outre les radiologues malgré des remarques critiques sur la qualité d'image de l'ULD-CT ont toujours déclaré un niveau de confiance diagnostique élevé.

Computed Tomography (CT) improved patients' health care. However CT has a major drawback, which is the ionizing irradiation of the patient with an ensuing radiation-induced cancer risk. This issue is particularly observed in emergency settings, where the CT is increasingly becoming a dominant tool for the care decision-making, often after a radiographic study. Although this attitude is justified in the majority of the cases, it could be deleterious. Thus the principles of radiation safety obligate to the optimization of radiation dose delivered to the patients. The main problem is that the chest is the most radiation sensitive region of the human body. Hence the research of the better trade-off between the dose reduction and a diagnostic image quality is mandatory. Recently, several technological improvements have been developed to optimize the radiation dose at CT. The newest and most important innovation is the iterative reconstruction (IR). IR improves the quality image indexes of a CT image generated with a lowered dose or equivalent to that reconstructed with filtered back projection. Finally this reconstruction method renders a modified CT image. The goals of this PhD thesis were: i) to establish an unenhanced CT protocol, delivering a dose in the range of a radiographic study (ULD_ultra-low-dose-CT), for chest pain indications with no need of contrast media administration and ii) to investigate the reaction of unaccustomed radiologists to ULD-CT imaging. To accomplish these tasks the work of this thesis has been split in three phases. In the first phase a study approaching globally the IR was carried out testing several CT protocols on phantoms, in order to optimize the CT protocols of our institution. The outcomes of this study opened the second phase. A standard dose CT, a low-dose-CT and an ULD-CT protocols were acquired on the chest of human cadavers. The third phase was characterized by the application of ULD-CT in clinical practice in emergency settings. Four scientific articles were produced to communicate the results of this doctorate work.

In conclusion, the ULD-CT protocol, reconstructed with high strengths of IR, conveyed a dose lower than the one of the national diagnostic reference level for a double projections chest X-ray. This ULD-CT protocol with IR is a valid alternative to the radiography for the study of the chest, for selected indications in emergency settings. Moreover, despite the radiologists were censorious about the ULD-CT image quality, they demonstrated always a high diagnostic confidence level.