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Impact of periodontal inflammation on the cardiac splenic axis: study of Neutrophils Extracellular Traps (NETs) and splenic microvesicles as mediators of procoagulant and inflammatory responses

Hanine El Itawi

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*ÉCOLE DOCTORALE DES SCIENCES DE LA VIE ET DE LA
SANTÉ*

Regenerative Nanomedicine – INSERM UMR 1260

THÈSE présentée par : **Hanine El Itawi**

Soutenue le : **19 Avril 2022**

Pour obtenir le grade de : **Docteur de l'Université de Strasbourg**

Discipline/ Spécialité : **BIOTECHNOLOGIE**

**Impact de l'inflammation parodontale sur
l'axe splénique cardiaque : étude des
Neutrophils Extracellular Traps (NETs) et
des microvésicules spléniques comme
médiateurs des réponses procoagulantes et
inflammatoires**

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To my Grand-father

To my Family

To Joumana

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“Through patience, great things are accomplished” Imam Ali (AS)

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LIST OF ABBREVIATIONS

ANO6	Anoctamine 6
ATP	Adenosine Tri-Phosphate
ADP	Adenosine di-phosphate
C12FDG	5-dodecanoylaminoFluoresein Di- β -D Galactopyranoside
CD	Cluster Differentiation
Chol	Cholesterol
C5	Convertase like enzyme
CHD	Coronary heart disease
CVD	Cardiovascular disease
DAPI	4,6-Diamidino-2-Phenylindole
DCs	Dendritic cells
DDR	Damage cell response
DHE	Dihydroethidium
DNA	Deoxyribonucleic acid
ECM	Extracellular matrix
ECs	Endothelial cells
EMPs	Endothelial cell-derived microparticles
EMVs	Endothelial cell-derived microvesicles
ERK	Extracellular signal regulated kinase

eNOS	Endothelial Nitric Oxide Synthase
FA	Fatty acids
GLA	Gamma-Carboxyglutamic Acid
GM-CSF	Granulocytes-Macrophages Colony-Stimulating Factor
GP	Glycoprotein
GTP	Guanosine triphosphate
Gvg	Gavage
HBSS	Hank's Balanced Salt Solution
H ₂ O ₂	Hydrogen peroxide
HDL	High Density Lipoproteins
HUVEC	Human Umbilical Vein Endothelial Cells
HSP	Heat Shock Protein
ICAM-1	Intracellular adhesion molecule 1
IgE	Immunoglobulin E
IP	Intraperitoneal injection
IL	Interleukin
ISEV	International Society of Extracellular Vesicles
KLF2	Kruppel like Factor
LIG	Ligature
LIG-PG	Ligature + Porphyromonas gingivalis
LDL	Low Density Lipoproteins
LMPs	Leukocytes-derived microparticles

LMVs	Leukocytes-derived microvesicles
LAMP1	Lysosomal Associated Membrane Protein 1
LPS	Lipopolysaccharide
Mac-1	Macrophage antigen-1
MAPK	Mitogen-Activated Protein Kinase
MHC	Major Histocompatibility Complex
miRNA	MicroRNA
MMPs	Metalloproteinases
MV	Microvesicle
MP	Microparticle
mMVs	Monocytes/ macrophage-derived microvesicles
mMPs	Monocytes/ macrophage-derived microparticles
mRNA	Messenger RNA
MZ	Marginal zone
NADPH	Nicotinamide Adenine Dinucleotide Phosphate
NET	Neutrophils extracellular traps
NF- κ B	Nuclear factor kappa-light-chain-enhancer of activated B
cells	
NKC	Natural killer cells
NLRP3	NOD-like receptor family pyrin domain-containing 3
nMPs	Neutrophils-derived microparticles
nMVs	Neutrophils-derived microvesicles

NO	Nitric Oxide
OX-LDL	Oxidized Low Density Lipoprotein
OMVs	Outer membrane microvesicles
PC	Phosphatidylcholine
PCR	Polymerase chain reaction
PG	Porphyromonas gingivalis
PE	Phosphatidylethanolamine
PL	Phospholipid
PMA/I	Phorbol Myristate Acetate/ Ionophore
PMPs	Platelet derived microparticles
PMVs	Platelet derived microvesicles
PS	Phosphatidylserine
RNA	Ribonucleic acid
ROS	Reactive oxygen species
SASP	Senescence -Associated Secretory Phenotype
SA- β -Gal	Senescence -Associated Beta-Galactosidase
SM	Sphingomyelin
SMVs	Splenic Microvesicles
TCR	T-Cells Receptors
TF	Tissue Factor
TLRs	Toll-Like Receptors
TNF	Tumor Necrosis Factor

T.Denticola	Treponema Denticola
T. Forsythia	Tanerella Forsytia
VCAM-1	Vascular Cell Adhesion Molecule 1
WP	White pulp

RESUME DES TRAVAUX

Rate et cœur, un axe fonctionnel ?

La parodontite est une maladie inflammatoire buccale d'origine infectieuse très répandue et la principale cause de perte de dents chez l'adulte. Elle est associée à une destruction progressive des tissus parodontaux conduisant à la formation de poches parodontales.

Étant impliqué dans l'apparition et le développement de nombreuses pathologies systémiques telles que les maladies cardiovasculaires et l'athérombose, la parodontite a été associée à une aggravation cardiovasculaire (*Sanz M. et al 2020*).

La progression des connaissances sur la physiopathologie sous-jacente à ces maladies a permis de mettre en évidence des liens entre eux tant au niveau clinique qu'aux niveaux cellulaires et moléculaires, dont les mécanismes initiateurs et régulateurs restent mal connus.

Les microvésicules (MV) sont des fragments de membrane plasmique libérés en réponse au stress cellulaire qui agissent comme des effecteurs cellulaires. Elles sont émises de la membrane plasmique des cellules activées ou apoptotiques, initialement caractérisées par leur activité procoagulante et

qualifiées de "microparticules" (*Ridger et al, 2017*). Elles sont émises par tous les types de cellules selon leur capacité de remodelage de la membrane plasmique. Dans le système vasculaire, d'origine endothéliale, plaquettaire, leucocytaire et de cellules musculaires lisses (*Boulanger et al, 2010*)

Initialement étudiées pour leurs propriétés procoagulantes sanguine, plus récemment, les microvésicules ont été reconnues comme ayant un rôle dans la communication cellule-cellule. (*Guillaume van Niel et al, 2018*) Elles sont actuellement reconnues comme de véritables effecteurs cellulaires car elles sont dotées d'une activité biologique intrinsèque. Elles sont capables de moduler de nombreuses réponses vasculaires telles que l'hémostase, l'inflammation, la vasomotricité, l'angiogenèse et la croissance vasculaire. Ces propriétés dépendent de l'origine cellulaire de la MV et du stress initiant leur libération et de leur capacité à se lier à la cellule cible. (*Cocucci E et al, 2009*)

Ainsi, dans le choc septique, les taux de MVs procoagulantes circulantes de neutrophiles sont corrélées à une hypercoagulabilité et à la présence de Neutrophil Extra cellular Traps (NETs) circulants. (*Steil et al 2016, DeLabranche et al 2017*). Les NETs sont composés de chromatine décondensée qui portent certains constituants cytoplasmiques et des granules des neutrophiles qui les émettent. La Nétose des neutrophiles est probablement un mécanisme évolutif de défense contre la déssimination des agents pathogènes envahisseurs qui sont piégés dans les NETs (*Brinkmann et al 2016*). En effet, les NETs ont été associés à la parodontite chez les

patients à risque cardiovasculaire, ainsi un axe splénocytaire avec invasion par les neutrophiles de la rate dans le cœur post-infarctus a été proposé (Moonen et al 2019) comme un nouveau mécanisme liant infection chronique et atteinte cardiovasculaire (Tian et al 2016).

Dans notre laboratoire, nous avons établi des méthodes d'extraction des MVs d'aorte de rat et démontré que ces MVs sont sensibles au microenvironnement vasculaire. Nous avons aussi montré que les MVs de rat d'âge moyen (48 semaines) ou âgé (92 semaines) isolées à partir de la rate sont pro-sénescences et procoagulantes vis-à-vis de l'endothélium uniquement lorsqu'elles sont émises dans un microenvironnement proinflammatoire (*El Habhab et al 2020*) et (*Qureishi et al 2019*).

Par ailleurs, d'autres données antérieures du laboratoire ont montré que le LPS induit l'excrétion de MV procoagulants de la rate de rat capables de favoriser la sénescence endothéliale et une action pro-inflammatoire et réponses procoagulantes. (El Habhab et al 2020). L'infection par LPS du *Porphyromonas Gingivalis* ou par la bactérie inactivée conduit à l'émission de MVs proapoptotiques par les cellules endothéliales HUVEC (*Bugueno et al 2020*).

La faisabilité d'un contrôle pharmacologique de la libération de MV prosénescences de la rate a été démontrée dans un modèle de rat. Le traitement oral par une formule optimisée d'oméga-3 s'est avéré protecteur à la fois contre le taux de libération des MV de la rate chez les rats d'âge moyen

et âgés, et contre leurs propriétés nocives pro-sénescences envers l'endothélium coronaire. (Qureshi et al 2020)

Le travail de thèse vise à étudier l'impact des MVs et des NETs (neutrophil extracellular traps) comme acteurs de la réponse cellulaire induite par la parodontite et cause possible de la tendance thrombotique chez les patients. Des expériences sont conçues pour acquérir une meilleure connaissance des interactions entre l'infection locale des dents, la réponse de la rate et les tissus cardiovasculaires. Elles se concentrent sur le changement du phénotypage de l'endothélium qui est initialement une surface protectrice et devient pro-inflammatoire, procoagulant et pro-sénescence après contact avec les MVs émises localement en réponse à *P. gingivalis*.

Les hypothèses émises après examen de la littérature et en s'appuyant sur les données du laboratoire sont :

- 1- Les MVs excrétées en réponse à une infection par des agents pathogènes parodontaux sont des acteurs à distance expliquant l'impact de la parodontite sur l'aggravation des conditions vasculaires perpétuent l'inflammation vasculaire chronique.
- 2- La libération des MVs spléniques et leurs propriétés varient selon la sévérité de l'infection et / ou le type de lésion tissulaire
- 3- Les MV libérées par les splénocytes en réponse à *Porphyromonas Gingivalis* sont délétères pour les cellules endothéliales et agissent

comme des médiateurs cardiovasculaires pro-inflammatoires et prosénescents

- 4- Les microvésicules splénocytaires et les NETs libérés en réponse à *Porphyromonas Gingivalis* favorisent l'athéromatose à des sites éloignés de l'infection dentaire

Les objectifs généraux du travail sont en conséquence :

- 1- Établir la preuve de concept dans un modèle murin de parodontite.
- 2- Caractériser la composition cellulaire de la rate et la libération des MVs par les splénocytes lors d'une infection parodontale par ligature combinée ou non à une infection locale par *Porphyromonas.gingivalis*.
- 3- Comparer les propriétés endothéliales proinflammatoires et procoagulantes des MVs tissulaires de souris dans ce modèle d'infection dentaire en utilisant la rate comme source majeure de MVs inflammatoires libérées en réponse à *P. gingivalis*.
- 4- Identifier les effets pro-sénescents des MVs sur l'endothélium coronaire en utilisant des cellules primaires dans un modèle de communication intercellulaire.
- 5- Identifier les NETs et les MVs comme acteurs circulants et distants de *P.Gingivalis* en comparant le modèle de ligature et l'injection intrapéritonéale de *P.gingivalis*.

6- Evaluer les répercussions de la parodontite sur le profil inflammatoire et procoagulant du tissu cardiaque.

Prolog

Spleen and heart contributing to pathological response in periodontitis.

Periodontitis is a highly prevalent, oral inflammatory disease of infectious origin and the primary cause of tooth loss in adults. It is associated with a progressive destruction of periodontal tissues leading to the formation of periodontal pockets.

Amazingly, periodontitis has been involved as a inducer in pathologies such as cardiovascular diseases and atherothrombosis, associated with cardiovascular worsened outcome ¹. The evolution of the knowledge of physio pathological mechanisms underlying both diseases has made it possible to highlight cellular and molecular links , although these mechanisms remain to be deciphered.

The thesis work is investigating relationships between different effectors possibly contributing to a remote action of the local periodontitis.

Recently, Neutrophil Extracellular Traps (NETs), a mesh of decondensed DNA shed by neutrophils in response to local infection, and already known to contribute to hypercoagulability, have been associated with periodontitis in patients at cardiovascular risk. ² Finally, leukocytes invasion of the spleen in the post-ischemic heart reperfusion has been proposed as a new mechanism

linking chronic infection and cardiovascular damage ³ possibly constituting a new spleen-cardiac deleterious axis.

Microvesicles (MVs) are plasma membrane fragments shed in response to cell stress that act as cellular procoagulant effectors. Previous data from the laboratory have shown that MVs may act as pro-inflammatory mediators promoting premature senescence of coronary artery endothelial cells ^{4,5} leading to endothelial dysfunction and the release of pro-senescent MVs and that infection by LPS of *Porphyromonas Gingivalis*, the main pathogen in periodontitis leads to the emission of proapoptotic microvesicles (MVs) by HUVEC endothelial cells.⁶ Previous *In vitro* data showed that LPS induces the shedding of procoagulant MVs from rat spleen that are able to promote endothelial senescence and a pro-inflammatory and procoagulant responses. ⁴ The feasibility of a pharmacological control of the release of pro-senescent MVs from the spleen was further demonstrated in a rat model. Oral treatment by an optimized omega-3 formula was found protective against both the rate of the release of spleen MVs in middle-aged and aged rats, and their pro-senescent noxious properties towards the coronary endothelium. ⁷

The thesis work aims to study the impact of MVs and NETs (neutrophil extracellular traps) as actors of the remote cell response after periodontitis and

a possible cause of thrombotic tendency in patients. Experiments are designed to gain a better knowledge of the interactions between local teeth infection, the spleen response and the cardiovascular tissues. They focus on the endothelial switch from a protective to a proinflammatory and procoagulant and prosenescent surface mediated by *P. Gingivalis*-induced MVs.

Chapter I

Microvesicles: Extracellular vesicles shed from the activated plasma membrane

I.1 Background: Properties and characterization of extracellular vesicles

The International society of extracellular vesicles (ISEV) underwrites extracellular vesicle (EV) as the generic term for particles naturally released from the cell that are delimited by a lipid bilayer, precluding a functional nucleus and asserting they cannot replicate.⁸

Extracellular vesicles are designated in the literature as microparticles, microvesicles, or exosomes or apoptotic bodies.⁹

All extracellular vesicles are distinguished on the basis of their subcellular origin, their size, their content and the mechanism leading to their formation.¹⁰

(see fig 1)

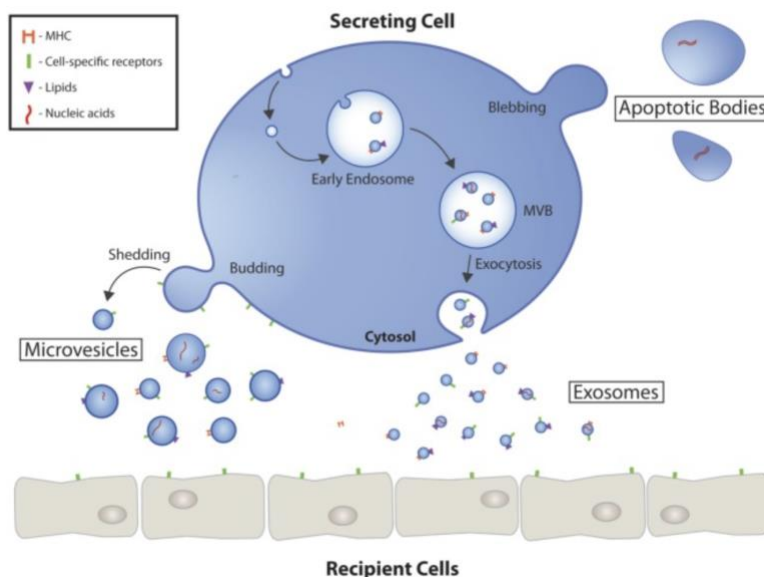


Fig 1: Schematic representation of the types of extracellular vesicles released by a cell. Exosomes, microvesicles and apoptotic bodies are secreted by the cell into the extracellular environment. Their biogenesis are different, exosomes are secreted by endocytosis,

*microvesicles and apoptotic bodies are released by plasma membrane blebbing in response to cellular stress.*¹¹(Gustafson et al 2017)

Exosomes

Exosomes are small, single-membrane, secreted organelles of ~30 nm to ~100 nm in diameter having the same form as the cell and enriched in proteins, lipids, nucleic acids, and glycoconjugates.¹² They are present in many biological fluids, including urine,¹³ blood,¹⁴ ascites,¹⁵ and cerebrospinal fluid,¹⁶ fractions of body fluids such as serum and plasma, and cultured medium of cell cultures . Exosomes are usually isolated by ultracentrifugation (100,000–200,000g).¹⁷ Regarding their biochemical composition, exosomes are surrounded by a phospholipid membrane containing relatively high levels of cholesterol, sphingomyelin, and ceramide and containing detergent-resistant membrane domains (lipid rafts)¹⁸

Apoptotic bodies

Apoptosis is a highly regulated process of cell death.¹⁹ During apoptosis, starting with the nuclear chromatin condensation, the process is followed by plasma membrane budding, progressing to the breakdown of the cellular content into distinct membrane enclosed vesicles termed apoptotic bodies or apoptosomes.²⁰

Identified by Kerr, Wyllie in 1972²¹ , apoptotic bodies are membrane structures that package cell organelles such as mitochondria, nuclear fragments, granules, cleaved DNA ...²²

They expose phosphatidylserine and contain DNA and RNA originating from nuclear membrane fragmentation.²³ (see table 1)

Characteristic	Microparticles	Exosomes	Apoptotic bodies
Size	100–1000 nm	40–100 nm	> 1 μ m
Mechanism of formation	Outward blebbing of plasma membrane	Fusion of multivesicular bodies with plasma membrane	Cell shrinkage and death
How detected	Flow cytometry, capture-based assays and electron microscopy	Electron microscopy and Western blotting (characterization with exosome-enriched markers)	Flow cytometry and electron microscopy
Characteristic features	Annexin V-positivity and presence of cell-specific surface markers	LAMP1, CD63 and TSG101	Annexin V-positivity, DNA and permeable membrane
Composition	Protein, RNA and miRNA	Protein, RNA and miRNA	Protein, DNA, cell organelles, RNA and miRNA
Membrane properties	Externalized phosphatidylserine, rich in lipid rafts and impermeable	Rich in lipid rafts and impermeable	Externalized phosphatidylserine and permeable

Table 1: Classification of different types of extracellular vesicles and methods for their detection ²⁴(Burger et al 2013)

Microvesicles (MVs)

Initially identified by Wolf 1967 as a platelet dust containing phospholipids, and capable of supporting coagulation,²⁵ microvesicles (MVs), also named microparticles, oncosomes ²⁶ or ectosomes²⁷, are submicron fragments of the plasma membrane that spill into the extracellular space of cells under cellular stress conditions.¹⁰ The ectosome nomenclature derives from the definition of ectocytosis introduced in 1991 by Stein and Luzio to describe the shedding of vesicles from the plasma membrane of stimulated neutrophils,²⁸ while

oncosomes are atypical large cancer-cell derived extracellular vesicles. However, when confirmation of the vesicles identity is achieved according to the recommendations of the ISEV 2018 norms, the most likely term to be used nowadays is microvesicles.⁸

MVs are released in biological fluids such as blood, urine, tears and saliva. In the blood, they circulate at low concentration in healthy individuals and their levels are modified in various cardiovascular and chronic diseases including diabetes, chronic renal failure, pre-eclampsia and hypertension.²⁴ Ranging in size between 100 to 1000 nm in diameter, they are released during cell-surface budding, and considered as physiological liposomes, since formed from the cell plasma membrane lipid bilayer. The MV membrane embeds a content of active proteins, signaling nucleotides, and metabolites as well as RNA, non-coding RNA and bioactive lipids.⁹ MVs expose phosphatidylserine, a procoagulant phospholipid.^{10 30} (see fig 2 and table 2)

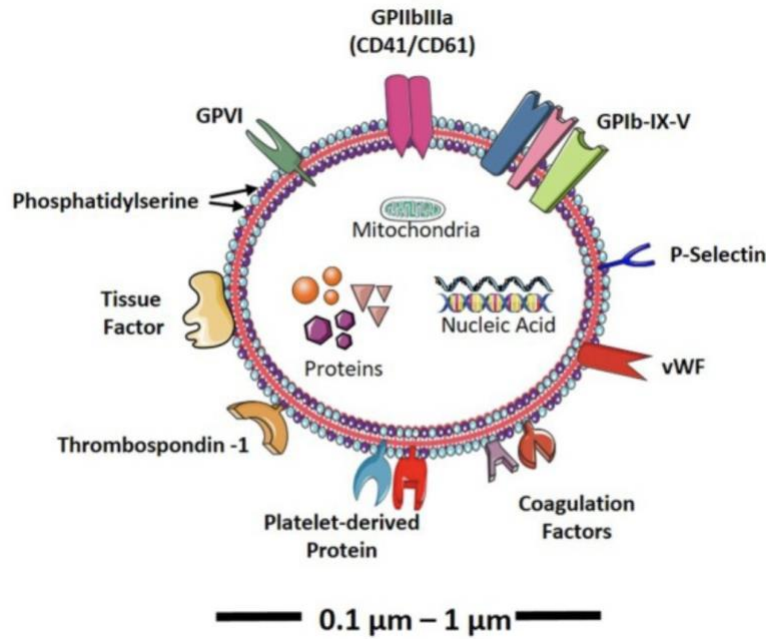


Fig 2: Schematic content and membrane of extracellular microvesicle released from platelet. (Zaldivia MTK et al 2017) ²⁹

Molecule	Type of cell producing microparticles	Target cell or environment
Receptor/membrane molecule		
Chemokine receptor CCR5 [72]	Peripheral blood mononuclear cells	Various cells
CXCR4 receptor [73,74]	Platelets	Various cells
Glycoprotein IIb/IIIa receptors [75]	Platelets	Neutrophils
Oncogenic receptor EGFRvIII (epidermal growth factor receptor variant III) [76]	Tumour cells	Various cells
Major histocompatibility complex (MHC) class II [77]	Immune cells	Immune cells
Tissue factor [48]	Monocytes	Platelets
Peroxisome proliferator-activated receptor gamma [78]	Platelets	Monocytes
Cytokines		
Interleukin-1beta [79–82]	Various cells	Various cells
Chemokine (C-C motif) ligand 5[83]	Platelets	Endothelial cells
Growth factors		
Vascular endothelial growth factor [84–85]	Platelets/tumour cells	Endothelial cells
Basic fibroblast growth factor [84,86]	Platelets/tumour cells	Endothelial cells
Platelet-derived growth factor [86]	Platelets	Endothelial cells
Lysis enzymes		
Matrix metalloproteinases [85]	Tumour cells	Extracellular matrix
Extracellular matrix metalloproteinase inducer [87]	Tumour cells	Extracellular matrix
Caspase 1 [88]	Monocyte	Smooth muscle cell
Lipids		
Arachidonic acid [89–91]	Platelets	Various cells
Platelet activated factor [92,93]	Various cells	Platelets
Ribonucleic acid (RNA)		
Messenger RNA [38,94]	Stem cells	Various cells
Micro RNA [95–97]	Stem cells	Various cells

Table 2: Table of bioactive molecules of extracellular microvesicle MVs.³¹ (Voukalis et al 2019)

Plasma membrane phospholipid distribution

Eukaryotic cells are surrounded by a lipid bilayer subdivided into compartments with distinct structural and functional identities termed rafts. Where glycerophospholipids forms almost 70% of the total lipid content of mammalian cells, the other 30% consists of cholesterol, sphingomyelin, and glycosphingolipids. Among the phospholipids, phosphatidylcholine (PC) is the most prevalent and accounts for 40%–50% of the total,³² whereas phosphatidylserine (PS) is the commensurate trifling constituent of most biological membranes.³³

In addition, the content of conventional phospholipids varies among organelles. Membrane phospholipid asymmetry is characteristic of eukaryote cells, and is regulated by an active process by flipases and floppases.³⁴ In resting cells phosphatidylserine is sequestered in the inner leaflet of the plasma membrane.³⁵

Phosphatidylserine

Phosphatidylserine (PS) species were first identified by Folch and coworkers in the 1940s.³⁶ Notwithstanding its low abundance in plasma membrane phospholipids, PS is of a substantial physiological importance owing to its unique physical and biochemical properties. It is the key to the recruitment of vitamin-K dependent coagulation factors³⁷, it also signals important

events such as the internalization of viruses by host cells³³ and the clearance of apoptotic cells via the binding of lactadherin that is secreted by macrophages and bridges PS and $\alpha V \beta 3$, an integrin exposed by the macrophages.³⁸

I.2 Mechanism of MV generation

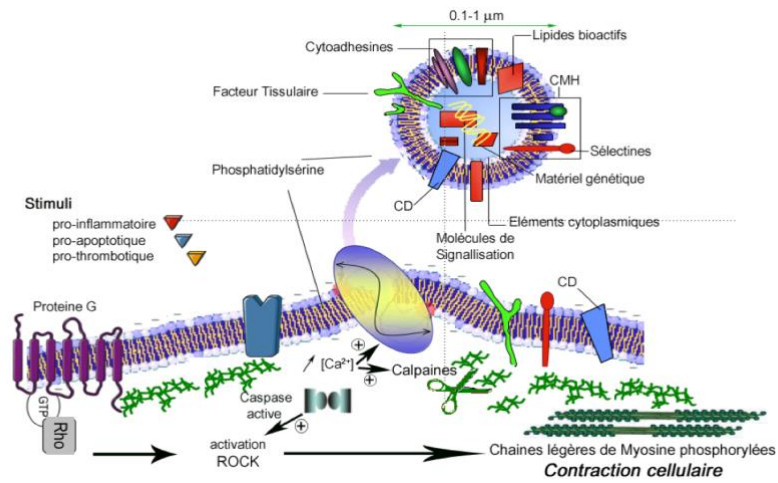
Loss of phospholipid asymmetry is a driving force for the membrane remodeling and generation of MVs.¹⁰ Unlike exosome formation, MV formation involves plasma membrane budding³⁹. Reorganization of the cytoskeleton and changes in membrane asymmetry of PS are key for the genesis of MV. In this respect, the dynamics of actin filaments seem crucial for the formation of MVs.²⁴ For instance, platelet activation leads to an increase in intracellular calcium, which in turn regulates the activity of transporters such as flippases, floppases and scramblases which are responsible for the movement of phospholipids between the two layers of the plasma membrane.³⁹ These proteins maintain the phospholipid asymmetry of the membrane at cell rest (fig 5). Activation of floppases and scramblases and inhibition of flippases in response to calcium influx induces exposure of PS at the outer leaflet of a cell membrane, whereas PS is sequestered in the inner leaflet of the plasma membrane at cell rest. The increase in cytoplasmic calcium concentrations causes the translocation of phosphatidylserine (PS), from the inner layer to the outer layer under the effect of a net floppase activity. At the same time, reverse anionic phospholipid

transporters (flippases) are inhibited by calcium. The transport of PS by floppases is very rapid while the reverse transport of other non-anionic phospholipids such as phosphatidylcholine is slower. The translocation of the PS creates a transient overload of the outer leaflet which leads to budding. Increased intracellular calcium also activates calpains and Rho kinases, responsible for cytoskeleton fragmentation,¹⁰ thus, the membrane tension is not contained by the cytoskeleton and a MV exposing PS is released.^{40 41}

This process is sometimes considered protective because MV carry stress-induced deleterious signals from the parent cell. Thus, inhibition of apoptotic endothelial cell Rho kinase prevents the release of MP exporting active caspase 3 and promotes detachment and cell death.⁴²

MVs are procoagulant because they carry PS which catalyzes the formation of the blood coagulation complexes and cellular effectors because they convey active proteins present in the cell at the time of their emission.⁴³ Bakouboula et al 2011. (see fig 3)

A-



B-

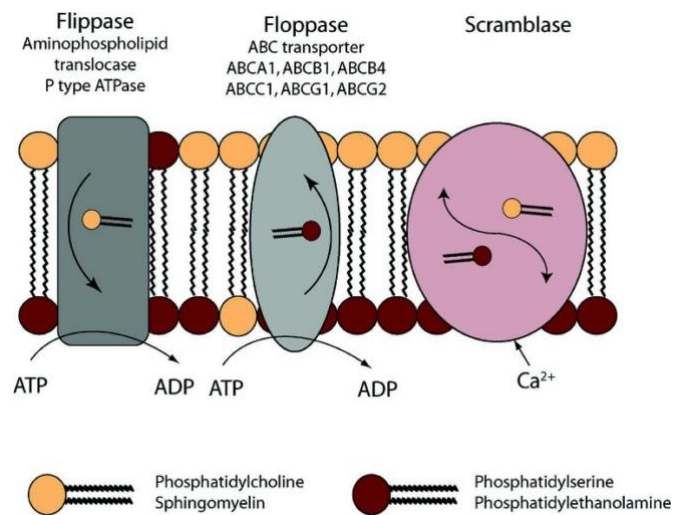


Fig 3: Mechanisms of generation of MVs in response to cell stimulation and membrane transporters A: cell response to stimuli: the activators bind to their specific receptor and induce a calcium influx. The increase in cytoplasmic calcium concentrations causes the translocation of phosphatidylserine (PS), from the inner layer to the outer layer under the effect of a net floppase activity. Proteases such as calpains and ROCK kinases are activated by high calcium concentrations and cause controlled proteolysis of the cytoskeleton, which promotes the release of MVs. B: Different types of phospholipid transporters in the membrane of eukaryotic cells. Flippase (repatriation of PC, floppases: externalization of PS, Scramblases:

mixing of phospholipids between the layers) ⁴⁴ (Quazi et al 2011 & authorized by co-author Florence Toti).

I.3 Methods of MV isolation from tissues, quantification and characterization

There are different strategies currently available to characterize EVs, including electron microscopy-based approaches and flow cytometry combined with antibodies against surface markers. Other strategies for studying EVs molecular signatures are based on molecular analysis of their cargo (mRNA, protein, or bioactive lipid content) by employing omics technologies aimed at the universal detection of mRNA species (transcriptomics), proteins (proteomics), lipids (lipidomics), and metabolites (metabolomics) ⁹. Bulk analysis techniques, such as Western blots, ELISAs, mass spectrometry, and sequencing, and bead capture assays, have been widely used and instrumental in the field to date, associating EV phenotype (molecular cargo) with function ⁴⁵.

As for MVs, the majority of clinical studies examine MVs isolated from plasma samples, which typically contain endothelial, leukocyte, platelet, and erythrocyte MVs. ³⁹ Several approaches can be used for the detection and characterization of MVs with sometimes a pre-analytical isolation phase by high speed centrifugation and washing, before analysis by various methods such as prothrombinase enzymatic assay, spectrophotometric measurement

of MV proteins and RNA concentration ⁷ and other proposed methods listed in table 3 .

Protocol	Method of quantification	Advantages	Disadvantages
Flow cytometry	Fluorescence and light-scattering properties of MPs in suspension	Available to most research facilities	Quantification of 100–400 nm may be imperfect
		Rapid	Cell origin identification is antibody-dependent
		Multiple antigens may be analysed in a single sample MPs analysed on an individual basis	
Immunoassays	Immunocapture of MPs and quantification based on the presence of surface antigen	Available to most research facilities No size restrictions	Quantification is done in bulk Quantifies based on a single antigen Does not allow for size determination
Functional assays	Procoagulant or prothrombinase activity of MPs	Available to most research facilities Provides an indication of biological activity	Quantification is done in bulk Measures only a single biological activity Does not allow for size determination
Atomic force microscopy	Cantilever is used to scan the surface of MPs and tip displacement is related to surface properties	Allows for very accurate sizing of MPs Allows for three-dimensional view of MP structure	Non-universal technology Determination of cell origin requires development of specialized antibody-coated surfaces
Nanoparticle tracking analysis	MPs are visualized by light microscopy and light scattering is observed; Brownian motion of individual particles is tracked by video	May be used for quantification	Not conducive to large sample numbers
		Clear idea of MP size Allows for quantification	Utility of assay for quantification is unclear Non-universal technology May be time-consuming

Table 3: Different methods for MVs quantification ²⁴ (Dylan Burger et al 2013)

According to the international society of extracellular vesicles (ISEV), there is no single optimal characterization method neither a recommendation on quantification of MVs, however, characterization of vesicles must be done using two technical complementary approaches⁸.

Chapter II
Tissular and vascular Microvesicles:
Biomarkers and cellular effectors

Inflammation is a major actor promoting altered vascular response and often associated with worsen cardiovascular outcome ⁴⁶. Plasma MVs are not only markers of cellular and tissue activation or damage but also actors of major physiological responses such as inflammation⁴⁷, atherosclerosis, ^{48,49} ³⁰cell survival and apoptosis ⁴⁹, endothelial function, ⁵⁰ ⁵¹ plasma membrane remodeling ^{52,53} and angiogenesis.⁵⁴ ³⁰

In the last decades, many studies explored the role of MVs as bioactive mediators, capable of raising and disseminating the signal responsible for their emission in the vessels and the extracellular space of the tissues in an autocrine or paracrine manner.⁵⁵ ⁴⁹ ^{54,56,57} They do exhibit proinflammatory effects and induce the production of cytokines and chemokines while promoting activation of inflammatory cells.²⁴

Circulating MVs mainly of platelet, leukocyte, and endothelial origin provide an additional phospholipidic surface for the assembly of blood coagulation factors and promote the coagulation cascade and thrombin generation. In the vasculature they constitute the principal reservoir of tissue factor (TF) activity, the cellular initiator of blood coagulation.⁵⁸ Emerging as a key marker of global vascular damage, MVs bearing TF mediate noxious cellular responses in diabetic thrombophilia and cardiovascular complications and act as injurious amplifiers of various biological responses such as thrombogenicity and atherothrombotic plaque remodeling.⁵⁹

II.1 Microvesicles and vascular inflammatory response

The endothelium is a major player in cardiovascular (CV) physiopathology.⁶⁰

In the healthy state, the endothelium is vasoprotective, mainly by the secretion of vasodilator agents such as nitric oxide (NO), the endothelium-derived relaxing factor⁶¹ and prostacyclin,⁶² and because the resting endothelium does not promote the assembly of blood coagulation factors (it does not expose PS and very little if any tissue factor). Endothelial dysfunction is an early pathogenic event of atherosclerosis, essential hypertension, and related cardiovascular disorders.⁶³

The loss of cytoprotective NO makes cells susceptible to apoptosis.

⁶⁴Endothelial MVs are potential biomarkers of cardiovascular disease. In addition, many studies have reported that MVs can directly alter the endothelial function.⁶⁵

According to the degree of the severity of pathological state associated with vascular dysfunction, the plasma concentrations of MVs are modified. Numerous clinical data indicate that plasma concentrations of endothelial-derived EMVs increase in obesity⁶⁶, physical inactivity⁶⁷, type 2 diabetes mellitus⁶⁸, end-stage renal disease⁶⁹, ischemic left ventricular dysfunction⁷⁰, and preeclampsia⁷¹. Furthermore, the phenotype of EMVs varies with the endothelial damage and reflects the initial stress. For instance, in response to platelet MVs, endothelial cells (ECs) release of pro-inflammatory cytokines

such as Il-6 or Il-8 cytokines and the expression of adhesion molecules ICAM-1,^{72,73} VCAM-1 and E-selectin⁷³. Interestingly, the majority of (EMVs) isolated from the site of coronary artery plaque during balloon angioplasty express the vascular cell adhesion molecule-1 (VCAM-1)⁷⁴. Of note, VCAM-bearing endothelial cells or derived MVs were in higher amounts (70%-80%) when isolated from patients with Myocardial infarction as compared to stable coronary artery disease. Because VCAM-1 expression was absent on ECs in the peripheral circulation from these same subjects, authors claimed that VCAM expression at the membrane of cells or EMP appear as unique markers in the plaque tissue. At least they demonstrated that inflammatory markers accumulate in the plaque. Similarly, MVs generated in vitro from endothelial cells human coronary endothelial cells (HCAEC) exposed to high glucose concentration, show increased NADPH oxidase activity and ROS levels,⁷⁵ underlining their potential noxious role in diabetes and cardiovascular associated disorders.^{76 77}

In blood, MVs are most often mainly released from platelets and to a lesser extent from leukocytes and endothelial cells⁷⁸. Plasma MVs are now also studied substantially as vascular effectors⁷⁹, and have been reported to be inflammatory effectors intensifying the secretion of a variety of pro-inflammatory mediators.³⁰ (see table 4)

Type of cell producing MPs	Target cell	Molecules involved in the pathogenesis of inflammation mediated by MPs
Endothelial Leucocytes T cells	Various inflammatory cells Endothelial Monocytes	Cytokines IL-1 β and TNF- α [113] IL-6 and MCP-1 [114] IL-8, TNF- α and IL-1 β [43,115]
Monocytes Platelet	Endothelial	Adhesion molecules Intercellular adhesion molecule-1, vascular cell adhesion molecule-1 E-selectin [91,116]
– Platelet	– Endothelial	Lipids Thromboxane A2 and cyclooxygenase [89]
Polymorphonuclear –	Macrophage –	Other transforming growth factor beta1 [117] Annexin V [118]
Monocytes Polymorphonuclear	Macrophage Various cells	peroxisome proliferator-activated receptor gamma protein [119] complement proteins (C1q) [51]

IL: interleukin; TNF: tumour necrosis factor; MCP-1: monocyte chemoattractant protein-1.

Table 4: Microvesicles and inflammation ³¹ (Voukalis et al 2019)

II.2 Microvesicles in atherosclerosis and thrombosis

Atherosclerosis is a multifaceted pathology combining inflammatory responses as well as certain metabolic imbalance such as elevated LDL-cholesterol and resulting in the formation of thickening of the arterial intima and the formation of atherosclerotic plaque. ⁸⁰ MVs are crucial actors in atherothrombosis, ^{48,49 30}. *In vitro*, plasma MVs foster the release of cytokines and cell adhesion molecules from endothelial cells and prompt the induction of tissue factor, the cellular initiator of the coagulation cascade.⁸¹ Studies have shown that the coagulation capacity of platelet-derived MVs (PMVs) is 50 to 100-fold higher than activated platelets. ⁸² An excessive amount of circulating PMVs has been observed in patients with atherosclerosis. ^{83 84}

In the sequence of events following the initial MV-mediated coagulation, EMVs and leukocyte MVs will later carry the plasminogen activator uPA which enables the transformation of plasminogen into plasmin. MVs bearing uPA will

contribute to fibrinolysis cross-talk by docking into the growing thrombus to resorb it and also promote extracellular matrix remodelling during tissue healing.⁸⁵ Indeed, the cellular uPA borne by EMV and leukocyte-derived MVs promote the plasmin formation ⁸⁶. (see fig 4)

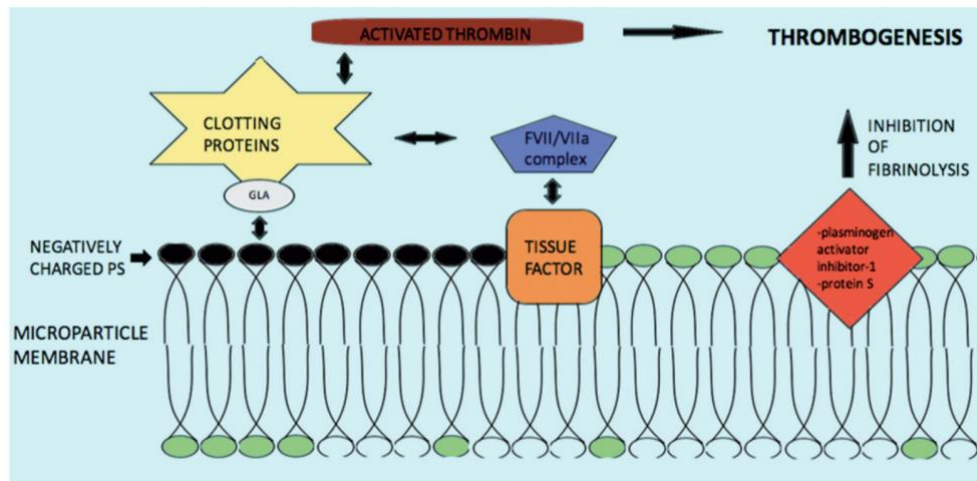


Fig 4: Mechanisms and molecules related with MVs-induced coagulation.

PS: phosphatidylserine; GLA:c-carboxyglutamic acid; clotting proteins factors VII, IX, X and prothrombin. PS electrostatically catalyzes the assembly of coagulation enzyme complexes by interacting with the GLA domain of the clotting factors called vitamin-K dependent factors. Tissue factor induced specifically at the surface of activated endothelial or leukocytes cells may also activate the coagulation cascade via the FVII/VIIa complex.³¹ (Voukalis et al 2019)

Many studies focused on the correlation existing between the level of EMVs in the blood and cardiovascular diseases. ^{5,69,88} CD31+MV's plasma levels were correlated with a higher risk of major adverse cardiovascular and cerebrovascular events and the need for revascularization ⁸⁹.The count of MVs of different origin, including EMV (CD31+, CD51/61+ and CD34+), Platelet MVs (CD42+), monocytes MVs(CD14+) and MV-derived from leukocytes

derived (CD45+) enabled the identification of characteristic patterns enabling the discrimination between patients with myocardial infarction (MI) from those with stable coronary artery disease and healthy volunteers.⁹⁰ Morel et al. described that patients with ST elevation myocardial infarction (STEMI) and unstable angina had higher circulating levels of procoagulant EMVs detected by CD105 labelling as compared with patients with stable angina⁹¹ or acute coronary syndromes. Patients with acute ischemic stroke were found to have increased levels of platelet-derived MPs bearing the integrin GPIIb-IIIa during the acute phase and up to 6 months later, putting forward that thrombotic propensity might last more than the acute phase of the infarct.⁹² Indeed GPIIb-IIIa is a platelet plasma membrane protein that enables the adhesion of platelets to fibrin and that is overexposed after platelet activation. In carotid, abdominal aorta and femoral arteries from patients with non-symptomatic atherosclerotic disease, elevated levels of circulating leukocyte-derived MVs (CD11a+) were measured⁹³ along with endothelial-derived MVs (CD105+). CD11a+ MVs concentrations correlated with the Framingham index that characterizes patients at cardiovascular risk and with higher carotid intima-media thickness assessed in 3 different vessels. Altogether, these data indicate the diagnosis value of MVs in the early detection of atherosclerotic disease⁹⁴.

Chapter III
**Periodontitis: a local infection with
cardiovascular consequences**

III.1 Periodontitis: a clinical overview

Periodontitis, is a chronic inflammatory disease associated with the formation of a dysbiotic biofilm, progressive destruction of the tooth-supporting tissues such as the gingiva and the underlying alveolar bone ⁹⁵ ultimately leading to tooth loss ⁹⁶ and appraised as a silent disease. ⁹⁷ Having various etiologic and contributory factors, ⁹⁸ severe type of periodontitis affects approximately 11% of the world's population. ⁹⁹ Mostly gram-negative anaerobic bacteria colonize subgingival biofilms. ¹⁰⁰ Innate and adaptive immune response are triggered in periodontitis. ¹⁰¹ *Porphyromonas gingivalis*, *Treponema Denticola* and *Tanerella Forsythia*, known as the “red complex” in gingival plaque, are responsible for periodontitis progression. ^{102 103}

III.2 *Porphyromonas gingivalis* (*P. gingivalis*): Role in inflammation and immune response

P. gingivalis is a gram-negative anaerobic bacteria, able to overthrow the host response and to nurture the malfunction of the homeostatic state in a complement dependant manner. ¹⁰⁴ It developed strategies to destabilize components of the host immune system such as Toll-like receptors and complement.

P. gingivalis undermines the innate immunity, demolishes the entire biofilm growth in the periodontium thus eliciting the homeostatic host-microbial balance, making it a keystone pathogen in periodontitis. It colonizes and set

the scene for inflammatory bone loss. *P. gingivalis* instigates dysbiosis and periodontitis in conventional mice due to the crucial enzymatic activity of the Arg-specific cysteine proteinases (gingipains) of *P. gingivalis* exhibiting complement C5 convertase-like activity.¹⁰⁵ (see fig 5)

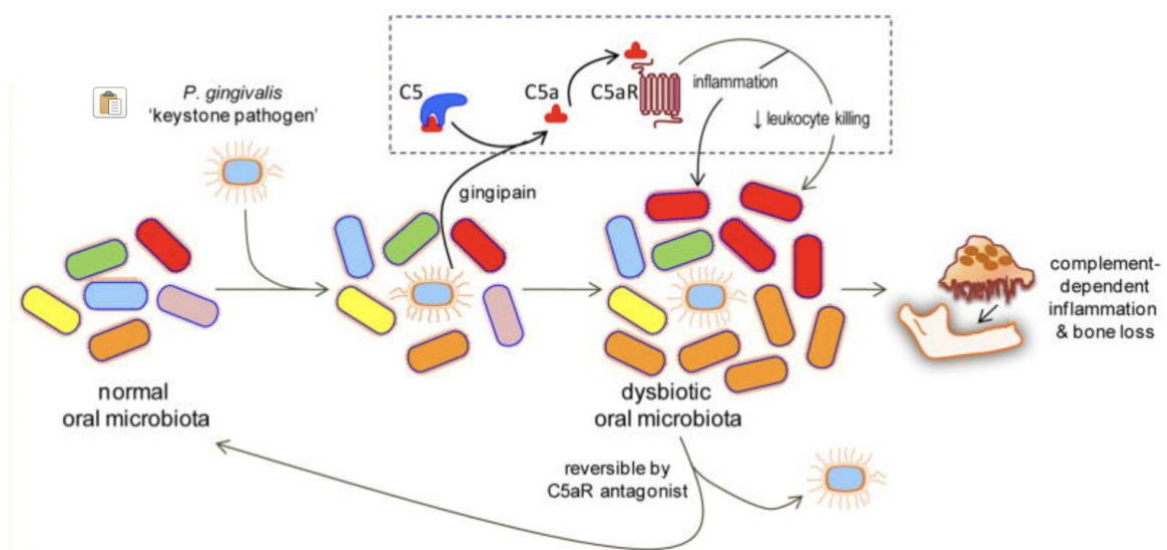


Fig 5: *P. gingivalis* leads the inflammatory disease. The bacterium's gingipain, a C5 convertase-like enzyme cleaves C5 giving rise to high levels of C5a locally. C5a-induced activation of C5aR triggers inflammation and also is censoriously involved in a subversive crosstalk with TLR2 that impairs leukocyte killing.¹⁰⁵ (by Hajishengallis et al 2012)

The possible mechanisms explaining the severity of the response are a remote action of the periodontal pathogens at distance, and/or the increased systemic inflammation mediated by pro-inflammatory cytokines such as interleukin (IL) - 1, IL-6 and TNF- α released in the blood flow.^{106, 107}

P. gingivalis harvests many virulence factors including lipopolysaccharide (LPS) ¹⁰⁸ inducing Toll-like-receptor (TLR)-mediated inflammatory responses ¹⁰⁹ and the recruitment of neutrophils and polymorphonuclear leukocytes (PMNs) at site of the initial infection ¹⁰⁷. The LPS from *P. gingivalis* activates TLR-4 or TLR-2, ¹¹⁰ paving the way for evasion to immune detection and favouring bacterial survival.

The unique ability of *P. gingivalis* to prompt TLR-2 signaling while TLR4-dependent recognition is significantly impaired, favors low-grade persistent infection. ^{111,112} At the vascular level, activation of TLR2 by LPS is associated with immunothrombosis, a mechanism that reinforces thrombotic pathways via exaggerated local coagulation.

In animal models, *P. gingivalis* stimulation led to the up-regulation of TLR2 expression and to pro-inflammatory cytokine secretion *in vitro*. It was also evidenced that TLR2 is crucial for alveolar bone loss caused by *P. gingivalis* infection ¹¹³ as well as for *P. gingivalis* LPS-activated nitric oxide, TNF- α , and IL-6 production by macrophages .¹¹⁴

P. gingivalis employs both complement and TLR signaling to induce bacterial persistence. Recognized by the TLR2 on neutrophils, *P. gingivalis* activates the adaptor protein MyD88 initiating for bacterial elimination. However, *P. gingivalis* produces gingipains, enzymes that function as complement C5 convertases. C5a complement fragment binds to its receptor (C5aR), which induces the E3 ligase Smurf1 to ubiquitinate MyD88 and mark it for

proteosomal degradation, beneficially inhibiting bacteria killing. (see fig 6)

Thrillingly, binding of *P. gingivalis* to the TLR2 also induces inflammation through a signaling pathway involving the adaptor molecule Mal and the enzyme phosphatidylinositol 3-kinase (PI-3K). Also, the same pathway can prevent actin polymerization through inhibition of the small GTPase RhoA and block phagocytosis.¹¹⁵

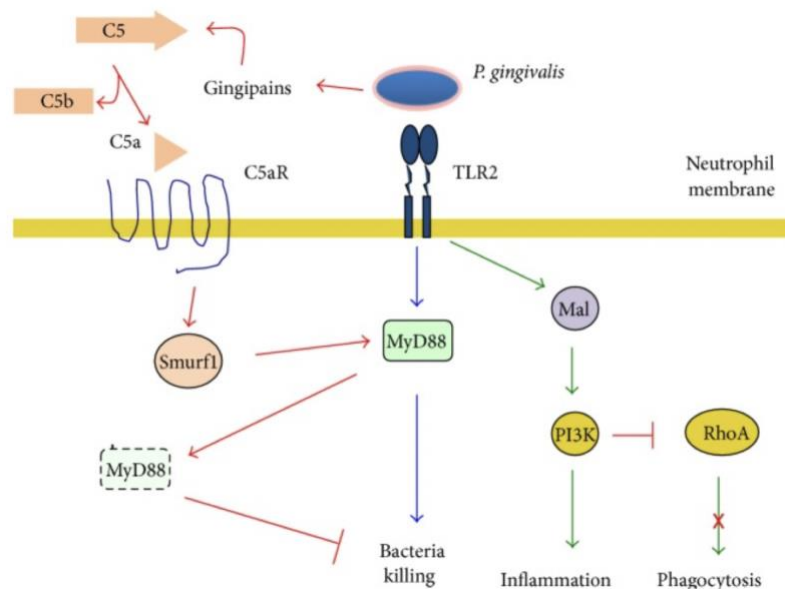


Fig 6: *P. gingivalis* employs both complement and TLR signaling to induce bacterial persistence. C5a: receptor for C5a. Mal adaptor protein; PI3K: phosphatidylinositol 3-kinase. RhoA: small GTPase Rho.¹¹⁵ (by Cortes-Vieyra et al 2016)

Neutrophils constitute the majority of leukocytes recruited to the gingival crevice or periodontal pockets, which are heavily invaded by subgingival microbial communities.^{116 117} Being indispensable for homeostatic immunity,¹¹⁸ neutrophils are dysregulated in periodontitis, and can cause collateral

tissue damage through the release of toxic and/or inflammatory molecules or tissue degrading proteases.¹¹⁹⁻¹²¹

As stated above, *P.gingivalis* expresses ligands that activate the toll-like receptor-2/toll-like receptor-1 complex and enzymes (HRgpA and RgpB gingipains) with C5 convertase-like activity that generate high local concentrations of C5a ligand so that *P.gingivalis* coactivates C5a receptor and toll-like receptor-2 in neutrophils and macrophages.

In neutrophils, ubiquitination and proteasomal degradation of the MyD88, inhibits the host-protective antimicrobial signaling in response to the C5a receptor-1/TLR2 dependent release of TGF β -1, that mediates MYD88 ubiquitination by the E3 ubiquitin ligase Smurf1. Moreover, the C5a receptor-1/TLR2-2 cross-talk activates the PI3-kinase, which inhibits phagocytosis through suppression of RhoA GTPase activity and inhibition of actin polymerization and the induction cytokine production., In macrophages, *P. gingivalis* activates C5a receptor-1 and induces intracellular Ca²⁺ influx, leading to a drastic enhancement of the cAMP-dependent signalling, otherwise weak when induced by TLR2 alone. cAMP-dependent protein kinase A (PKA) inhibits nuclear factor-kappaB and glycogen synthase kinase-3beta signaling, thereby suppressing inducible nitric oxide synthase activation (iNOS) and -oxidative destruction of the pathogen. (see fig 7)

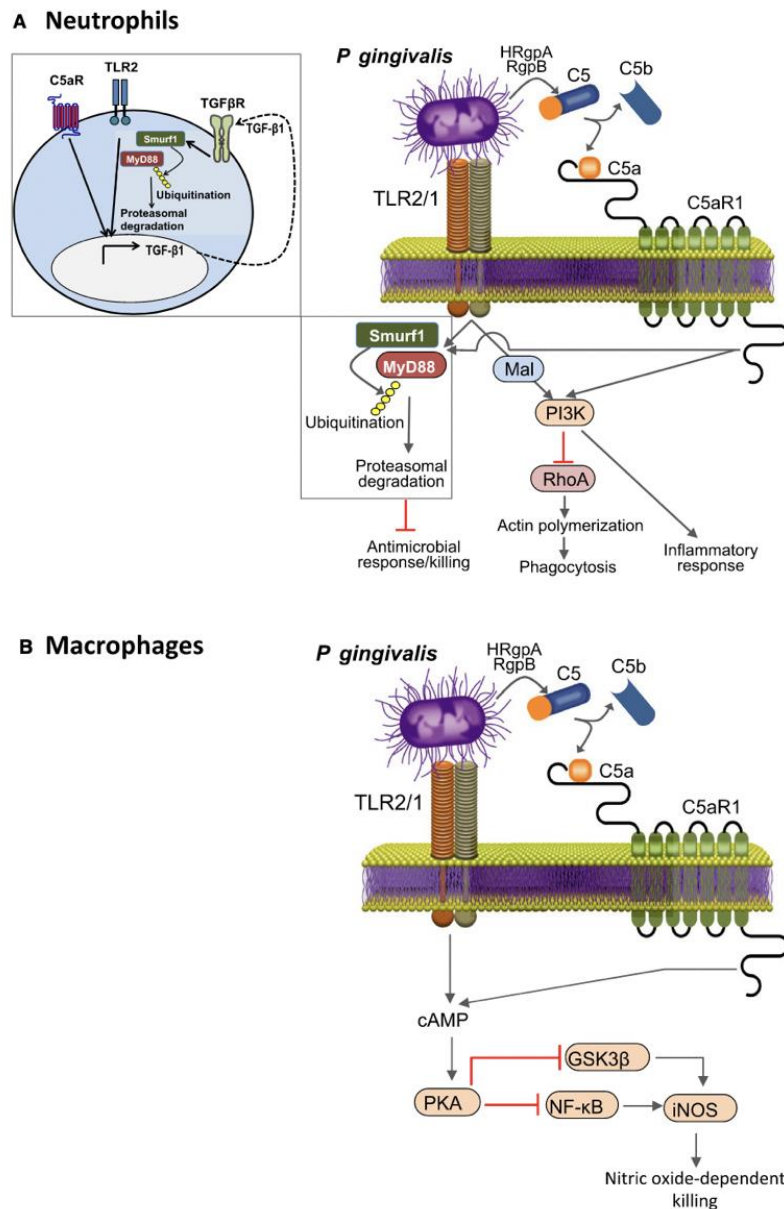


Fig 7: *P. gingivalis*-induced C5a receptor-1/toll-like receptor-2 crosstalk in neutrophils and macrophages. GSK, glycogen synthase kinase; iNOS, inducible nitric oxide synthase; Mal, myeloid differentiation primary response protein 88 adaptor-like; MyD88, myeloid differentiation primary response protein 88; NF- κ B, nuclear factor-kappaB; PI3K, phosphoinositide 3-kinase; PKA, protein kinase A; TGF, transforming growth factor; TLR, toll-like receptor. ¹²² (by Hajishengallis et al 2020)

III.3 Periodontitis and endothelial dysfunction

Endothelial dysfunction occurs early in the pathogenesis of arterial disease, in response to a wide range of factors that have been shown to predict cardiovascular events in epidemiologic studies.¹²³ Periodontal diseases are associated with major systemic diseases such as cardiovascular diseases, diabetes, or adverse pregnancy outcomes.¹²⁴ For more than a decade, the link between systemic inflammation and periodontitis has been studied¹²⁵, in particular by focusing on endothelial dysfunction. (see fig 8)

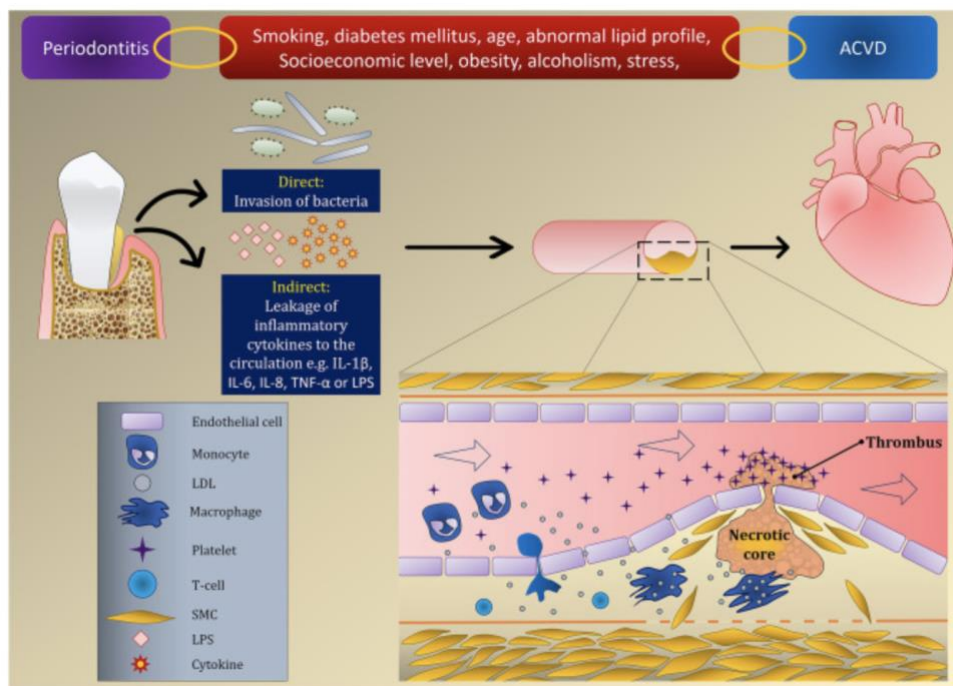


Fig 8: Link between periodontitis and atherosclerotic cardiovascular diseases induced by endothelial dysfunction¹²⁶ (by Zardawi et al 2021)

Different oral bacterial species have been identified in individual atheromas.¹²⁷ The mechanisms underlying bacterial colonization of plaque worsening atherosclerosis are activation of the immune system, bacteremia, direct

involvement of bacterial activated inflammatory mediators, pro-inflammatory cytokine involvement and predisposing factors that can be found in both periodontitis and atherosclerosis.¹²⁸

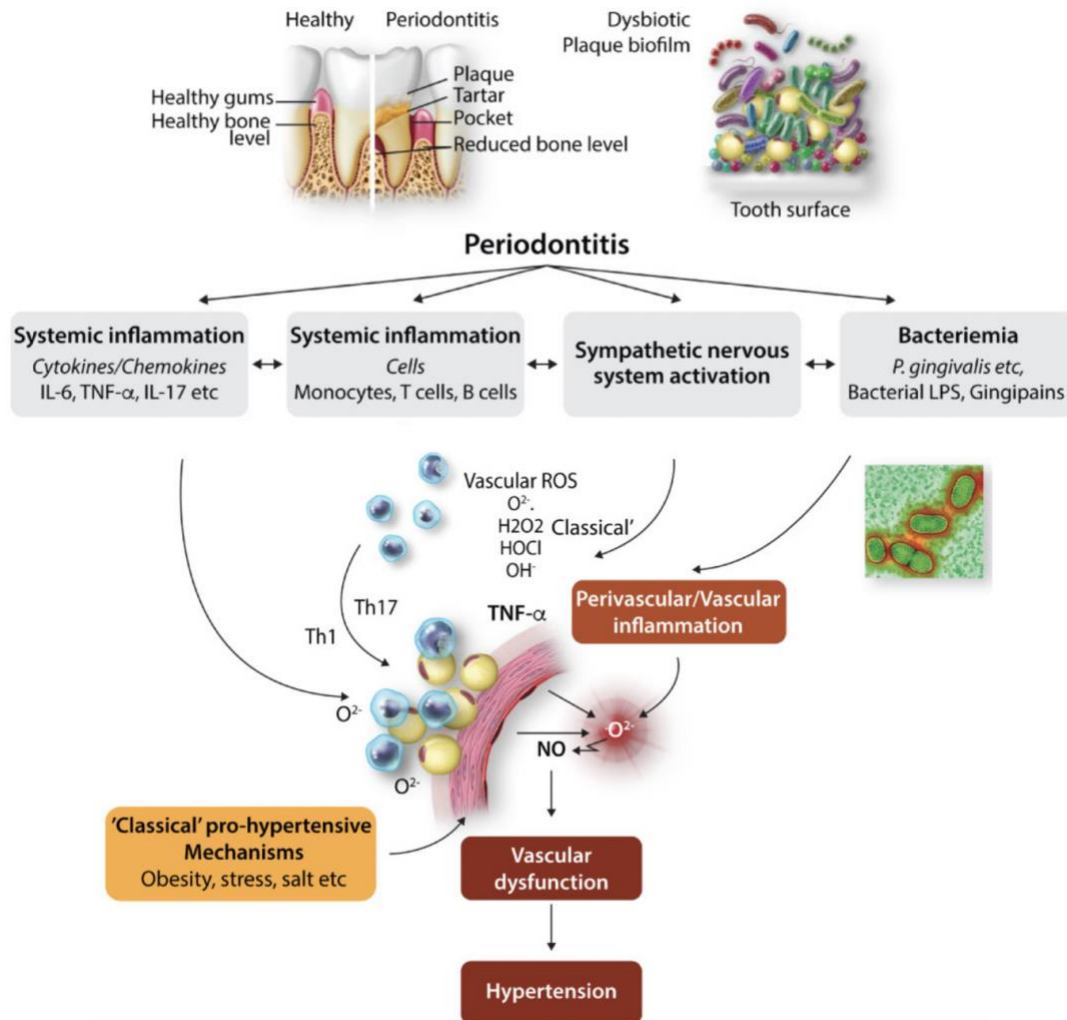


Fig 9: Periodontitis leads to hypertension and vascular dysfunction. Prospective mechanisms causally linking periodontitis with hypertension and vascular dysfunction. NO, nitric oxide; O-2, S, superoxide; Th, T-helper cells; ROS, reactive oxygen species¹²⁹ (by Aguilera et al 2020)

New approaches such as massive sequencing correlated findings from different samples, including atheroma and subgingival/oral samples,¹³⁰ thereby confirming that periodontal pathogens can reach and colonize

atheroma plaques. Living *P.gingivalis* and *Aggregatibacter actinomycetemcomitans* were found in atheromatous tissue.¹³¹ Several in vitro studies indicates also that different periodontal pathogens, in particular, *P.gingivalis* colonize endothelial cells^{6,132,133}.

The hypothesis of a remote pathogen action is also supported in animal models. Rabbits with experimentally induced periodontal disease, develop fatty streaks in the aorta.¹³⁴ In normocholesterolemic pigs, *P. gingivalis* induced aortic and coronary lesions,¹³⁵ while it accelerated atherosclerosis in murine models.¹³⁶

Finally, in recent studies, the treatment of animals with patients sera induced endothelial dysfunction in mice,¹³⁷ and the up-regulation of ET-1, ICAM-1, E-selectin, IL-1, and sCD14,¹³⁸ all surrogate markers of the endothelial activation and inflammatory response. However, data on periodontitis direct outcomes in humans at risk of developing atherosclerosis remain scarce.

III.4 Periodontitis and systemic diseases: impact of *Porphyromonas Gingivalis* on cardiovascular disorders

Being involved in different systemic pathologies, including rheumatoid arthritis, cardiovascular pathologies, and neurodegenerative diseases, *P. gingivalis* is a clear evidence of correlations existing between oral health and systemic inflammation.¹³⁹ (see fig 10)

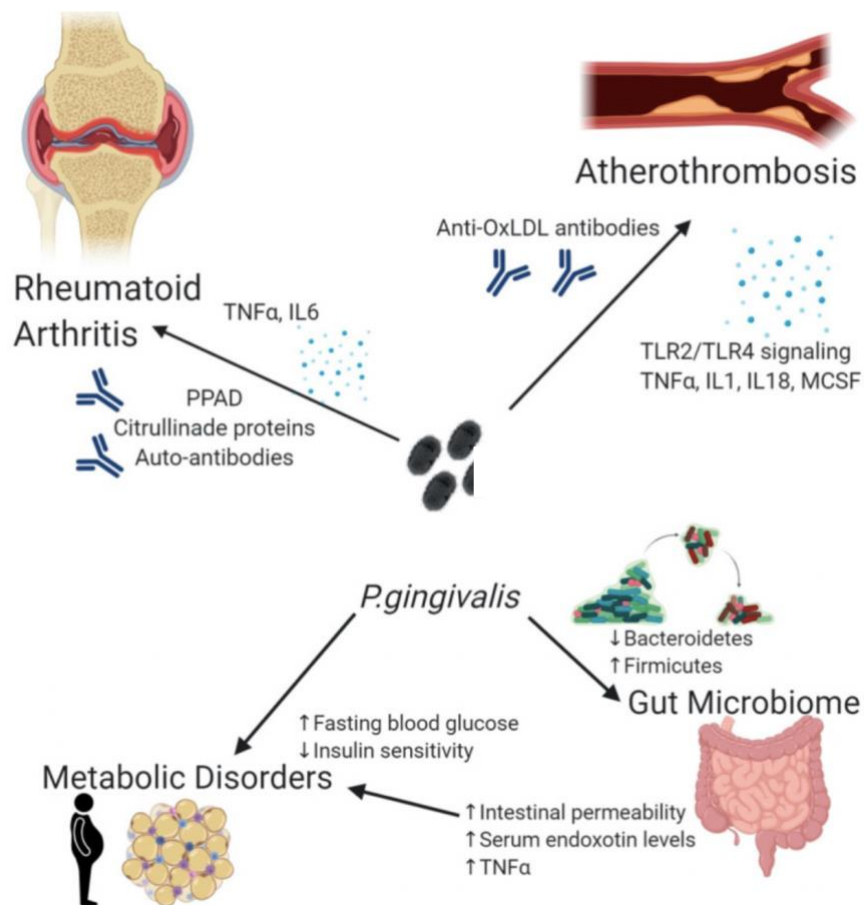


Fig 10 : *P. gingivalis* empires the progression of multiple chronic inflammatory diseases. Through the cross-reactive mediators in atherothrombosis, rheumatoid arthritis, the increased levels of systemic inflammation, gut microbiome dysbiosis, metabolic disorders. (↑ = increase ↓ = decrease). ¹⁴⁰ (by Mulhall et al 2020 & authorized by co-author Olivier Huck)

P. gingivalis secretes a peptidyl arginine deiminase (PPAD) with a broad spectrum of action and particular interest in atherosclerotic lesions. ¹⁴¹ In addition, the periodontium of periodontitis patients with no signs of rheumatoid arthritis expresses citrullinated proteins. Furthermore, the serum from these patients contain higher levels of antibodies to citrullinated and non-citrullinated human peptides, suggesting that the overload in citrullination caused by periodontitis leads to a loss of tolerance to citrullinated peptides. This strongly

suggests a cross-reaction against citrullinated proteins of the joint, eventually favoring rheumatoid arthritis. ¹⁴² (see fig 11)

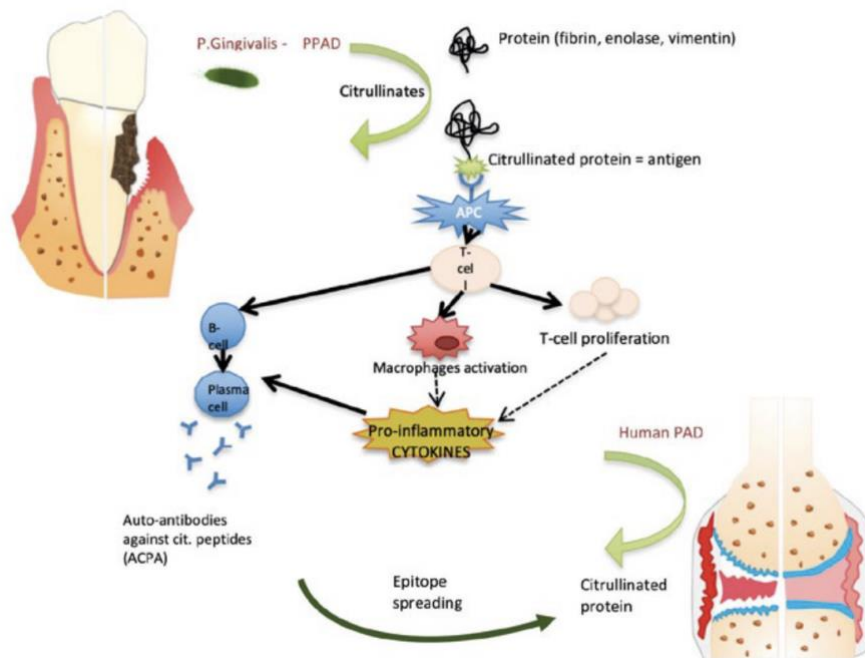


Fig 11: *P. gingivalis* in rheumatoid arthritis. *P. gingivalis* breaking immune tolerance to citrullinated proteins in rheumatoid arthritis (RA) by bacterial citrullination of proteins through PPAD, initiating an immune response leading to loss of tolerance for citrullinated joint proteins in the joints.

Abbreviations : PPAD: peptidyl arginine deiminase from *P. gingivalis*; APC: antigen presenting cell; TNF: tumour necrosis factor; IL: interleukin; GM-CSF: granulocyte-macrophage colony-stimulating factor¹⁴³ (by Lopez-Oliva et al 2019)

Higher levels of autoantibodies against citrullinated proteins were assessed in patients with rheumatoid arthritis, they were targeting citrullinated histone 2B and correlated the presence of high scores of higher coronary artery calcification. The data suggest a potential role of sero-reactivity to citrullinated histones in atherosclerosis,¹⁴⁴ an hypothesis supported by growing evidences of the role of NETosis in immunothrombosis. Chronic oral infection by *P.*

gingivalis results in significant increases in oral bone resorption, aortic inflammation, viable bacteria in oral epithelium and aorta, and plaque development. *P. gingivalis* persists within vascular tissue through cell-to-cell transmission¹⁴⁵ and was reported to accelerate atherogenic plaque formation in ApoE mice fed with a high fat diet.¹⁴⁶

In mice, periodontal pathogens induce myocarditis and/or myocardial infarction¹⁴⁷. (see fig 12) Relationships between periodontal disease and myocardial infarction were hardly replicated or confirmed yet.^{148 149}

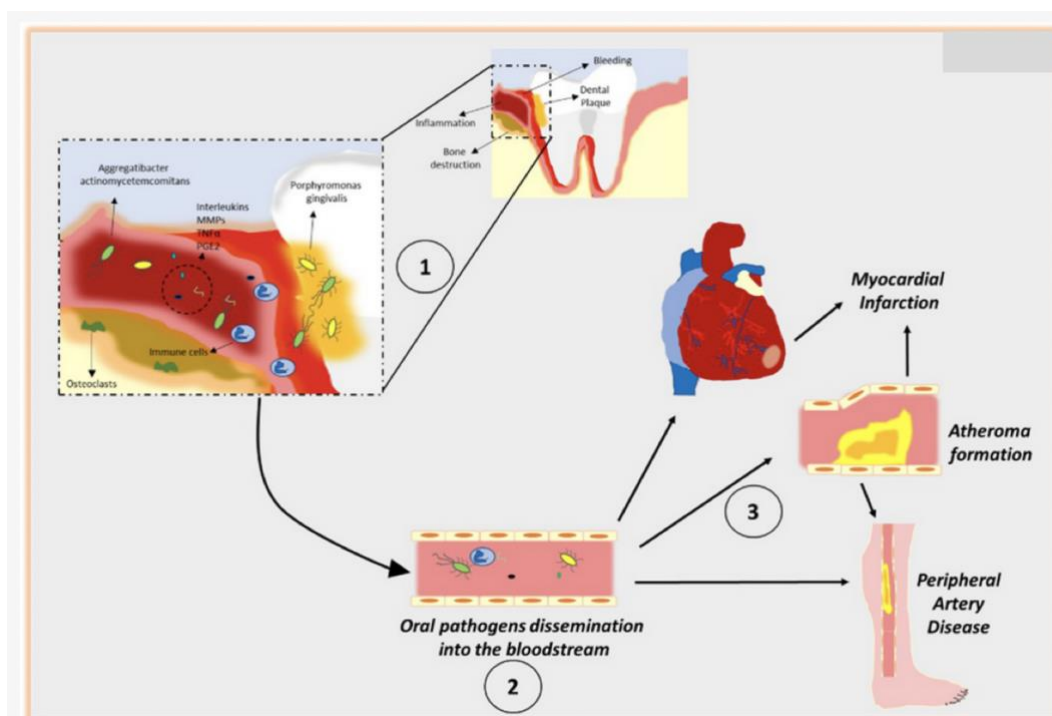


Fig 12: Possible inflammatory mechanisms linking periodontitis to Cardiovascular diseases (CVDs). (1) The imbalance in pathogens of the biofilm leads to gingival epithelium inflammation that releases inflammatory mediators, such as interleukins (ILs), prostaglandin E2 (PGE2), tumor necrosis factor alpha (TNF- α) and MMPs, that recruit immune cells. This inflammatory response induces alveolar bone reabsorption, by osteoclasts. (2) At a chronic

stage, oral pathogenic dissemination into the bloodstream leads to the onset of CVDs including atherosclerosis, myocardial infarction and peripheral artery disease (3).

III.5. *P.Gingivalis* impact on endothelial response

In vitro, the endothelial response to *P. gingivalis* has been assessed using HUVECs. LPS of *P.Gingivalis* or the bacteria itself, lead to the emission of proapoptotic microvesicles (MVs).⁶ In addition, It was found that Gram-negative bacteria produce outer membrane vesicles (OMVs) at various stages of their growth, especially in the environment of infected tissues.¹⁵⁰ *P.gingivalis* OMVs were found more virulent than the parent bacteria¹⁵¹ . OMVs strongly promote co-aggregation between different oral bacterial species that do not or only weakly copolymerize such as *Streptococcus*, *Actinomyces*, and *Candida albicans*. OMVs also inhibit and disperse biofilms in a gingipain-dependent manner, thereby creating a favorable environment for *P. gingivalis*. Moreover *P. gingivalis* OMVs enhance adhesion and invasion of epithelial cells by *Tannerella forsythia*¹⁵². (see fig 13)

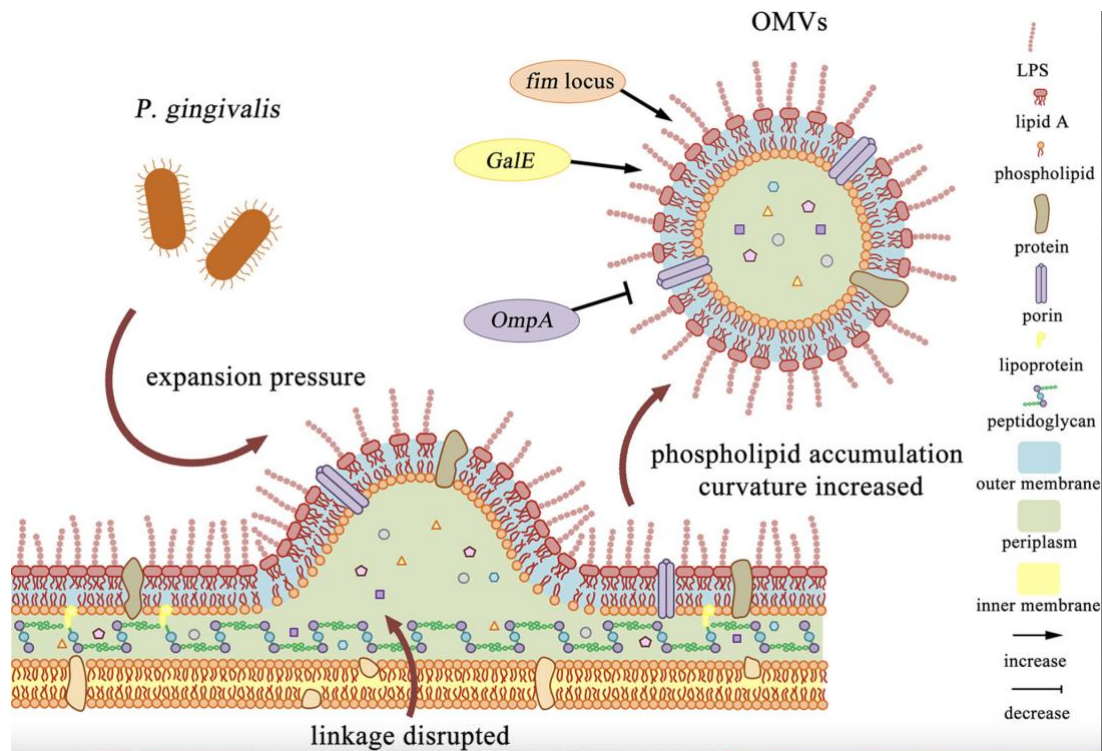


Fig 13: Production of *P. gingivalis* outer microvesicles (OMVs). 1. After the cell wall disruption, phospholipids accumulation in the outer membrane leaflets, and the expansion pressure continues to produce, which intensifies the further enrichment of outer membrane components. The linkage between the peptidoglycan and the outer membrane layer is disrupted, and finally *P. gingivalis* OMVs are formed. 2. The *fim* locus and *GalE* mutant strains reduced or even eliminated the production of *P. gingivalis* OMVs, while the *OmpA* mutant strain overproduce *P. gingivalis* OMVs. ¹⁵³ (By Zhang et al 2021)

Bacteria associated with periodontitis can pervade into coronary vessels as well ¹⁵⁴. The major consequence of *P. gingivalis* infection is the proliferation of smooth muscle cells in the distal aorta and the risk of aneurysms. ¹⁵⁵ It was found that *P. gingivalis* OMVs promote calcification of vascular smooth muscle cells in a concentration-dependent manner through ERK1/2-RUNX2. ¹⁵⁶ *In vitro* and *in vivo* models showed that *P. gingivalis* OMVs significantly increase vascular permeability leading to vascular edema and mortality in a gingipain-dependent manner. ¹⁵⁷

These findings reinforce the hypothesis that *P. gingivalis* infection is a risk factor in cardiovascular diseases and in the development of atherosclerosis.¹⁵⁸

Nevertheless, the clinical assessment of all pathological aspects potentially supported by chronic gingival infection by *P. gingivalis* remains to be strengthened.

In addition, the respective contribution of the cellular damages and the sequential occurrence remain to be established.

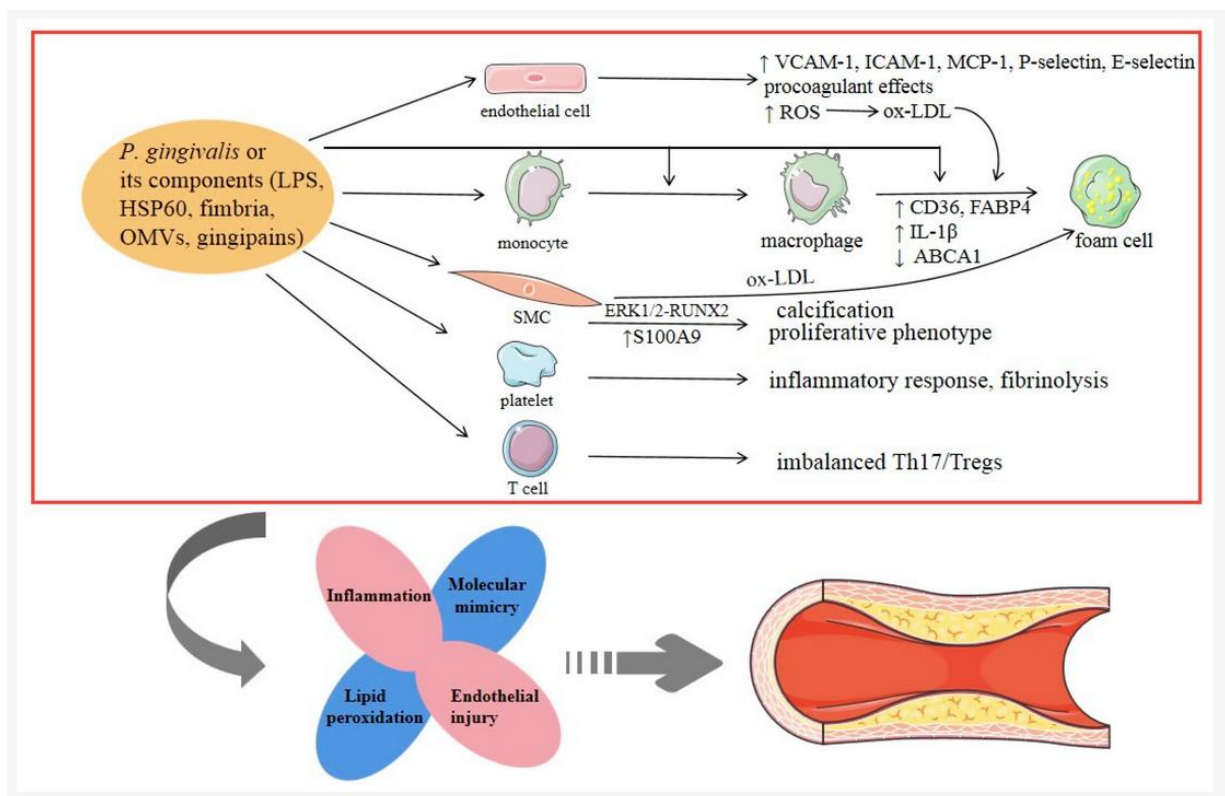


Fig 14: *P.gingivalis*-induced stimulation of accelerated atherosclerosis. Possible mechanisms: inflammation , endothelial injury, lipid peroxidation, and molecular mimicry. ox-LDL: oxidized low-density lipoprotein.¹⁵⁹ (by Mai et al 2020)

Chapter IV: The spleen

VI.1 Anatomy and cell composition

The spleen is the largest secondary lymphoid organ in the body and possesses a wide range of immunological functions.¹⁶⁰ It is divided by function and structure into the red and white pulp separated by the marginal zone (MZ) in rodents and the perifollicular zone in humans. Lacking afferent lymphatic vessels, all cells and antigens enter the spleen via the blood flow. The White pulp (WP) the primary immunologic region of the spleen in both species, and the red pulp (RP) constitutes the majority of the tissue with a distinct immune function.¹⁶¹

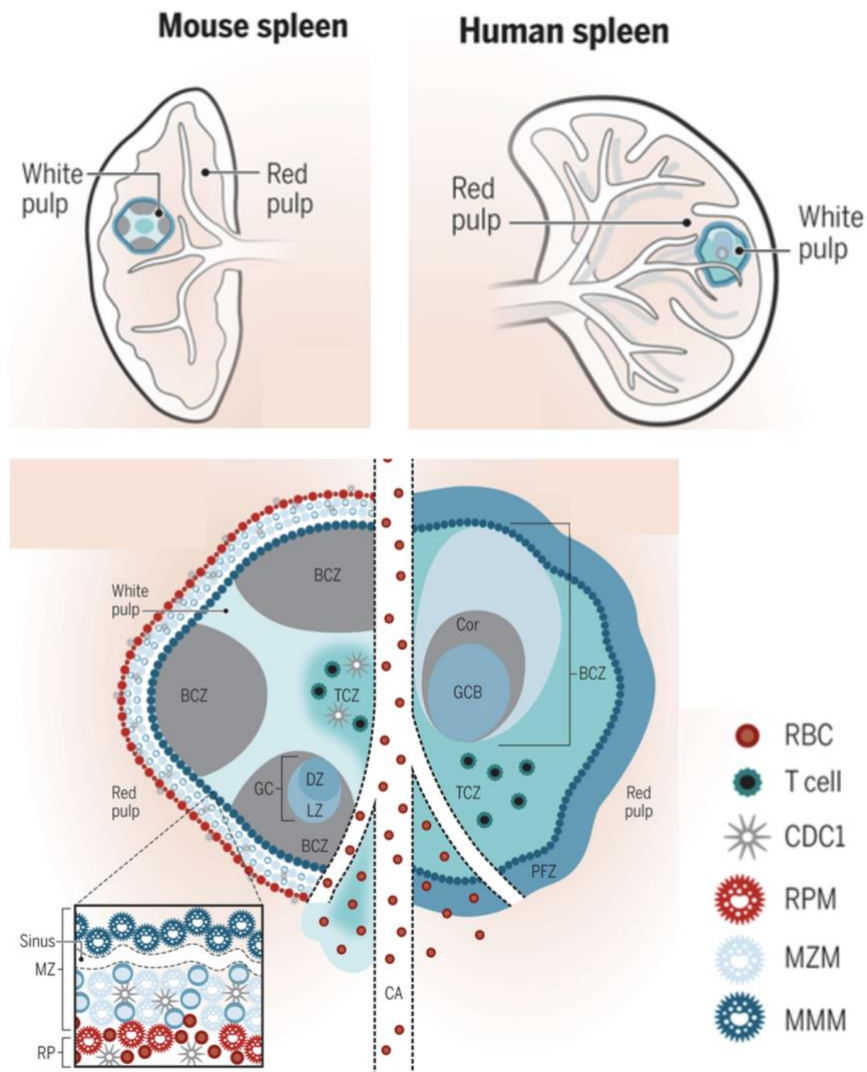


Fig 15: Mouse and human splenic immune cellular architecture.

Structural differences between the murine and human splenic immune system.

The organization of T cell zone (TCZ) and B cell zone (BCZ) follicles ,shown with light zone, LZ, and dark zone, DZ, organization in mouse spleen within the WP and the border between the WP and RP, the MZ (marginal zone) in mouse or perifollicular zone (PFZ) in human (dark blue outer ring). The extent to which the mouse MZ and human PFZ are analogous remains unknown. the precise layering and composition of macrophage subsets in the MZ is known for mice (bottom left box) CD169+ MMMs (dark blue) form a concentric ring around the WP with MZMs (light blue) and MZB cells (darker blue) but not for humans due to imaging techniques limitations. In humans, MZB cells surround activated B cells, containing a GC (In the human spleen on the right) and Corona (“Cor”). The homeostatic location of dendritic cell (DC) subsets in mice is shown (with cDC2s in the bridging channel, BC, and

*cDC1s in the TCZ, MZ and RP, red pulp). Release of blood into the MZ of the WP from a central arteriole (CA) is shown.*¹⁶⁰(Lewis et al 2019)

Immune cells in the spleen include different subsets of T and B cells, dendritic cells (DC) and macrophages making the spleen to be the most important organ for antibacterial and antifungal immune interactions, but also providing numerous other functions namely filtration, destruction of old red blood cells (RBCs)¹⁶² and downstream activation of adaptive immune cell types.¹⁶³

VI.2 Splenic Immune response and microvesicles

Spleen microvesicles (SMVs) are representative markers of pathophysiological conditions. Elevated levels of thrombocytes and their MVs were observed in splenectomized zebrafish.¹⁶⁴ In vitro, isolated rats SMV initiate an early pro-inflammatory, pro-coagulant and a pro-senescent response in endothelial coronary artery cells.⁴ The SMV content and their noxious properties vary according to the age of the rat and could be counteracted by oral treatment.⁷ In addition, injection of *P. gingivalis* significantly increased the shedding of procoagulant SMVs. In addition, the important role of neutrophil-derived MVs isolated from the spleen and inducing endothelial senescence was confirmed by immunodepletion.⁴

Chapter V: The heart

V. 1 Immune cells in the heart

The heart tissue is not only a muscle submitted to electrical pulses but also the host of a variety of cells. In addition to cardiomyocytes and mesenchymal cells, the cardiac tissue contains immune cells and all the cellular equipment of a vessel like endothelial cells, pericytes and circulating blood cells. The macrophages are the major immune cell population in the resting heart. They are found in the interstitium and around endothelial cells. Inflammatory monocytes and neutrophils are not present in the myocardial tissue but can be observed upon tissue damage. Mast cells, dendritic cells, B cells, NK cells and regulatory T cells are found sporadically in cardiac tissue.

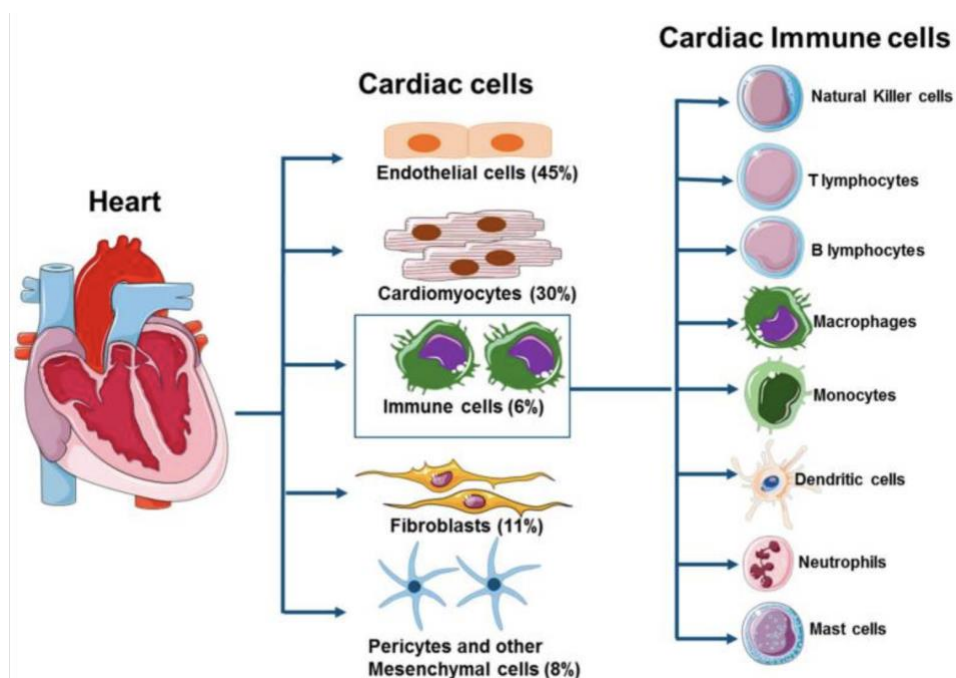


Fig 16: Cellular composition of the heart. The heart tissue contains different sub-types of immune cells depending on the physiopathological condition.

V.2 Evidences of inflammation in cardiac tissues

Inflammation has been implicated in the pathophysiology of various cardiac diseases. Heart failure and cardiomyopathy are associated with a 4–6-fold increase in atrial fibrillation prevalence.¹⁶⁵ In the pathophysiology of heart failure, inflammation modulates the cell signaling activation patterns associated with fibrosis, apoptosis and hypertrophy¹⁶⁶. In addition, serum levels of tumor necrosis factor- α (TNF- α), were significantly in patients with elevation of diastolic heart failure and a history of atrial fibrillation suggesting an inflammatory signature and a possible paracrine effect.¹⁶⁷ The inflammatory response to ischemia and reperfusion is a basic process for cellular debris removal and injured tissues repair. Similarly to the neurohormonal activation observed after acute myocardial infarction, inflammation might as well induce a systemic response that favors adverse remodelling.¹⁶⁸

Through inflammatory processes, the NLRP3 inflammasome in the heart is activated by two independent steps: Initiating and triggering. (see below)

V.3 Inflammatory signalling pathways in cardiac tissues

The inflammatory pathways in the heart trigger the inflammasome and downstream apoptosis. Activation will be initiated through the TLR-dependent sensing of damage-associated molecular patterns (DAMP) exposed by pathogens or injured cells or tissues at the vicinity of the cardiac cells. This

“priming” of the inflammasome pathway initiates the NF- κ B-dependent transcription and the up-regulation of various components of the inflammasome cascade like caspase-1, NLRP3 and ASC and the immature forms of IL-1 β , IL-18, (Pro-IL). Priming may also occur directly through NOD2 that also targets NF- κ B. The primary signal is necessary but insufficient to form the inflammasome in cardiomyocytes in the absence of the trigger signal. Eventually, the response will be amplified through P2X7 receptors activated by high concentrations of extracellular ATP released by activated or damaged cells. P2X7 receptors activation leads to K⁺ efflux, a step that triggers NLRP3 activation. Another mechanism triggering the inflammasome, is the lysosomal destabilization by indigestible material that leads to the leakage of the cathepsin B and the induction of K⁺ efflux favoring NLRP3 activation. Upon binding to the serine threonine kinase Nek7 that senses the K⁺ efflux, NLRP3 is activated by phosphorylation. In cardiomyocytes, the mitochondria count is high and their damage causes important oxidative stress through the release of ROS leading to the unfolded protein response also targeting NLRP3 via the capture of ROS by TXN further enabling the dissociation of the complex TXN/TXNIP. Mitophagy and autophagy maintain low levels of NLRP3 activation by effective clearance of mitochondrial debris that otherwise would favor lysosome destabilization.

After ischaemia, the activation of the inflammasome occurs upon binding of the tyrosine–protein kinase BTK and of apoptosis-associated speck-like protein

containing a CARD (ASC). The active NLRP3 oligomer functions as a platform for the polymerization of ASC into filaments, and in turn for the branching of caspase 1 filaments branches.

Finally, the activation of the inflammasome promotes the secretion of the pro-inflammatory cytokines IL-1 and IL-18 that are freed from their pro-peptide through the proteolytic cleavage by caspase 1. Gasdermin D (GSDMD) is also essential to interleukin secretion by forming a pore in the plasma cell membrane. Indeed, when cleaved by caspase 1 is able to oligomerize.

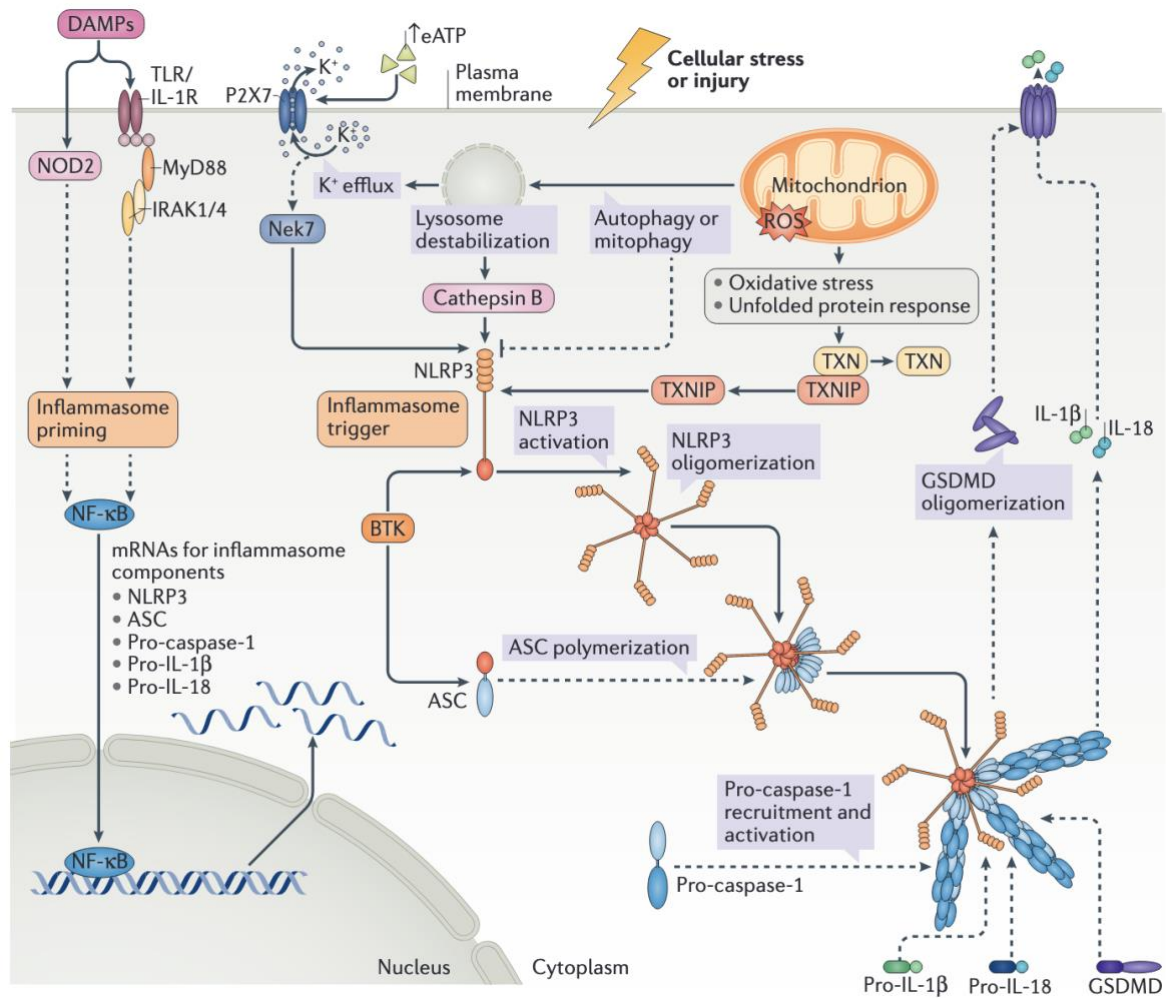


Fig 17: The formation of the inflammasome in the heart. ¹⁶⁸(by S. Toldo and A. Abbate 2018)
 TLRs: Toll-like receptors; MyD88 myeloid differentiation primary response protein, and
 IRAKs: interleukin-1 receptor-associated kinases). NOD2: nucleotide-binding
 oligomerization domain-containing protein 2. TXNIP): Thioredoxin-interacting protein;
 (TRX) thioredoxin.

Chapter VI: Endothelial and immune senescence

VI.1 The different types of senescence

Aging is a universal, ingrained process distinguished by the progressive loss of tissue and organ function over time, resulting in progressive risk of pathologies, such as cardiovascular disorders, cancer, diabetes and neurodegenerative diseases.¹⁶⁹ The theory of aging affirms that human aging is the result of cellular aging, whereupon an enlarged proportion of cells reach senescence.¹⁷⁰ Originating from the Latin word *senex*, senescence means growing old. It has been demonstrated that senescent cells accumulate in tissues with age.¹⁷⁰

Cellular senescence is defined as a cellular state of stable and long-term loss of proliferative capacity, withholding normal metabolic activity and viability.¹⁷¹ It is an irreversible growth arrest that arises in response to persisting or sustained damaging stimuli, such as DNA damage, telomere shortening, telomere dysfunction and oncogenic stress leading to suppression of potentially dysfunctional, transformed, or aged cells.¹⁷²

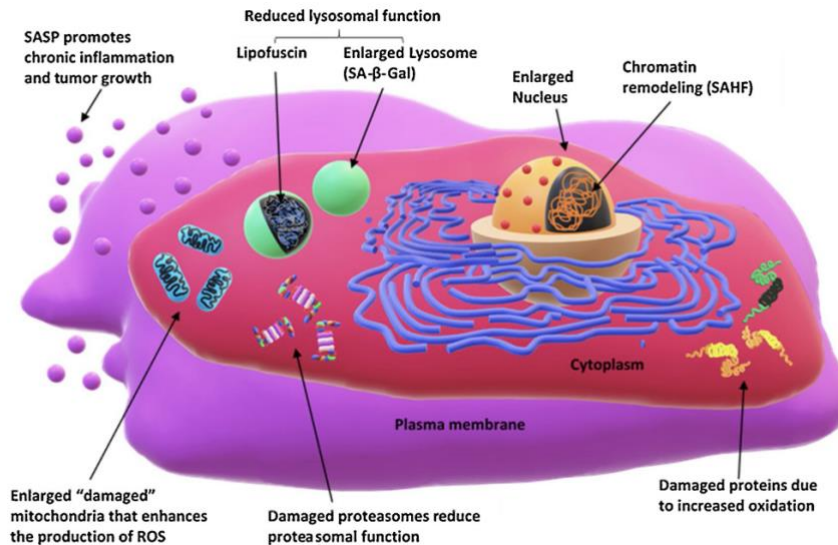


Fig 18: Signs of cellular senescence. ¹⁷⁰(by Kamal et al 2020)

Based on the stimuli's nature, cellular senescence can be categorized into telomere-dependent senescence and non-telomeric senescence respectively termed replicative senescence and stress-induced premature or accelerated senescence. ¹⁷³ DNA damage, oncogenic mutations, reactive metabolites, mitogens, insulin-like growth factor 1 (IGF-1), telomere erosion, epigenetic stress, proteotoxic stress, and damage-associated molecular pattern proteins (DAMPs) are various types of senescent stimuli.

Characterized by a flat, expanded morphology, and resistant to apoptosis, senescent endothelial cells also reveal changes in gene expression and chromatin organization and share common senescence-associated biomarkers such as senescence associated β -galactosidase (SA- β -gal) ¹⁷⁴⁻¹⁷⁶ and a senescence-associated secretory phenotype (SASP) that has IL-1 α , IL-

6, NFκB, C/EBPβ, ROS, or GATA4 as regulators. “Senomorphics” block the harmful and deleterious effects of the SASP. As a counter-regulatory response, senescent cells up-regulate their anti-apoptotic pathways (SCAPs), thus promoting high resistance to apoptosis. In turn, SCAPs represent the targets of “senolytics” that selectively kill senescent cells by impairing the SCAPs.¹⁷⁷

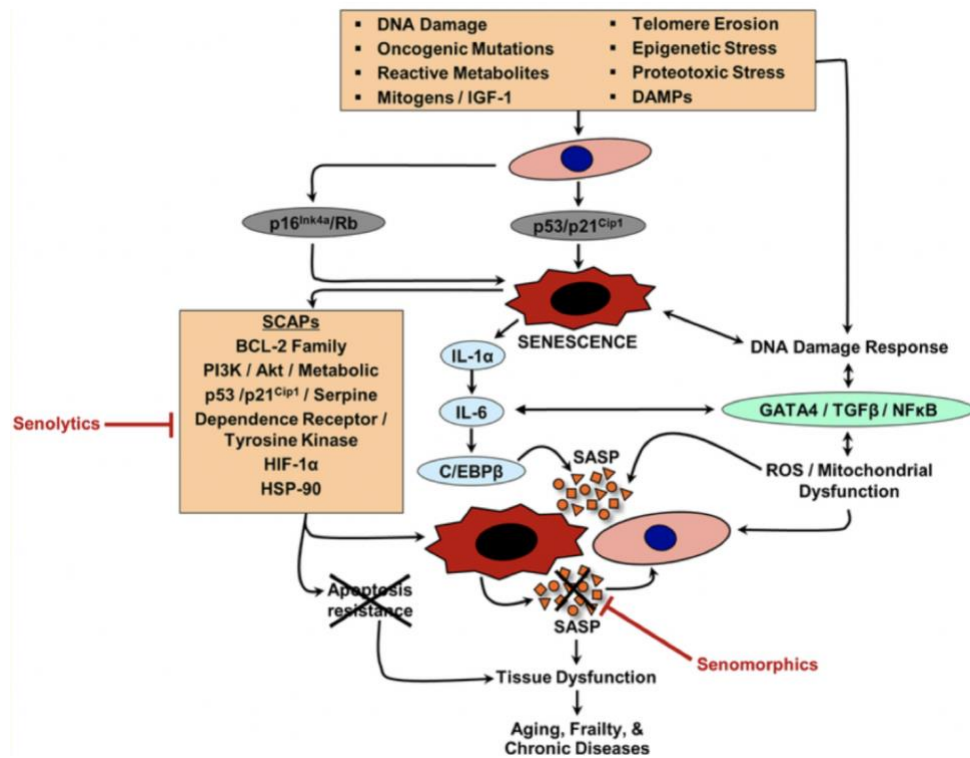


Fig 19: Mediators of senescence, SCAPs, the SASP, and effects of senescent cells.¹⁷⁷ (by J. N. Farr and S. Khosla 2020)

VI.2 Endothelial senescence in inflammation, atherosclerosis, thrombosis and aging

The Increase mean age of populations is a crucial challenge in the pathogenesis of cardiovascular disease (CVD) ^{178 179}. Senescent ECs exhibit reduced endothelial nitric oxide (NO) production and increased endothelin-1 (ET-1), enhancing thrombosis, inflammation, and atherosclerosis with impairment of vessel tone, angiogenesis, and vascular integrity, ¹⁸⁰ all driving the progression of CVD.¹⁸¹ However, the molecular mechanisms of EC senescence, their initiation and control are not yet completely understood.

In advanced human atherothrombotic plaque lesions, there is an increased expression of senescent markers p16 and p21 easily observed in vascular smooth muscle cells (VSMCs), and associated with the large flattened cell shape and S-A β Galactosidase activity. Through replicative senescence, human VSMCs adopt an “osteoblast-like” phenotype and promote vascular calcification. In addition, they produce less collagen and secrete more proteases. As detailed above, senescent VSMCs secrete various pro-inflammatory cytokines as part of their senescence-associated secretory phenotype (SASP). These cytokines stimulate adjacent non-senescent ECs and VSMCs to express adhesion molecules and release cytokines, and/or trigger monocyte (MA) recruitment. Also VSMC senescence promotes fibrous cap thinning. Plaques manifest a direct evidence for replicative VSMC

senescence in human atherosclerosis, where telomere integrity, oxidative stress, plaque vulnerability and inflammation are potential triggers.¹⁸²

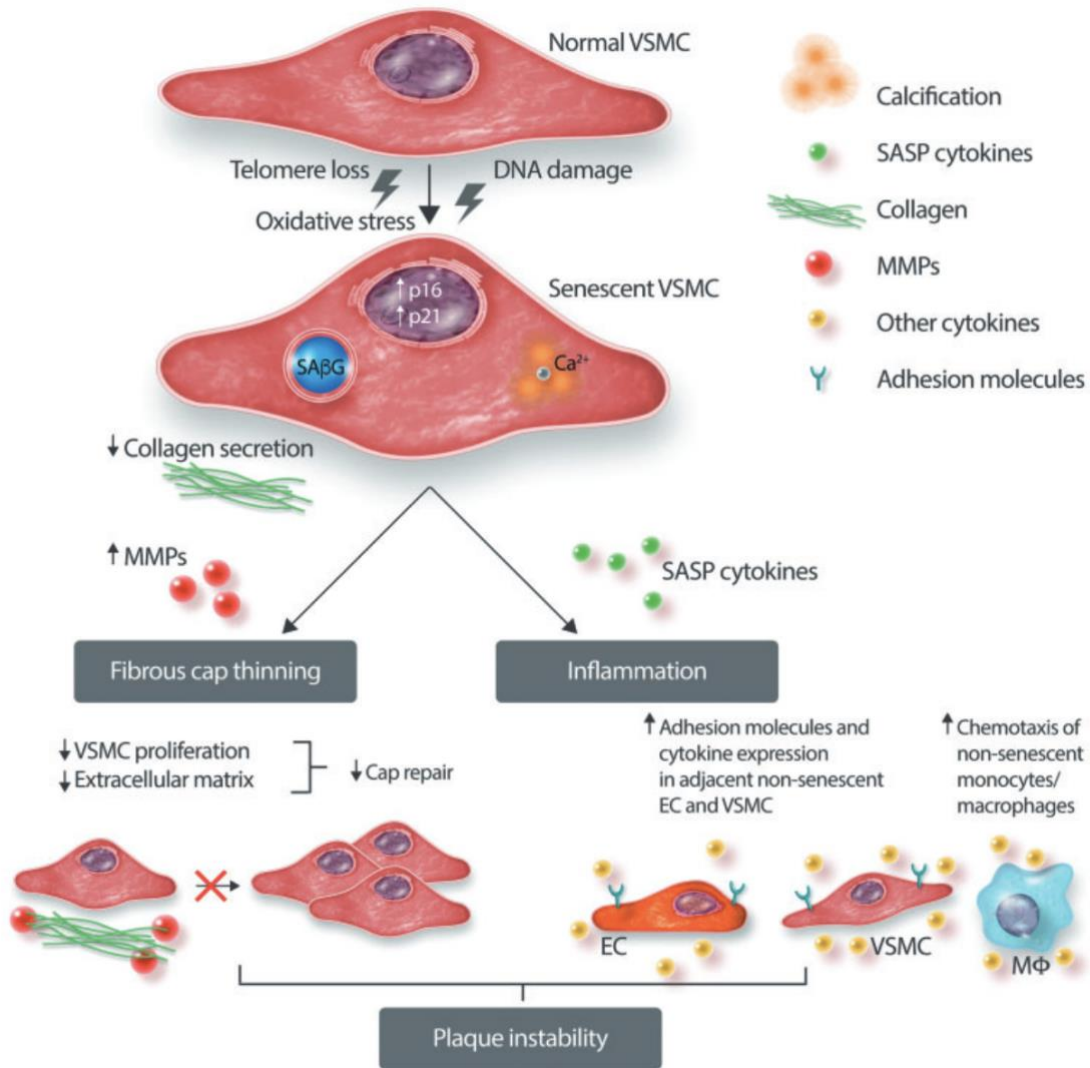


Fig 20: VSMC senescence in atherosclerosis. Through the establishment of the SASP, senescent VSMCs that are Unable to proliferate, put on the line plaque instability and inflammation.¹⁸² (by Gorenne et al 2006)

VI.3 Microvesicles of leukocyte and endothelial origin as effectors of endothelial senescence

MVs from patients with coronary artery disease promote increased endothelial expression of SGLT1, SGLT2, VCAM-1, and the down-regulation of eNOS, and induce endothelial dysfunction and senescence. Previous data from the laboratory suggest the role of spleen-derived MVs in endothelial senescence. In rats, age was an indispensable trigger for the shedding of pro-senescent spleen-derived leukocytes microvesicles (SMVs) measured after spleen harvest. Such SMVs prompted premature senescence of primary coronary endothelial cells. The enhanced and progressive release of pro-senescent EMVs shed from middle-aged and old rat splenocytes suggested the feasibility of an early pharmacological control of the pro-senescent effects of SMVs. Indeed, oral treatment of the animals by omega-3 reduced and even abolished the pro-senescent action of the SMVs.⁷ Using the same SMV endothelial cross-talk model in rats, SMVs generated from LPS or PMA/calcium ionophore treated splenocytes were able to trigger endothelial dysfunction and early senescence, suggesting that bacterial infection may also trigger endothelial senescence.⁴

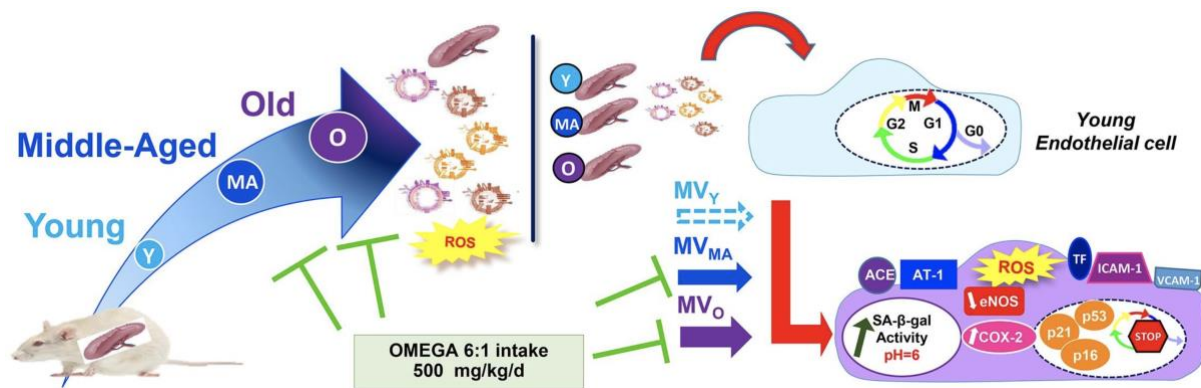


Fig 21: SMVs become prosenescent with ageing as measured in coronary endothelial primary cells. ECs show a pro-inflammatory and procoagulant phenotype with over-expression of VCAM-1, TF, ICAM-1, ACE and down-regulation of eNOS and over-expression of COX-2. MV_Y: SMVs isolated from young individuals, MV_{MA} from middle-aged rats, MV_O from old rats Intake of a specific formulation of omega-3 abolishes the noxious properties of SMVs (by Qureshi et al 2020 & authorized by the first author Qureshi AbdulWahid)

VI.4 Immunosenescence

Immunosenescence is a process of immune dysfunction that happens within age. It remodels lymphoid organs and is associated with infections, autoimmune diseases, and malignant tumors. Degeneration of the thymus and declined IL-7 secretion are major factors of immunosenescence, followed by a decrease in telomere length and telomerase activity.¹⁸³ Senescent T cells show reduced SA-β-galactosidase activity, cytotoxic activity, expression of functional molecules such as IFN-γ, scarce proliferation, and also arrested cell cycle, due to an increase expression of the cyclin kinases, P16 and P21, and elevated ROS production.¹⁸³ Circular RNAs, and microRNAs were reported as specific T-cell senescence biomarker^{184 185}. As a proof of concept of the impact of immunosenescence, 7-week-old C57BL/6 irradiated mice transplanted with

bone marrow cells from 48-week-old individuals showed less functional deterioration and histological tubular injury than those treated with 8-weeks old bone marrow cells. The paradoxical beneficial effect in the acute phase of kidney injury may have been due to a decreased inflammatory response possibly linked to the proportion of senescent BM cells .¹⁸⁶

Nevertheless, the contribution of each immune cell line, belonging to either adaptative or innate immune responses, remains to be deciphered during immunosenescence.

When stimulated with proinflammatory stimulus such as LPS, neutrophils are the first recruited at the injury site with a quite short life-span. While their count increases with ageing, they show altered effector functions such as chemotaxis and intracellular killing but phagocytosis and their adhesive ability remain stable. Senescent neutrophils produce increased amount of metalloproteinase and cytokines , NF-kB continuous activation and PI3Kinase modified pathways.^{187,188}

Natural killer cells as well as macrophages are also affected in immunosenescence. NK cells increase in number while their cytotoxicity decreases and macrophages proliferation becomes impaired.^{188,189} As for B cells, antibodies diversity is limited, disabling the immune system from high affinity antibodies production.¹⁸⁷

Together, all these age-related changes decrease effector functions and increase the susceptibility to infections and various pathological cell responses

like dysfunctional mitochondria, oxidative stress and NLRP3 inflammasome activation. Inflamm-aging is also associated with central obesity and increased gut permeability and contributes to the initiation and progression of atherosclerosis , diabetes, dementia peripheral vascular and chronic diseases.¹⁹⁰

**Chapter VII:
Neutrophils: a revised role in immunity and
thrombotic disorders**

VII.1 Neutrophils: a first line of defense against pathogens and actors of innate Immune response

Neutrophils are main actors in the innate immune system, they are heterogeneous in morphology, phenotype and function.¹⁹¹ They are incessantly generated in the bone marrow from myeloid precursors and can reach up to 2×10^{11} cells produced daily.¹⁹² During inflammation, neutrophils are recruited in tissues, and with time the cells undergo apoptosis and are removed by macrophages and dendritic cells.¹⁹³ In humans, 50–70% of circulating leukocytes are neutrophils, whereas only 10–25% are in mice^{169,170}. Three types of neutrophil granules are formed consecutively during their maturation, and they are filled with pro-inflammatory and degradation proteins.^{192,194,195} They are azurophilic (primary) granules, containing myeloperoxidase (MPO), specific (secondary) granules, containing lactoferrin, and gelatinase (tertiary) granules, containing matrix metalloproteinase 9 (MMP9).¹⁹⁶

Different intra and extracellular mechanisms are implicated in pathogens elimination by neutrophils. First, neutrophils have a phagocytosis ability. After they are encapsulated in their phagosomes, pathogens are destroyed by ROS produced by NADPH oxygenase and/or cleaved by proteolytic proteins released by the granules (cathepsins, defensins, lactoferrin and lysozyme).

^{192,197}

Second, the antibacterial proteins, are also released from the neutrophil granules into the extracellular milieu via a specific process termed degranulation, thereby enabling the destruction of extracellular pathogens. Highly activated neutrophils can eliminate extracellular microorganisms by releasing neutrophil extracellular traps (NETs).¹⁹⁸

VII.2 Netosis and formation of NETs

Netosis is the mechanism of neutrophil extracellular traps (NETs) formation.¹⁹⁹

NETs are made of decondensed chromatin that forms meshes of DNA fibers with approximately 200-nm pores²⁰⁰. NETs are coated with nuclear proteins (histones), granule proteins, like neutrophil elastase and myeloperoxidase, and cytosolic proteins such as S100 calcium-binding proteins A8, A9, and A12, as well as actin and α -actinin²⁰¹⁻²⁰³.

NET formation occurs via two processes: non-lytic or vital NETosis and lytic NETosis. Both lytic and non-lytic NETosis can cause thrombosis. In lytic fibrosis, PAD4 causes hypercitrullination of histones driving nuclear swelling due to chromatin decondensation, followed by release of NETs containing DNA and histones.

When Occurring without the necessity of cell lysis, the release of extracellular traps is mediated by vital NETosis.²⁰⁴

Upon stimulation, eosinophils²⁰⁵, basophils²⁰⁶, mast cells²⁰⁷, and macrophages²⁰⁸ were also described to release extracellular DNA.

Initiation of the NETosis signaling occurs through the ERK MAPKinase pathway that triggers nuclear activation of chromatin decondensation and the shattering of the nuclear membrane. The shedding chromatin fibers by passing through the cytoplasm embark bactericidal proteins like myeloperoxidase, neutrophil elastase and also bear citrullinated histones. Histone citrullination is mediated by peptidylarginine deiminase (PAD) and is mandatory for NET release.

VII.3 Neutrophils and NETs in sterile Inflammation

Inflammation in the absence of pathogens and their products is referred to as sterile inflammation. ²¹⁰ Numerous stimuli may lead to sterile inflammation like ischemia reperfusion, macroscopic or particle-induced trauma. In this case, immune cells (DCs or macrophages) or nonhematopoietic cells (endothelial or epithelial cells) sense a variety of stimuli and initiate inflammatory pathways, some of them being shared with pathogen-induced inflammations (TLR, NALP3,) whereas others (RAGE, IL1- β -R) are distinct to sterile inflammation (see figure 24). In the end of the process, tissue repair relies on macrophages that clear necrotic or apoptotic neutrophils and produce factors that accelerate the healing process (resolvins, TGF- β). Growth factors released in the healing area by vascular cells (e.g., VEGF) also contribute to the restoration of the tissue. For instance, IL-4 produced by eosinophils is sensed by FAPs to mediate repair after acute skeletal muscle necrosis. Induced sterile

inflammation may trigger the adaptive immune responses, as in the case of organ transplantation.

Neutrophil recruitment in response to sterile inflammatory stimuli contributes to the immunological damages observed in many diseases, such as ischemic injuries/infarction, trauma, autoimmunity, drug-induced liver injury. As an ultimate neutrophil activation, Netosis takes place from 2–3 h up to 8 h from activation. About 20%–60% of isolated human neutrophils typically release NETs 2–4 h after contact with microbes or chemicals, however, they are able to respond within minutes when activated by LPS-stimulated platelets under conditions of flow.²¹² It is worth noting that neutrophil stimulated in vitro by fMLP (N-formyl-Met-Leu-Phe) ²¹³ release MVs but do not extrude NETs, suggesting that the two mechanisms are not directly dependent one from the other.

The mechanisms by which neutrophils respond to sterile tissue injury and cell death are of both homeostatic innate immune responses and pathogenic immune responses in disease.²¹⁴

Neutrophils are leukocytes exposing CD11b and able to roll on the endothelium through interaction with different endothelial membrane proteins like E-Selectin, VCAM, ICAM . Tethered neutrophils are able to secrete chemokines (CXCLs) and interleukins (IL-8), and contribute to maintain the inflamed endothelial phenotype. In addition neutrophils also interacting with

naïve platelets via P-Selectin and Mac-1 binding promote platelet activation. Altogether, these interactions at the endothelial layer favor a procoagulant state at the vicinity of the site where neutrophils and maintain local inflammatory mediator production. Such mediators nurture cell activation and consecutive exposure of procoagulant phosphatidylserine as well as the induction of tissue factor (TF) finally exposed at the surface of both the inflamed endothelium and activated neutrophils. Importantly, TNF, IL-1 and ROS produced by the neutrophils extruding NETs are also inflammatory and oxidative mediators triggering ECs.

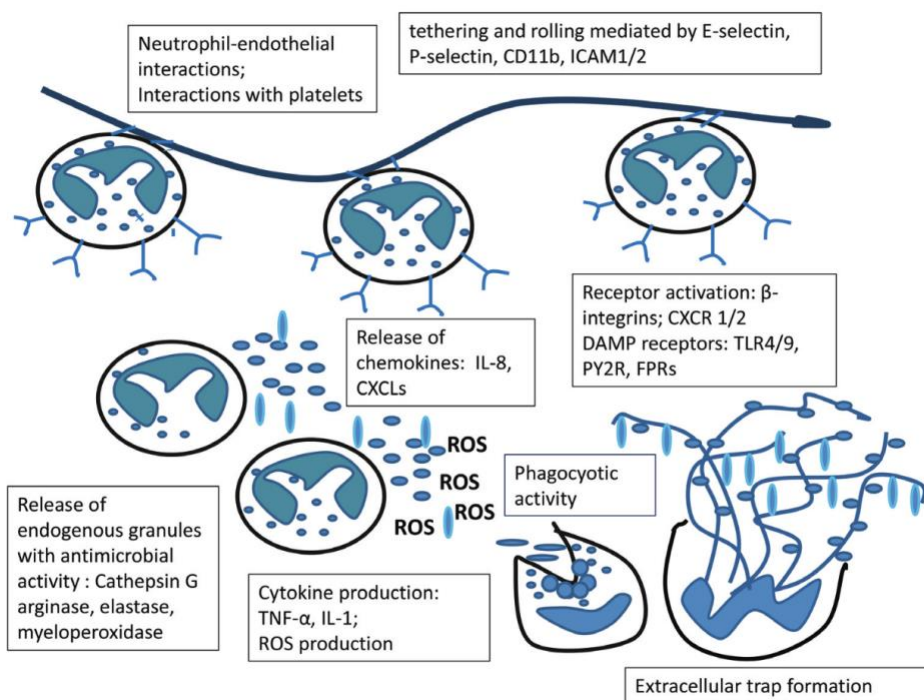


Fig 22: Neutrophils in response to sterile inflammation. Neutrophils produce NETs after activation by CD11b, integrin alpha M, ICAM, intercellular adhesion molecule; IL-8, interleukin-8 (chemokine receptor ligand 8); CXCLs, chemokine ligands; CXCR, chemokine receptor; DAMP, damage associated molecular pattern; TLR, Toll like receptor; IL-1, interleukin 1; PY2R, purinergic receptor; FPR, formyl peptide receptors; and TNF α , tumor necrosis factor-alpha.²¹² (by Edwards et al 2020)

In murine models of deep vein thrombosis (DVT), it has been shown that the citrullinated histone H3 (citH3) born by NETs promotes a red blood cell and platelet rich thrombus.²¹⁵ Platelet activation by histones involves stimulation of platelet TLR2 and TLR4 receptors.²¹⁶ Activated platelets formed as a result of the NET-platelet interaction bind to neutrophils to promote NETosis.²¹⁷ This cycle favors thrombus formation.

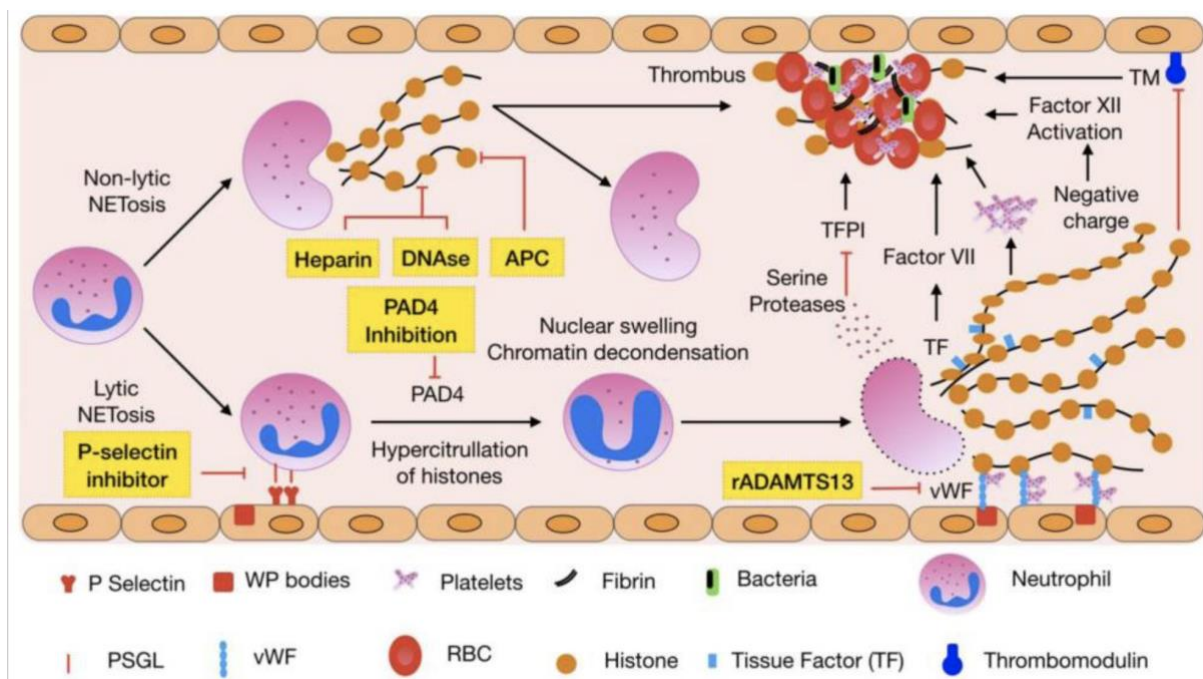


Fig 23: NET formation in thrombosis by lytic and non lytic NETosis APC= activated protein C, DNase= deoxyribonuclease, NET= neutrophil extracellular traps, PAD4= peptidylarginine deiminase, PSGL= P-selectin ligand 1, RBC= red blood cell, TF= tissue factor, TFPI= tissue factor pathway inhibitor, TM= thrombomodulin, vWF= von willebrand factor, WP= weibel palade bodies.²¹⁸ (by S. Kapoor, A. Opneja and L. Nayak 2018)

Because DNA is a polyanionic molecule, a proportion of its surface not covered by histones would offer docking sites for the recruitment of blood coagulation factors. These vitamin-K dependent factors would then bind to the exposed anionic charges via their Gla domain in the same way as they would on phosphatidylserine exposed by stimulated vascular cells. In a murine sepsis model by cecal-puncture ligation, NET-driven thrombin generation was abolished in factor XII knockout mice suggesting that the intrinsic coagulation pathway would act as an alternate process for coagulation.²¹⁹ Via interaction with von Willebrand Factor, a macromolecule that binds to platelets and endothelium, DNA-bound histones activate platelets and also exert an inhibitory action on thrombomodulin, the main endothelial anticoagulant membrane protein. Propensity to coagulation will be re-enforced by the release of granule serine proteases from the neutrophil undergoing NETosis, that will inhibit the tissue factor inhibitor TFPI normally controlling the initial step of the coagulation cascade depending on tissue factor. Several strategies to limit NETs-driven coagulation have been proposed. They are based on 1) the use of DNase to limit NET half-life at the vicinity or in the thrombus, 2) PAD4-inhibitors to reduce citrullination of histones on chromatin fibers, 3) inhibitors of the interaction of platelets with vWF, like P-selectin inhibitors or ADAMS 13 that cleaves vWF, Recombinant proteins derived from the sequence of natural anticoagulants like activated protein C (APC) that interacts with TM to limit the generation of thrombin have been also evoked. Finally, heparin that enhances

the anticoagulant activity of antithrombin, a circulating natural anticoagulant trapping thrombin and factor Xa seems to have a dual benefit by also accelerating the activity of the DNase 1, at least *in vitro*.²²⁰

VII.4 NETs and Microvesicles: tissue vascular partners in thrombogenicity

In humans, several studies demonstrated a positive correlation between the concentration of circulating NET markers and the atherosclerotic lesion size in different cohorts of patients. These markers contribute to enlarge the lesion size by attracting and activating monocytes and dendritic cells as well as releasing high amounts of inflammatory mediators, such as MMPs, NE, cathepsin G, and cathelicidin.²²¹ Once activated by platelet-derived CCL5 in early stages of atherogenesis, neutrophils adhere on arterial endothelial cells. The neutrophils degranulation products promote the endothelial recruitment and adhesion of monocytes via formyl-peptide receptors. Neutrophil proteins and NETs perpetuate local inflammation by activating dendritic cells and macrophages within the vessel wall. As a result, more LDL are converted into its oxidized form and facilitates foam cell formation and plaque growth. Finally, in late stages of atherothrombosis, NETs can induce endothelial damage and promote the recruitment of new activated cells and potentially the erosion of the plaque.

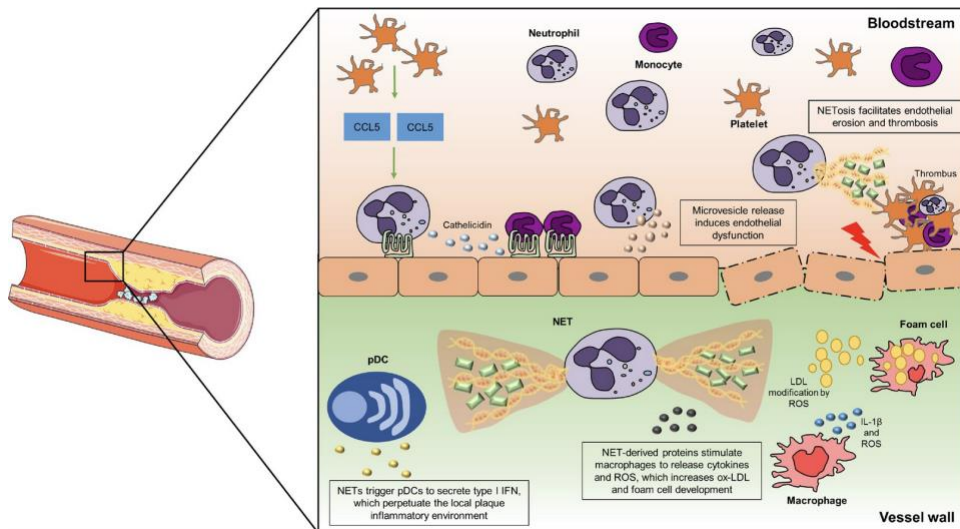


Fig 24: Role of neutrophils in atherosclerosis. CCL5, CC-chemokine ligand (CCL)5; IFN, interferon; IL, interleukin; LDL, low-density lipoprotein cholesterol; NET, neutrophil extracellular trap; Ox-LDL, oxidized low-density lipoprotein cholesterol; pDCs, plasmacytoid dendritic cells; ROS, reactive oxygen species. ²²¹ (by Bonaventura et al 2019)

It is now demonstrated that, leucocyte-derived MVs induce endothelial activation thus enhancing protease and adhesion molecules expression resulting in endothelial dysfunction and leucocyte recruitment within the vessel wall.

Human polymorphonuclear neutrophils (PMNs) have the potency to release MVs and exosomes. ²²² Such MVs contain granule proteins and surface membrane-expressed components such as complement receptors and CD59 released from the plasma membrane to the extracellular space.

Neutrophils-derived MVs express PS, annexin A1 and adhesion molecules such as CD11b. Of note, Annexin A1 has anti-inflammatory properties by inhibiting phospholipase A2 (PLA2) and promotes neutrophil detachment as well as the phagocytosis of apoptotic neutrophils by macrophages. In fact,

Annexin A1 limits neutrophils extravasation and both exogenous and endogenous annexin A1 counter-act the action of activated effects innate immune cells, particularly the generation of proinflammatory mediators.

Protein analysis of neutrophil-derived MVs (NMVs) has revealed the presence of granule proteins such as myeloperoxidase, lactoferrin, elastase, matrix metalloproteinase 9, and proteinase 3.²²³ Altogether, data from the literature indicate that neutrophil-derived MVs, found at high levels at the injury site of injury and in bloodstream, amplify inflammatory processes with a variety of pathological outcomes ranging from autoimmune disorders to infectious conditions and atherosclerosis.²²¹

El Habhab et al. showed that MVs shed from activated splenocytes prompt early pro-inflammatory, pro-coagulant and pro-senescent responses in coronary endothelial cells and that the depletion of neutrophil MVs from the culture medium preserved the endothelium.⁴

In summary, growing evidences of an association between neutrophil MVs and NETs open a large field of investigations to better understand the link between thrombosis and inflammatory responses and decipher the mechanisms and cellular partners involved in sterile and non-sterile inflammation.

Hypothesis

This work was undertaken to better understand how periodontitis can worsen the vascular conditions. In particular, the possibility that MVs shed in response to periodontal infection act as remote thrombogenic actors is by in the hypothesis. Altogether and based on the central assumption of a worsening of vascular conditions by perpetuated chronic vascular inflammation three hypothesis can be drawn:

- 1- The release of spleen MV and their properties vary with the severity of the infection and/or the type of tissue damage (mechanical vs. biological insult)
- 2- MVs released from splenocytes in response to *Porphyromonas Gingivalis* are deleterious to endothelial cells and act as pro-inflammatory cardiovascular mediators
- 3- Circulating spleen Microvesicles and NETs released in response to *Porphyromonas Gingivalis* favor atherothrombosis at sites remote from the dental Infection

Aims

To explore our hypothesis, we chose to establish the proof of concept in a murine model of periodontitis.

The following aims were defined:

- 1- To characterize the spleen cellular composition and the release of MVs by splenocytes upon periodontal infection using a silk ligature impregnated or not with *P. Gingivalis*.
- 2- To identify the pro-senescent effects of MVs on the coronary endothelium using an in vitro model.
- 3- To identify NETs and MVs as circulating and remote actors of *P.gingivalis* by comparing the ligature model and the intraperitoneal injection of *P.gingivalis* .

Results

Article 1

Isolation of Splenic Microvesicles in a Murine Model of Intraperitoneal Bacterial Infection

(Accepted manuscript) DOI: 10.3791/63480

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(Published)

I-Background

The majority of clinical studies examine MVs isolated from plasma samples, which typically contain MVs of endothelial, leukocyte, platelet, and erythrocyte origin.³⁹ Several approaches can be used for the detection and characterization of MVs several requiring a preanalytical procedure.

The most commonly studied tissular MVs are those from atherosclerotic plaques, the cardiac tissue itself, or cancer tissues.^{224,225 226}

In mice, SMV assessment could be of particular interest in situations where active molecules or therapeutical devices are precious and limited in quantity, or for comparative purposes of different genetic modification in Knock-in or Knock out mice.

The study of spleen derived MVs (SMVs) in the context of cardiovascular dysfunction appears consistent with the recently evoked cardio splenic axis, as a new response driven by pericardiac inflammation post myocardial infarction.^{227 228 229}

Indeed, based on the proposed link between periodontitis and enhanced cardiovascular risk, a part of the work explores the possibility of an elevated procoagulant and pro-inflammatory activity in spleen, pertaining to the remote action of microvesicles released after local gum infection by *P.gingivalis*.
(see second manuscript)

The first objective of this study was to establish a methodological approach for the isolation of splenic MVs SMVs from a periodontal *P.gingivalis* infection murine model. In this context, we studied the variation of the biochemical parameters of MVs, in order to assess the relevance and correlation between the different methods for the quantification and characterization of these MVs. To achieve this aim, we first studied the different characteristics of SMVs isolated from young C57BL6 mice to establish a reliable procedure with minimal inter-individual variations in the assessment of SMVs. (see manuscript N°1 jove)

The first series of experiments also enabled to establish labelling procedures of the spleen tissue for further “en face” investigations (see methods for MV investigation part II)

In both manuscripts, C57BL6 mice were investigated and overall different subsets were assessed and compared either to untreated mice or to mice submitted to oral gavage. Mice were either submitted to local gum injury combined or not with *P.gingivalis* infection using silk threads eventually soaked with the bacterial suspension. Another group of mice consisted of intraperitoneally infected individuals, to mimick an acute and local infection known to recruit neutrophils.

In the laboratory we have established a model for the study of microvesicles isolated from the spleen as an alternative approach to investigate immune and leukocyte responses associated to vascular diseases and procoagulant

tendency. Indeed, in small animals, the blood volume is a limiting issue for extensive characterization of MVs as circulating surrogate makers of organ dysfunction. At the opposite, the murine spleen is a larger source of MVs.

II- Methodological approaches for MVs measurement in our laboratory:

Data from the laboratory obtained in rats, had confirmed that the spleen MVs concentration and cell origin profile reflects the physio-pathological conditions and could be an alternate approach to plasma MV assessment. Strikingly, oral treatment by a specific combination of omega 3 was able to modify the baseline level of SMVs generation, thereby adding a new interest to the model since it could be useful to evaluate pro-drugs.⁷ Nevertheless, our previous data on the action of pathogens of SMV generation and phenotype profile were only established after in vitro LPS stimulation of isolated rat splenocytes.⁴

The approach chosen for the measurement of SMVs in extracts and washed final suspensions of SMVs was to select easy-to handle routine methods, like spectrophotometry, colorimetric assay of the protein content or TPRS (Tunable Resistive Pulse Sensing) that would spare minimal amount of the suspensions. They were compared to our gold standard prothrombinase assay (see article). Their respective advantages and limits are given in the table below. To establish the procedure, we compared animals treated by intraperitoneal injections of *P. Gingivalis* with untreated littermates, with the perspective of the secondary article dedicated to periodontitis.





METHODE		AVANTAGES	DESAVANTAGES
Dosage Prothrombinase		<ul style="list-style-type: none"> Dosing in series Reproducibility Sensitivity 	<ul style="list-style-type: none"> Expensive No enumeration (PS surface eq) No size identification
NanoDrop		<ul style="list-style-type: none"> Small quantity used for dosing Automated, repeatable Nucleic acids and proteins Dosing in series Immediate result 	<ul style="list-style-type: none"> No size identification Sensitive to cellular stimulus (Different export of proteins)
Nanosizer		<ul style="list-style-type: none"> Size distribution Peak homogeneity 	<ul style="list-style-type: none"> Long acquisition time Definition of refractive index Sensitive to aggregation and microcrystals. No characterization of PS
Dosage colorimétrique au bleu		<ul style="list-style-type: none"> Measure of cytoplasmic and membrane proteins independently of their structure 	<ul style="list-style-type: none"> Result in one hour Lysate (losses) Sensitive to the amounts of aromatic AA. Sensitive to cellular stimulus

Table 5: Comparison of different methods for MVs characterization

Isolation of Splenic Microvesicles in a Murine Model of Intraperitoneal Bacterial Infection

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Abstract

Microvesicles (MVs) are submicron fragments released from the plasma membrane of activated cells that act as proinflammatory and procoagulant cellular effectors. In rats, spleen MVs (SMVs) are surrogate markers of pathophysiological conditions. Previous *in vitro* studies demonstrated that *Porphyromonas gingivalis* (*P. gingivalis*), a major periodontal pathogen, enabled the endothelial shedding and apoptosis while lipopolysaccharide (LPS) favors the shedding of splenocyte-derived microvesicles (SMVs). *In vivo* studies showed the feasibility of pharmacological control of SMV shedding. The present protocol establishes a standardized procedure for isolating splenic SMVs from the *P. gingivalis* acute murine infection model. *P. gingivalis* infection was induced in young C57BL/6 mice by intraperitoneal injection (three injections of 5×10^7 bacteria/week). After two weeks, the spleens were collected, weighed, and the splenocytes were counted. SMVs were isolated and quantified by protein, RNA, and prothrombinase assays. Cell viability was assessed by either propidium iodide or trypan blue exclusion dyes. Following splenocyte extraction, neutrophil counts were obtained by flow cytometry after 24 h of splenocyte culture. In *P. gingivalis*-injected mice, a 2.5-fold increase in spleen weight and a 2.3-fold rise in the splenocyte count were observed, while the neutrophils count was enhanced 40-fold. The cell viability of splenocytes from *P. gingivalis*-injected mice ranged from 75%-96% and was decreased by 50% after 24 h of culture without any significant difference compared to unexposed controls. However, splenocytes from injected mice shed higher amounts of MVs by prothrombinase assay or protein measurements. The data demonstrate that the procoagulant SMVs are reliable tools to assess an early spleen response to intraperitoneal *P. gingivalis* infection.

Introduction

Microvesicles (MVs), also termed microparticles or ectosomes, are plasma membrane fragments with a diameter of 0.1-1.0 μm released in body fluids and the extracellular space in response to various cell stimuli. First identified as platelet dust exposing procoagulant phospholipids, mostly phosphatidylserine (PSer), MVs constitute an additional surface for the assembly of the blood coagulation complexes^{1,2}. The key role of circulating MVs as procoagulant effectors have been demonstrated in patients with Scott syndrome², a rare genetic disease that leads to dysfunctional PSer exposure and bleeding (**Supplementary Figure 1**). MVs have been extensively studied as circulating biomarkers of thrombotic risk in chronic diseases associated with cardiovascular disorders such as diabetes, chronic kidney disease, preeclampsia, and hypertension^{3,4}. They are currently recognized as true cellular effectors in fluids or organ tissues like the myocardium¹. Because they convey active proteins, lipids, and miRNA, they remotely modulate vascular responses such as hemostasis, inflammation, vascular angiogenesis, and vascular growth or tissue remodeling⁵.

While clinical studies examine the prognosis value of MVs concerning risk factors, MVs isolated from the patient's fluids or tissue enable the *ex vivo* assessment of their effector properties⁶. The deciphering of the mechanisms governing MV biogenesis and cross-talk abilities is generally achieved in cell culture models to identify active molecules exposed by or encapsulated within the MVs and downstream signaling. The MV interactions with target cells will depend on membrane protein/protein binding, when appropriate counter-ligands are available, and/or lipid fusion⁷.

Under physiological conditions, MVs circulating in the plasma mostly originate from vascular cells, as identified by the lineage cluster differentiation markers (CD)^{8,9}. However, in pathology, notably in cancer¹⁰ and graft rejection^{11,12}, MVs are shed from the damaged tissue and bear noxious procoagulant and proinflammatory features. These are detected in the systemic circulation, making them useful probes for monitoring protective or rejuvenation therapies, and possible pharmacological targets¹³. Because MVs circulate as a dynamic storage pool reflecting vascular and tissue cell homeostasis in health and disease, a better understanding of their remote action also needs to be investigated *in vivo*, after IV injection or nasal instillation in small animals^{14,15}. Indeed, MVs have been considered major contributors to the intricate pathways coupling exaggerated inflammation and thrombosis¹⁶.

Periodontitis is an inflammatory disease of infectious origin affecting tooth-supporting tissues^{17,18} and is associated with thrombotic risk. It is characterized by gingival bleeding, alveolar bone destruction, tooth mobility and can ultimately lead to tooth loss. Periodontitis is highly prevalent worldwide and affects more than 50% of the population, with 11% presenting a severe form¹⁹. Periodontitis is induced by bacterial dysbiosis of the subgingival biofilms, which sustain an exacerbated inflammatory response that triggers tissue destruction²⁰. Over the last decade, periodontitis has been linked to systemic diseases such as cardiovascular disorders, diabetes, and rheumatoid arthritis. The possible explanations are the action of the periodontal pathogens at a distance and/or the increased systemic inflammation mediated by

proinflammatory cytokines such as interleukin (IL)-1, IL-6, and TNF- α ^{21,22}.

Among pathogens associated with the periodontitis onset and development, *Porphyromonas gingivalis* (*P. gingivalis*)²³ is found in most severe lesions that harvest several virulence factors, including lipopolysaccharide (LPS)²⁴ inducing Toll-like-receptor (TLR)-mediated inflammatory responses²⁵ and the recruitment of neutrophils and polymorphonuclear leukocytes (PMNs) at the site of the initial infection²⁶. The LPS from *P. gingivalis* activates TLR-4 or TLR-2, facilitating immune detection and bacterial survival evasion²⁷. At the vascular level, activation of TLR2 by LPS is associated with immunothrombosis. The unique ability of *P. gingivalis* to prompt TLR-2 signaling while TLR-4-dependent recognition is significantly impaired favors persistent low-grade infection^{28,29}.

In vivo procedures to study the MV responses to low-grade pathogen chronic and sustained infection are scarce. Methodological approaches for tissular MVs extraction are poorly described in the literature and generally concern the harvest of MVs from pathological tissues like solid tumors, liver steatosis, atherothrombotic plaques, or grafts^{11,29,30}, while the spleen senses bacteria and viruses in the bloodstream. It also stores erythrocytes, platelets, lymphocytes, monocytes, basophils, and eosinophils involved in the immune response. Granulocytes like neutrophils from the red pulp also generate reactive oxygen species (ROS) and proteases that destroy pathogens and prevent infection from spreading^{31,32}. Amazingly, and to the best of our knowledge, spleen MVs are not investigated in the context of pathogen-induced tissue insults. There is a global unmet need to study the variations of tissular MVs in physiopathology.

In vitro data from our laboratory showed that LPS induces the shedding of procoagulant MVs from rat splenocytes, which induces the senescence of cultured coronary endothelial cells and promotes a proinflammatory and proinflammatory procoagulant endothelial phenotype¹¹. The feasibility of the pharmacological control of the spleen MVs was further demonstrated after treating the animal with an optimized omega-3 formula. The oral gavage of middle-aged and aged rats was found to be protective against both the shedding of procoagulant MVs from splenocytes and their prosenescent noxious properties towards the coronary endothelium³³.

Compared to blood, the spleen offers the advantage of being an important source of leukocytes in one individual. In addition, a splenic-cardiac axis has recently been proposed^{3,34}, making the spleen a possible contributor to the infection-related cardiovascular risk of beneficial interest for pharmacological control. The assessment of the SMVs properties or release is key in understanding pathogen-induced or inflammatory responses with no alternative methodology to date. Interestingly, it can be achieved in treated animals and in different physiopathological models (age, hypertension, diabetes). Indeed, by comparing middle-aged and aged rats³³, the differences in spleen MVs properties and release can be evidenced following a simple 24 h splenocyte culture.

Given the above evidence of the alteration of the effector properties of spleen MVs and the feasibility of their pharmacological control in rats, a standardized protocol is described herein for the isolation of murine spleen MVs. The procedure would better fit in-depth investigations of the *in vivo* mechanisms supporting SMVs-mediated effects, eventually in engineered mice. The procedure was established in C57BL/6 mice using a local intraperitoneal infection by *P.*

gingivalis, to establish proof of a remote action of the pathogen on spleen MV (SMV) effector properties.

Protocol

All experimental protocols were approved by and followed the relevant guidelines of the local Ethics Committee (APAFIS#28745-2020121815051557) and animal care of the home University and of the INSERM. Male Young C57BL/6 mice, 6-8 weeks of age, were used for the experiments. Mice were regularly examined to evaluate pain and stress, and their weights were monitored daily. Unless otherwise stated, all extracting buffers and solutions must be sterile and at room temperature.

1. Animal preparation

1. Administer the mice with six intraperitoneal injections of *P. gingivalis* (PG) every 2 days for 2 weeks (three injections of 5×10^7 bacteria/week, **Supplementary File 1**).
2. Anesthetize the mice using a combination of 100 mg/kg of ketamine and 10 mg/kg of xylazine.
3. Sacrifice the anesthetized mice and harvest the spleen after laparotomy.

NOTE: The specific conditions for *P. gingivalis* infection and the sacrifice of the animals for spleen harvest are detailed in the "animal experiment" section of **Supplementary File 1**. The schematic representation of the protocol steps is shown in **Figure 1**.

2. Extraction of splenocytes

1. Using a scalpel, mince the spleen tissue into ~1 mm slices in a Petri dish already filled with 3 mL of RPMI containing antibiotics (Streptomycin (100 U/

mL)/Penicillin (100 U/mL), Fungizone (250 mg/mL), L-glutamine (2 mM)), and supplemented with 10% Fetal Bovine Serum (FBS) (see **Table of Materials**).

2. Transfer the slices to a sieve (see **Table of Materials**), which is from beforehand attached to a 50 mL polystyrene tube.
3. Use the plunger of a syringe as a pestle to crush the tissues on the sieve.
4. Rinse the sieve with the RPMI medium (3 mL).
5. Centrifuge the cell suspension eluate at $450 \times g$ for 5 min at room temperature and discard the supernatant with caution by backflow.

3. Removal of erythrocytes via an osmotic shock

1. Add 1 mL of ACK buffer (see **Table of Materials**), mix well, incubate for 3 min at room temperature and shake gently by hand rotation.
2. Dilute by adding 9 mL of RPMI and mix well using aspiration and backflow.
3. Centrifuge at $450 \times g$ for 5 min at room temperature.
4. Discard the supernatant by aspiration and backflow, and resuspend the pellet in 5 mL of RPMI medium.
5. Mix gently (aspiration/backflow) and eventually remove any lipidic debris by pipetting or using a sieve.

4. Adjustment of isolated splenocyte concentration

1. Fill a 1.5 mL microtube containing 900 μ L of RPMI.
2. Using a micropipette, take 100 μ L of the cellular suspension, add to the 1.5 mL microtube containing 900 μ L of RPMI medium, and mix well.

3. Transfer 10 μL of the diluted cells into a microtube, add 10 μL of the trypan blue exclusion dye, and mix well.
4. Place 10 μL of the solution (step 3.3) into the counting slide of the automatic cell counter (see **Table of Materials**) and determine the cell count.
NOTE: The device software gives two values: the total cell number and the living cell number and percentage.
5. Adjust the concentration of living cells to 3 or 5 $\times 10^6$ cells/mL ($V_{\text{max}} = 20 \text{ mL}$; max total capacity is 100 $\times 10^6$ cells/mL).
6. Seed the cells in a 75 mL flask containing RPMI.
7. Incubate the flask vertically in a humidified incubator at 37 °C for 24 h.
CAUTION: Trypan blue is a mutagenic and carcinogenic agent^{35,36}. Ensure to wear gloves while counting, even outside of the hood. Immediately discard tips and fluids into containers and wash the bench surface.
NOTE: If the collected cells are less than 50 $\times 10^6$, use a 25 mL culture flask. The cell number should not vary much from one individual to the other. The percentage of living cells is generally superior to 80% at this step.
4. Centrifuge the SN1 at 450 $\times g$ for 15 min at room temperature.
5. Discard pellet and centrifuge again at 450 $\times g$ for 15 min at room temperature. Rapidly withdraw and collect SN2 (note the volume).
6. Transfer SN2 into 1.8 mL microtubes with conical shape bottoms. Keep 100 μL of SN2 for an eventual measurement of the initial MV concentration to calculate the isolation yield in case too much debris eventually impairs MV measurement in SN1.
7. Add 5 mL of RPMI medium to the pellet (cells) and count the splenocytes.
NOTE: The cell suspension can also be fixed for flow cytometry characterization in 0.1% paraformaldehyde (final concentration)³⁷.
8. Centrifuge SN2 at 14,000 $\times g$ for 1 h at 4 °C and eventually refrigerate the rotor in advance by running the empty rotor at 4 °C. This step generates SN3.
9. Immediately withdraw SN3 from each microtube by inverting over a single sterile 50 mL tube (under the hood). Note the SN3 volume.
10. Gently mix SN3 using a pipette under the hood. Keep aliquots for eventual measurements in the suspension.
NOTE: The solution is now depleted of MVs but contains the soluble mediators and exosomes.

5. Isolation of splenocyte microvesicles

1. After 24 h, pour the flask content into a 50 mL polypropylene or polystyrene tube.
2. Centrifuge at 450 $\times g$ for 15 min at room temperature to remove cells and debris.
3. After centrifugation, keep 100 μL of the 1st supernatant (SN1) for an eventual measurement of the initial MV concentration to calculate the isolation yield. Note the SN1 volume.
11. Scrape each microtube (closed) on a spiked rack to mechanically favor the resuspension of the MVs in the pellet.
12. Add 200 μL of Hank's balanced saline solution without Ca^{2+} and Mg^{2+} (HBSS) in the first microtube (see **Table of Materials**).

13. Resuspend the MV pellet of the first tube by gentle aspiration/backflow cycles (~10 times) using a 1 mL micropipette. Take great care to avoid foaming as this will promote the oxidation of the suspension vesicles and other moieties.
14. Harvest the first 200 μ L of resuspended MVs and pour them into the second tube over the pellet. Gently mix as above, and then pour again into the third tube and mix gently. The suspension becomes more and more turbid from tube to tube. Close the third tube.
15. Initiate the collection of the next three microtubes as above (step 4.14).
16. Collect all the resuspended MVs in a single (or two) collector microtube (2 mL with conical shape bottom). Keep 50 μ L for the eventual calculation of the yield of this step. Note the suspension volume.
17. Centrifuge the collector tube at 14,000 x g for 1 h at 4 °C. This step generates SN4.
18. Immediately discard the SN4 (pour over a supernatant collecting tube). Keep an aliquot of SN4 to calculate the yield of the purification step and gently resuspend the pellet in 500 μ L of HBBS (without Ca^{2+} and Mg^{2+}). Keep a 50 μ L aliquot of the resuspended pellet to calculate the purification yield and note its volume.
19. Store the resuspended pellet at 4 °C for up to one month for functional assays under sterile conditions or at -20 °C for structural assays.
20. Calculate the purification yield (see NOTE below) of each step or the whole procedure by measuring the concentration of MVs in supernatants and/or pellet suspensions.

NOTE: Purification Yield (%): $\frac{([\text{MV1}] \times \text{SN1 volume})}{([\text{MV4}] \times \text{final suspension volume})} \times 100$.

This yield needs to be rationalized to the number of splenocytes isolated from the culture flask and counted in step 4.4. The present experiment's purification yield is ~70% starting from 111×10^6 cells and 60 mL of supernatant.

1. Evaluate the loss of SMVs caused by the procedure by measuring the SMVs remaining in the supernatants depleted of SMVs and mainly containing exosomes (SN2 and SN4).
2. Measure the MV concentration by TRPS or prothrombinase assay³⁸ for high sensitivity and specificity.

CAUTION: Harvest the MVs after centrifugation by the rapid upside-down pouring of the supernatant. Waiting or using U-shape microtubes will prompt MV loss on the microtube wall. Never use a micropipette to discard the supernatant; the pellet can be aspirated instead. Never delay the process after the centrifuge is stopped. Overspeed centrifugation will result in contamination of the MV pellet by exosomes.

NOTE: The centrifugation speeds and duration are optimized for an MV enrichment with minimal contamination by exosomes. This protocol is not reliable to study spleen monocyte/macrophage MVs because these cells can phagocyte and rapidly recapture their own MVs³⁹. The protocol cannot be paused and restarted later because of loss of cells due to cell viability.

Representative Results

The data provided give a full representation of the whole procedure, using two main animal conditions: control untreated young C57BL/6 mice and their littermates subjected to six intraperitoneal (IP) PG injections every 2 days, for 2 weeks. They also show the remote action of an intraperitoneal PG injection on the spleen response after 2 weeks. Splenocyte microvesicles were quantified by either prothrombinase enzymatic assay or by measuring their proteins and RNA concentration by spectrophotometric, and the proportion of neutrophils was determined by flow cytometry^{33,38} in the splenocyte suspension (sections 2-4 of **Supplementary File 1** and **Supplementary Figure 2**).

Spleen weight and cell number increase after 2 weeks of IP injection in *P. gingivalis*

In young adult mice, the PG injection leads to a significant 2.6-fold increase in spleen weight after 2 weeks, likely due to the immune response. Indeed, the total splenocyte count was also raised by 2.3 folds (**Figure 2**, $n = 5$ mice per each condition, $p < 0.0001$ by Student's T-test).

Splenocyte viability is not impaired by 2 weeks of injection in *P. gingivalis*

Similar viability rates were measured between treated and untreated mice after splenocyte isolation or 24 h after cell culture. Nevertheless, when the initial percentage of living cells at t_0 was below 76%, viability was reduced in both groups by ~50% after 24 h. (see Ctl 1-3, **Table 1**, as an example). Conversely, and whatever the animal condition, the 24 h recovery was enhanced when the proportion of living cells reached 90% or more at t_0 , pointing at the crucial role of the first isolation steps (**Figure 3**).

Splenocyte neutrophil count is enhanced in *P. gingivalis*-injected mice

After double staining, neutrophils were identified by flow cytometry as Mac1⁺ and LYG-6-(Gr1)⁺ (see **Table of Materials** and section 4 in **Supplementary File 1**). In response to PG, the neutrophil spleen count was significantly enhanced by 40-folds just after cell isolation (t_0 , $4.8\% \pm 0.6$ vs. $0.86\% \pm 0.06$). Nevertheless, it is worth considering that after 24 h culture, the neutrophil proportion in the splenocyte suspension increases from $4.8\% \pm 0.6$ to $14.67\% \pm 2.02$ (**Figure 4**).

The shedding of MVs from splenocytes increases in mice infected by *P. gingivalis*

Following the protocol, we proved that the isolated splenocytes released more MVs when mice were subjected to PG infection. By comparison, to control individuals and the measurement assay, MVs shed in the supernatant were roughly tripled in PG-injected mice, using either the detection by prothrombinase assay that refers to the total surface of procoagulant anionic phospholipids borne by SMVs (**Figure 5A**), the protein content of SMVs measured by spectrophotometry (**Figure 5B**), or the RNA content of SMVs assessed by spectrophotometry (**Figure 5C**, $n = 5$, Prothrombinase: $p = 0.002$; protein content: $p = 0.003$; RNA content, $p = 0.008$, by Student's T-test). The higher fold-range extent was obtained using the prothrombinase assay that showed a very low background.

Interestingly, a correlation can be established between the SMVs protein content and SMVs measured by prothrombinase assay (**Supplementary Figure 3**). In addition, the SMVs size distribution did not vary as determined in preliminary experiments (**Supplementary Figure 4**) comparing SMVs from PG-stimulated and

unstimulated mice (median diameter 193 nm vs. 189 nm). These diameter values are close to those of SMVs isolated from rat splenocytes in response to a 24 h incubation with LPS (5 µg/mL) or Phorbol myristate acetate (25 ng/mL) and ionophore (1 µM), (median diameter, 222 nm vs. control 212

nm)¹¹ (**Supplementary Figure 5**). In addition, the protein content of the SMVs can be assessed by western blot, which enables the characterization of specific cytoplasmic or membrane proteins preferentially exported into the SMVs (**Supplementary Figure 5**).

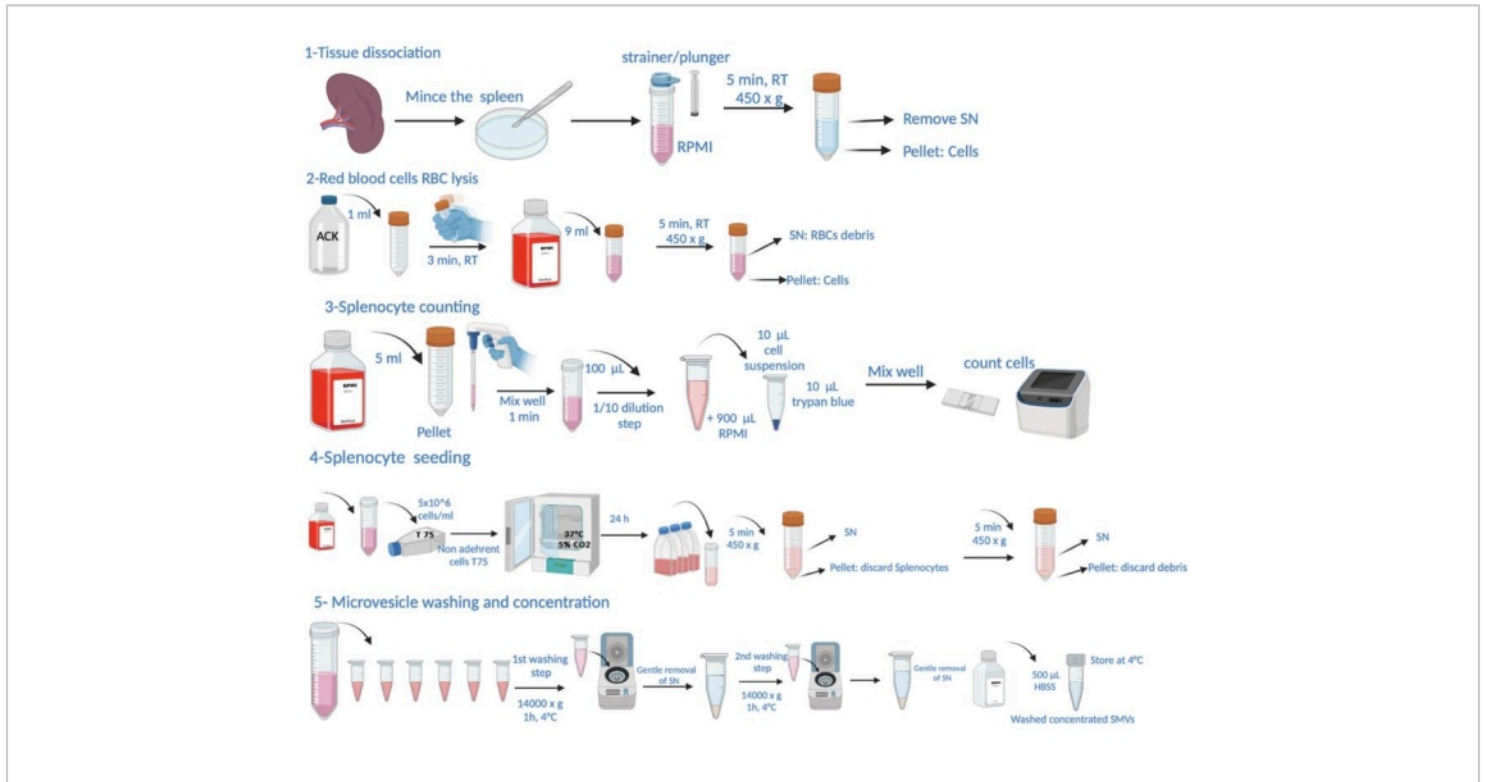


Figure 1: Schematic representation of the protocol steps. This consists of tissue dissection, red blood cell (RBC) lysis, splenocyte counting, seeding, microvesicle harvest from supernatant, washing and concentration determination. [Please click here to view a larger version of this figure.](#)

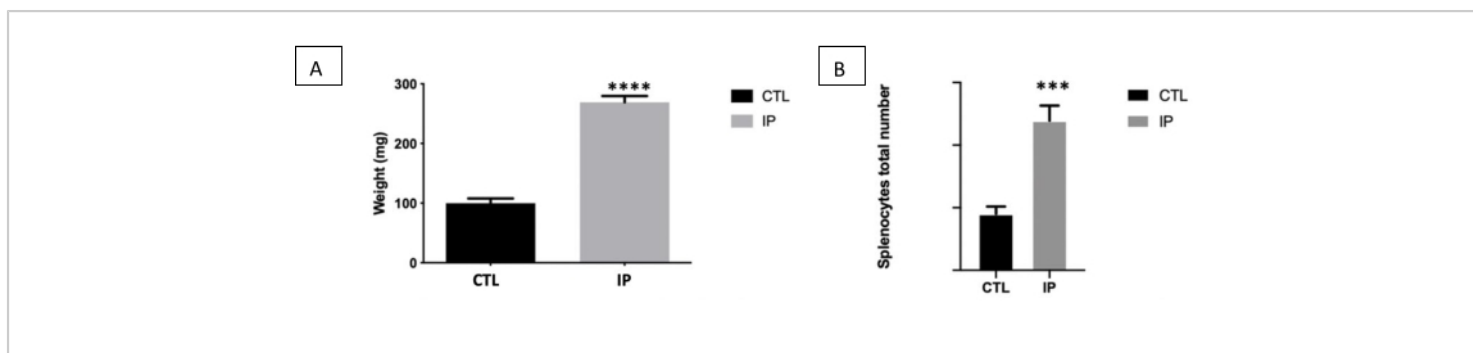


Figure 2: IP injection of *P. gingivalis* significantly enhances spleen weight (A) and splenocyte count (B). CTL: untreated mice, IP: mice subjected to PG injection for 2 weeks. Data are expressed as mean \pm SEM. n = 5: ***: $p < 0.0001$ and 0.0005, respectively. [Please click here to view a larger version of this figure.](#)

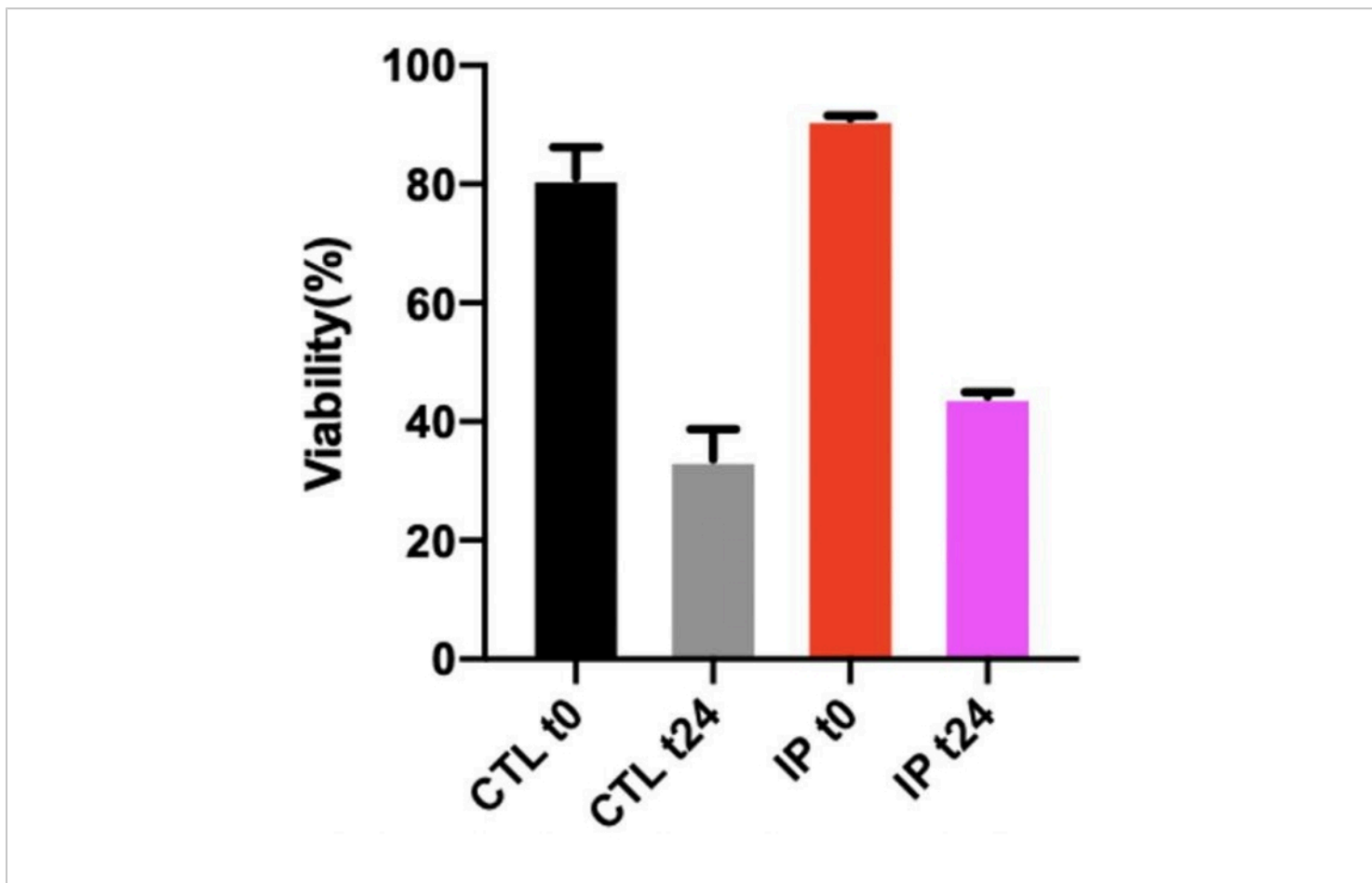


Figure 3: Splenocyte viability is reduced 24 h after splenocyte culture, whereas IP injection of *P. gingivalis* does not alter cell viability. CTL: untreated mice, IP: mice subjected to PG injection for 2 weeks, t0: viability measured immediately after isolation, t24: after 24 h culture. Data are expressed as mean \pm SEM. n = 5, ***: $p < 0.0001$ by Student's T-test. [Please click here to view a larger version of this figure.](#)

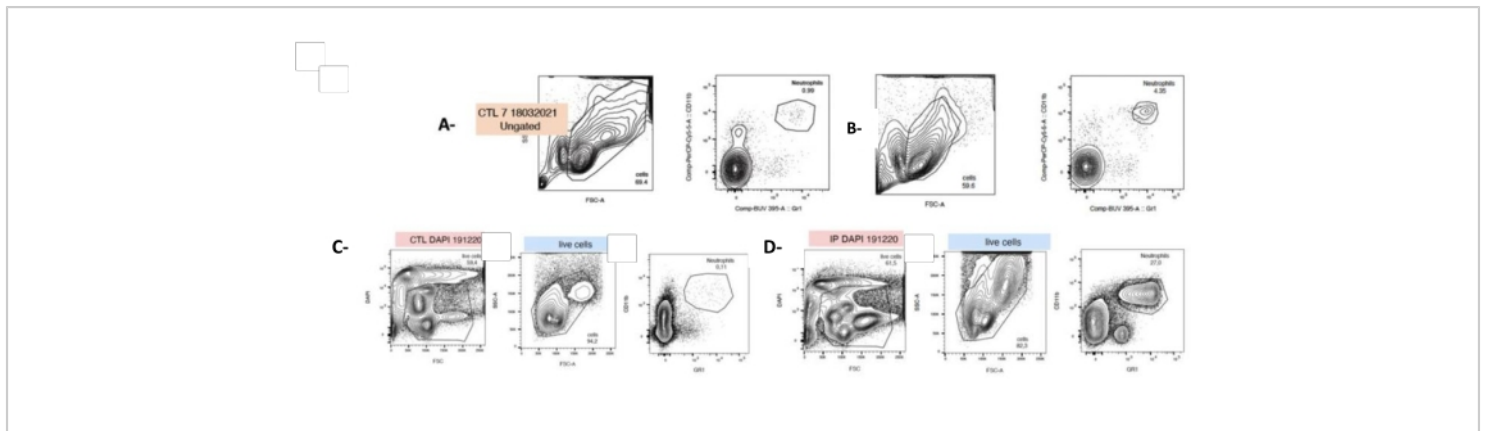


Figure 4: *P. gingivalis* injection increases the neutrophil count at t0 and after 24 h of cell culture. Cells were freshly isolated from the harvested spleen and labeled with fluorescent antibodies directed against granulocytes (LyG-6 Gr1) or neutrophils (LY6-C) and identified in the CD11b⁺ gate that delineates monocytes, granulocytes, and neutrophils. Neutrophils were identified as LY6-C⁺, CD11b⁺, and LYG-6 Gr1 low. Representative plots showing SSC/FSC and CD11b⁺, and LYG-6 Gr1 double staining for each condition at t0 (**A,B**) or 24h after seeding (**C,D**). A,C: untreated mice splenocytes; B,D: splenocytes from mice subjected to IP injection of *P. gingivalis*. FSC: Forward Scatter; SSC: Side Scatter; CTL: unexposed mice. n = 5, ***: *p* < 0.0001, 10000 events acquired per sample. [Please click here to view a larger version of this figure.](#)

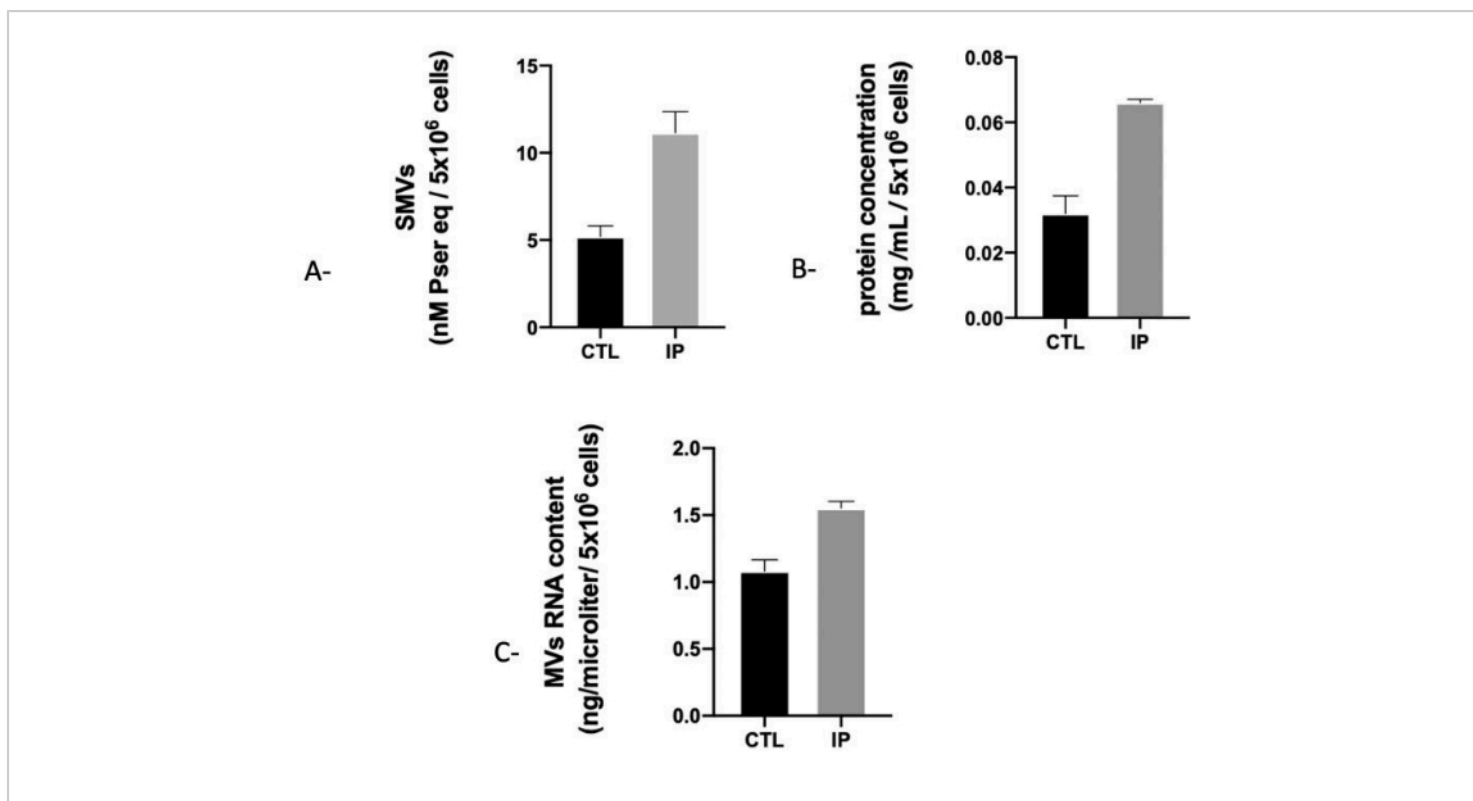


Figure 5: *P. gingivalis* favors enhanced MV splenocyte shedding after 24 h culture. Splenocytes were isolated from *P. gingivalis* infected and control mice and cultured for 24 h and SMVs measured by different assays. Black bars: untreated mice (CTL), grey bars (IP): mice subjected to *P. gingivalis* injection for 2 weeks. A: Quantification by prothrombinase assay, B: protein concentration of the intact SMVs determined by spectrophotometry, C: RNA content of SMVs determined by spectrophotometry. Data are expressed as mean ± SEM. n = 5, **: p < 0.0001, by Student's T-test. [Please click here to view a larger version of this figure.](#)

Animal condition	Spleen weight	Splenocytes number	Viability (%)	Viability (%)
			after cell isolation	
	(mg)	(10 ⁶ cells)		After 24 h cell culture
			(t0)	
Ctl 1	108	25	75	24
Ctl 2	112	55	70	26
Ctl 3	118	52	73	26
Ctl 4	83	38	91	46
Ctl 5	78	55	96	46
IP 1	243	150	91	43
IP 2	250	138	93	46
IP 3	283	85	90	46
IP 4	270	100	91	43
IP 5	300	125	91	43

Table 1: Comparison of splenocyte viability rates between the treated and untreated mice after splenocyte isolation.

Supplementary Figure 1: How procoagulant MVs are procoagulant? For details, see **Supplementary File 1**.

[Please click here to download this File.](#)

Supplementary Figure 2: The microparticles (MP) captured-based prothrombinase assay. For details, see **Supplementary File 1**.

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Supplementary Figure 3: Correlation plot between measurements of SMVs by prothrombinase assay and by spectrophotometric protein assay in untreated or *P. gingivalis* treated mice.

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Supplementary Figure 4: Analysis of the size distribution of SMVs isolated from mice (A) and rat splenocytes (B).

The suspension of SMVs was obtained from the spleen of untreated mice (Control MVs) or individuals subjected to gum damage without LIG MVs or with local addition of *P. gingivalis* (LIG-PG MVs). SMVs from rats were harvested in the supernatant of isolated splenocytes subjected to a 24 h stimulation by LPS (LPS MVs) or PMA (PMA MVs) as described elsewhere³⁷. Mean dia: Mean diameter; Mode dia: median value of the diameter. Measurements were performed using a 400 nanopore to assess the largest size distribution range. [Please click here to download this File.](#)

Supplementary Figure 5: Identification of the protein content of MVs from rat splenocytes isolated from young rats by western blot. For details, see **Supplementary File 1**. [Please click here to download this File.](#)

Supplementary File 1: Details on the experimental procedures and explanations for Supplementary Figures 1,2,5. [Please click here to download this File.](#)

Discussion

The present study confirms that the spleen is a major and reliable source of MVs with physiopathological relevance compared to other sources like blood, of limited volume in mice. Provided precautions are taken, the method is easy to set up and does not require expensive equipment. Since no alternate way other than *in vivo* assessment is available, the current model appears to be a valuable method to study the impact of pro-drugs on MV shedding. Importantly, the standardized protocol for harvesting murine splenic microvesicles (SMVs) presented here should fit the unmet needs for the *in vivo* study of the control of SMV-mediated effects, eventually in engineered mice after injection or nasal instillation.

The present method also shows that SMVs are relevant preclinical tools to investigate remote effects of local infections, like *P. gingivalis* IP infection. Indeed, using multiple approaches, significant variations between SMVs released from *P. gingivalis*-treated vs. untreated animals were measured, suggesting a remote effect of the local IP injection, already detectable after 2 weeks. Preliminary data from our laboratory using other remote *P. gingivalis* infection sites confirmed that *P. gingivalis* may initiate a 1.7-fold SMV elevation as early as day-7 post-infection.

It is also observed that the *P. gingivalis*-induced remote effects were confirmed by spleen analysis with significant variations in weight, cell viability, and total count. Furthermore, *P. gingivalis* prompted a 6.5-fold increase in the spleen neutrophil count when measured by immunostaining just after splenocyte isolation (t0). Accordingly, variations of the SMV cell origin profile would indicate the shedding of parental cells caused by the initial condition of the animal.

Because SMVs released in the supernatant of 24 h splenocyte cultures were tripled when isolated from IP-injected mice, they appear reliable biomarkers of remote spleen activation by *P. gingivalis*, making them eventual tools to monitor pharmacological control.

In vitro, the splenocytes culture can be performed using 10% FBS, depleted or not from exosomes. In the current experiments, no differences were observed, and variations between untreated splenocytes remained detectable to the same extent with both types of FBS.

In the present procedure, a 2-week duration did not lead to significant variations of the spleen weight in untreated mice. It is, however, important to keep in mind that the spleen weight may vary with age, as previously reported in a series of young, old, and middle-aged control rats.¹ In such a case, the SMV quantification needs to be expressed as a cell count ratio.

The present procedure was optimized for a murine model and suitable for further transgenic mice investigations. Although the major drawback of the murine model is a small spleen weight compared to rats³³, the adapted splenocyte and SMV isolation procedures described herein prevent cell damage and loss, while all contaminating erythrocytes are fully discarded. Washing is crucial for a good splenocyte purification yield and needs to be performed gently with no

more than 1 mL of ACK lysis buffer per spleen in 9 mL of RPMI to enable extensive elimination of red blood cells. This step may be repeated until the pellet is white. This procedure does not allow the investigation of monocytes and should be adapted for adherent cells in such eventuality.

After 24 h culture, the SMV concentration measured in cell culture supernatants reflects the balance between MV generation and MV recapture by the cultured splenocytes. Therefore, in adapted versions of the above procedure, special attention needs to be given to the presence of cells with professional or accessory phagocyte activity (monocytes, endothelial cells, etc.), and kinetics of the SMV release in supernatant should be carefully established accordingly.

Disclosures

The authors have nothing to disclose.

Acknowledgments

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Article 2

P. gingivalis alters spleen response in a murine periodontitis model

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Introduction

Periodontitis is a highly prevalent, oral inflammatory disease of infectious origin and the primary cause of tooth loss in adults. It is associated with a progressive destruction of periodontal tissues leading to the formation of periodontal pockets. Periodontitis has been evoked in the progression of physio-pathological mechanisms both at the clinical, cellular and molecular levels,² although the contributive mechanisms and how they interplay remain elusive.

Initially, identified by Wolf 1967 as a platelet dust containing phospholipids, and capable of supporting coagulation,²⁵ microvesicles (MVs), are submicron fragments of the plasma membrane that shed into the extracellular space in response to a variety of cellular stress conditions.⁴ MVs are released in biological fluids such as blood, urine, tears and saliva. In the blood, they circulate at low concentration in healthy individuals and are elevated in various cardiovascular and chronic diseases including diabetes, chronic renal failure, pre-eclampsia and hypertension.²³⁰ Ranging in size between 100 to 1000 nm in diameter, they are released during plasma membrane budding, and considered as physiological shuttles supporting cellular cross-talk. Indeed, the MV membrane embeds proteins, signaling nucleotides, and metabolites as well as RNA, non-coding RNA and bioactive lipids that were present at the site of

their emission.²³¹ MVs are considered pro-coagulant because they expose phosphatidylserine, a phospholipid that catalyzes the assembly of the complexes of blood coagulation .²³²

The spleen is the largest secondary lymphoid organ in the body and possesses a wide range of immunological functions ³. It is an important source of MVs.⁷ Previous data from the laboratory have shown that (i) spleen MVs may act as pro-inflammatory mediators promoting premature senescence of coronary artery endothelial cells, ^{7 4} leading to endothelial dysfunction and the secondary release of pro-senescent endothelial MVs and (ii) that the LPS of *Porphyromonas Gingivalis*, the main causative pathogen in periodontitis, induces to the shedding of proapoptotic endothelial-derived microvesicles (MVs) from cultured endothelial HUVEC.⁶

In vitro and in vivo data from the laboratory also identified *LPS* as an inducer of the shedding of pro-coagulant, pro-senescent and pro-inflammatory MVs from rat splenocytes.⁴ The feasibility of a pharmacological control of the release of prosenescent MVs from the spleen was further demonstrated in a rat model of ageing. Oral treatment by an optimized omega-3 formula was found protective against both the increased release of SMVs isolated from middle-aged and aged rats, and their noxious endothelial prosenescent effects assessed in primary coronary endothelial cells . ⁷

This work aims to study the impact and remoted effects of *P.gingivalis* local gum infection on the spleen tissue. Experiments are designed to gain a better knowledge of the interactions between local teeth infection and the spleen response.

Materials and methods

Animal experiment

8 weeks old C57BL6 mice (Janvier, Le Genest-Saint-Isle, France) were used in this study. Briefly, *P. gingivalis* (ATCC 33277) was cultured in anaerobic conditions in Brain heart Infusion medium (Bio-Rad, France) supplemented with hemine and menadione as described previously.

Experimental periodontitis was induced in mice gum with silk ligatures (LIG), *P.gingivalis* soaked ligatures, *P.gingivalis* oral gavage (LIG-PG) for 2 or 4 weeks. In some experiments of *P.gingivalis*, infection was performed by intraperitoneal injection (IP) of (5.10^7 bacteria) for 2 weeks. IP-treated mice were eventually treated by a PAD4-4 inhibitor injected simultaneously to IP (CL amidin, 4mg/ml)

Protocols were approved by the Ethics Committee “Comité Régional d’Ethique en Matière d’Expérimentation Animale de Strasbourg (CREMEAS)” (APAFIS#28745-2020121815051557). Mice were examined to evaluate pain and stress, and their weight monitored daily. All infection procedures were repeated 3 times per week)

Mouse splenocyte isolation and culture

Splenocytes were obtained as detailed elsewhere (see manuscript 1)

After sacrifice, fresh mouse spleens were weighed, washed in PBS (phosphate-buffered saline, Lonza, USA) and cleaned from any fat debris. Under sterile conditions, spleens were cut using a scalpel into 1mm slices before homogenization by the plunger of a 2ml syringe used as a pestle and further filtered through 100- μ m sterile strainers (Sarstedt, Germany). Following 450g centrifugation for 5 min, the cell pellet was re-suspended in a 1-ml ammonium-chloride-potassium erythrocyte lysis buffer for 5min, then completed with 9ml RPMI-1640 medium (PAN biotech) supplemented with L-glutamate (2mM), penicillin (100 U/mL), streptomycin (100 U/mL), fungizone (250 mg/mL) and 10% fetal bovine serum (FBS) (Dutscher). Cells were counted, seeded at 5×10^6 cells/mL in a 75 mL culture flask for adherent cells and incubated in humidified incubator at 37°C, with CO₂ for 24 hours.

Characterization of splenocytes

Isolated splenocytes were characterized by flow cytometry (FACS 543 FORTESSA), according to a standardized protocol using APH7, BV786, PerCP-Cy5.5, Alexa Fluor700, BUV395 and eFluor 450 labelled monoclonal antibodies against mouse CD4, CD8, CD19, LY-6C, LYG-6 (GR-1), (BD Biosciences) and CD11b (Mac-1) (e-Biosciences). Data were analyzed by FlowJo.

Isolation and quantification of splenocytes microvesicles

After 24 hours culture, supernatants were collected under sterile conditions. Splenocytes and cell debris were discarded by centrifugation at 450 g, 15 min at room temperature. Supernatants were further centrifuged twice at 14000g, 60 min, 4°C, washed pelleted SMVs were concentrated in Hanks Balanced Salt Solution (HBSS, without phenol red, without calcium and magnesium, Lonza, Belgium) and stored at 4°C for a maximum of 1 month. Prothrombinase assay was performed to quantify SMVs after their capture on Annexin-A5 coated micro-wells using a microplate spectrophotometer in kinetic mode. Annexin-5 has high affinity for phosphatidylserine (PhtdSer) exposed at the surface of MVs. In this assay, PhtdSer is the rate-limiting factor of the generation of thrombin from prothrombin detected at 405 nm using a chromogenic substrate (PNAPEP-0216, cryopep, Montpellier, France) ⁴⁰. SMV concentration was referred to as nanomolar PhtdSer and was obtained by subtracting the OD values measured using isotype control biotinylated IgGs.

Protein content of splenic microvesicles

MVs protein content was measured by spectrophotometry using a Nanodrop (Thermo Scientific)

Characterization of oxidative stress in spleen tissues

Oxidative stress was determined in spleen tissue using DiHydroEthidium (DHE), a redox-sensitive fluorescent probe. Tissues were embedded in molds

containing Tissue-Tek optimum cutting temperature (OCT) compound (Sakura 4583, Leiden, Netherlands) and snap-frozen in liquid nitrogen, and cryosectioned (10 μ m) and mounted on slides. Slides were then incubated with DHE (2.5 μ M) for 30 min, at 37°C in a dark slide humidified chamber. After 3 washings with PBS, slides were mounted under coverslip using fluorescence mounting medium (DAKO, USA), dried in dark and analyzed by confocal microscopy (Leica) with a 20X magnification lens. Level of oxidative stress was quantified using the Image J software.

Western blot

Spleen lysates (30 μ g) were obtained by incubation in RIPA for 30 min on ice. SDS-PAGE electrophoresis was performed at 10% (Sodium dodecyl sulfate polyacrylamide gel electrophoresis) at 100 volts for 2 hours (Bio-Rad). After transfer onto a nitrocellulose membrane (Amersham GE Healthcare, USA) for 30 min at 25 V, the aspecific sites were saturated by 1h incubation the membranes in a TBS solution (Euromedex, Strasbourg) containing 5% BSA and 0.1% of Tween 20. Membranes were then incubated overnight at 4°C with the primary antibodies directed against: VCAM-1 (1/1000; abcam, Cambridge, UK) and TF (Biomedica 11-4509). After washing, the a secondary antibody was incubated for 1 h at room temperature (1/10000, anti-rabbit or anti-mouse immunoglobulin G, Cell Signaling Technology). The detection of the bands was carried out by chemiluminescence (Fisher, Bioblock Scientific) and the analysis

of the optical density of each band performed by ImageQuant LAS 4000 imager (GE Healthcare). Optical densities are presented as a ratio, optical density of the band of interest to that of the GAPDH (1/10000; abcam Cambridge, UK) a maintenance protein.

Statistical analysis

Data are expressed as mean \pm standard error mean (S.E.M) for n different experiments and analyzed by Graphpad Prism 5. Statistical variance between two groups was determined by applying unpaired-T test. Differences were considered statistically significant at $P < 0.05$.

Results

1- Impact of *P. Gingivalis* on spleen weight and cell count and cell viability

After 2 weeks no significant modification in spleen weight, viability or cell count could be observed between control individuals or those treated by ligature or ligatures impregnated or not with *P. Gingivalis*. Only IP injection led to a modification of spleen weight, independently of the co-injection of the PAD-inhibitor, suggesting a spleen cell proliferation or recruitment.

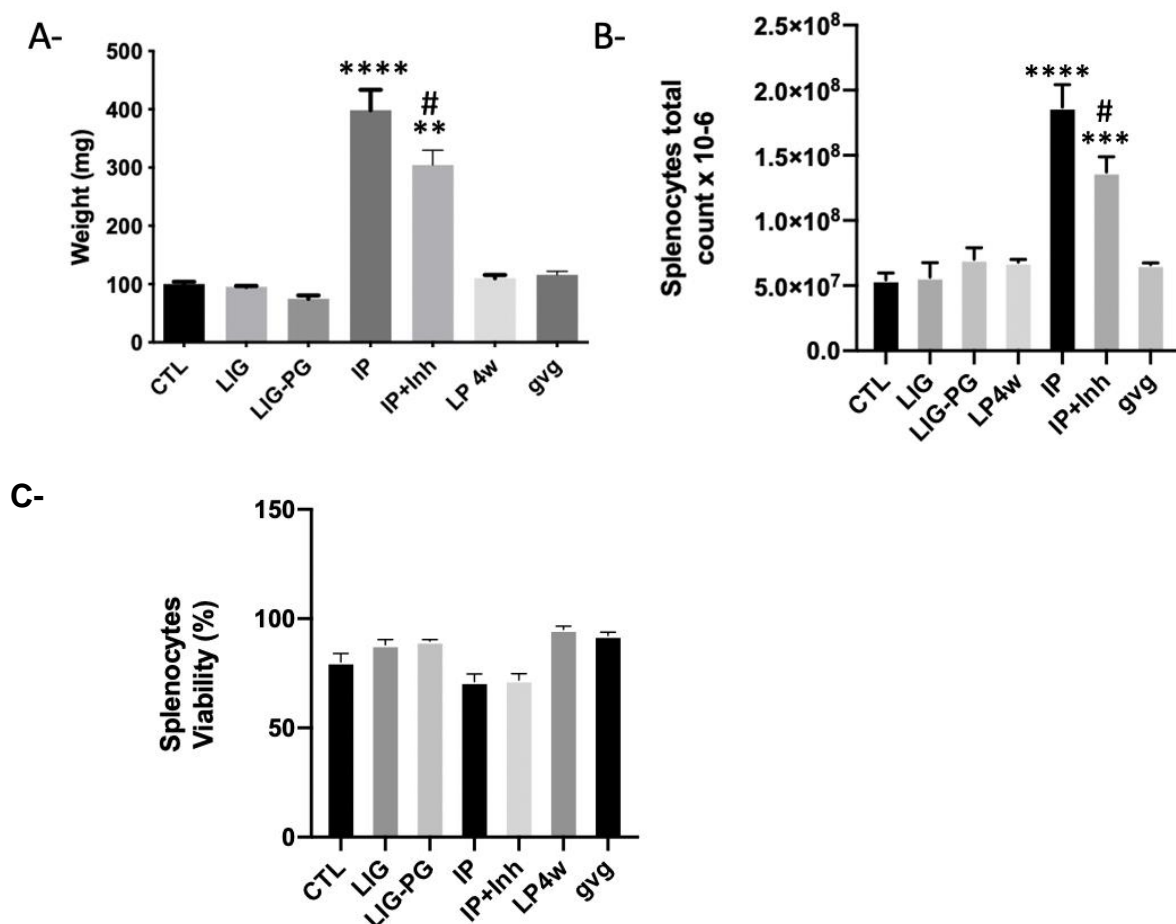


Fig 1: IP injection of *P. gingivalis* significantly enhances spleen weight (A) and splenocyte count (B) that is reduced by the PAD4 inhibitor.

CTL: untreated mice, IP: mice submitted to P. Gingivalis IP injection for 2 weeks, LIG: mice submitted to 2 weeks gum ligation, LIG-PG : mice submitted to 2-weeks gum ligation with a thread impregnated with P.gingivalis, LP4W: mice submitted to gum ligation with a thread impregnated with P.gingivalis for 4-weeks , IP+I: mice submitted to simultaneous P.gingivalis and PAD4 inhibitor IP injections for 2-weeks, gvg: mice submitted to oral gavage for 2 weeks
Data are expressed as mean± SEM. n=5: ***: $p < 0.0001$ & 0.0001 versus CTL, respectively;
#: $p < 0.05$ vs. IP.

2- P. gingivalis increases the splenocyte ability to shed SMVs independently of histone citrullination

After 24h culture, only splenocytes extracted from individuals treated by intraperitoneal injection of P. Gingivalis showed enhanced ability to shed SMVs as measured by prothrombinase assay or protein content culture medium. SMVs concentration doubled as compared to the SMVs from splenocytes of control spleens (IP vs CTL, $p < 0.01$). Only the IP treatment enhanced the shedding of SMVs and the PAD4 inhibitor had no effect, suggesting that histone citrullination is not causative. Interestingly, when the *P. Gingivalis* treatment was extended from 2 weeks to 4 weeks, SMV shedding returned to the baseline levels of control individuals. Noteworthy, the delivery of *P. Gingivalis* by oral gavage was ineffective indicating that *P. Gingivalis* would not activate spleen cells via a digestive route.

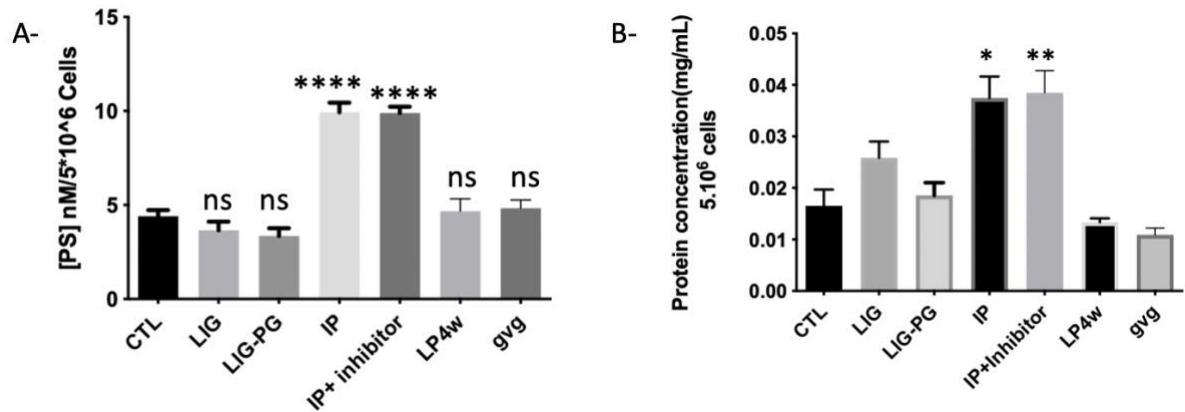


Fig 2: IP injection of *P. gingivalis* favors enhanced splenocyte shedding in vitro.

SMVs were assessed by protein content, or prothrombinase assay. CTL: untreated mice, IP: mice submitted to *P. Gingivalis* injection for 2 weeks, LIG: mice submitted to gum ligation for 2 weeks, LIG-PG : mice submitted for 2 weeks to gum ligation with a thread impregnated with *P.gingivalis*, LP4W: mice submitted to gum ligation with a thread impregnated with *P.gingivalis* for 4 weeks, IP+I: mice submitted to simultaneous *P.gingivalis* and PAD4 inhibitor IP injections for 2-weeks, gvg: mice submitted to oral gavage for 2 weeks. Data are expressed as mean± SEM. n=5 ****: $p<0.0001$

3. The cell composition of the spleen varies with the mode of administration of *P. Gingivalis*.

Modifications of cell composition in response to 2 weeks treatments was assessed by flowcytometry. Data indicate that even the gum ligature (LIG) is able to induce a significant elevation of spleen monocytes, neutrophils, although to a less extent as compared to *P. Gingivalis* IP injection that tripled monocytes counts and raised neutrophils by ten folds as expected following intense initiation of innate immunity. Compared to the sole ligature, impregnation of the thread by *P. Gingivalis* did not significantly alter the monocyte, neutrophil or granulocyte cell counts. By contrast, no modification

of the B, T4 and T8 lymphocyte counts could be observed in LIG nor LIG-PG after 2 weeks or even 4 weeks, suggesting a minor contribution of the adaptative immunity. Nevertheless, IP injection significantly reduced the T and B lymphocyte counts confirming the feasibility of their mobilization through vascular routes as compared to gavage. Interestingly, oral gavage deeply reduced the count of T8 lymphocytes as compared to IP injection.

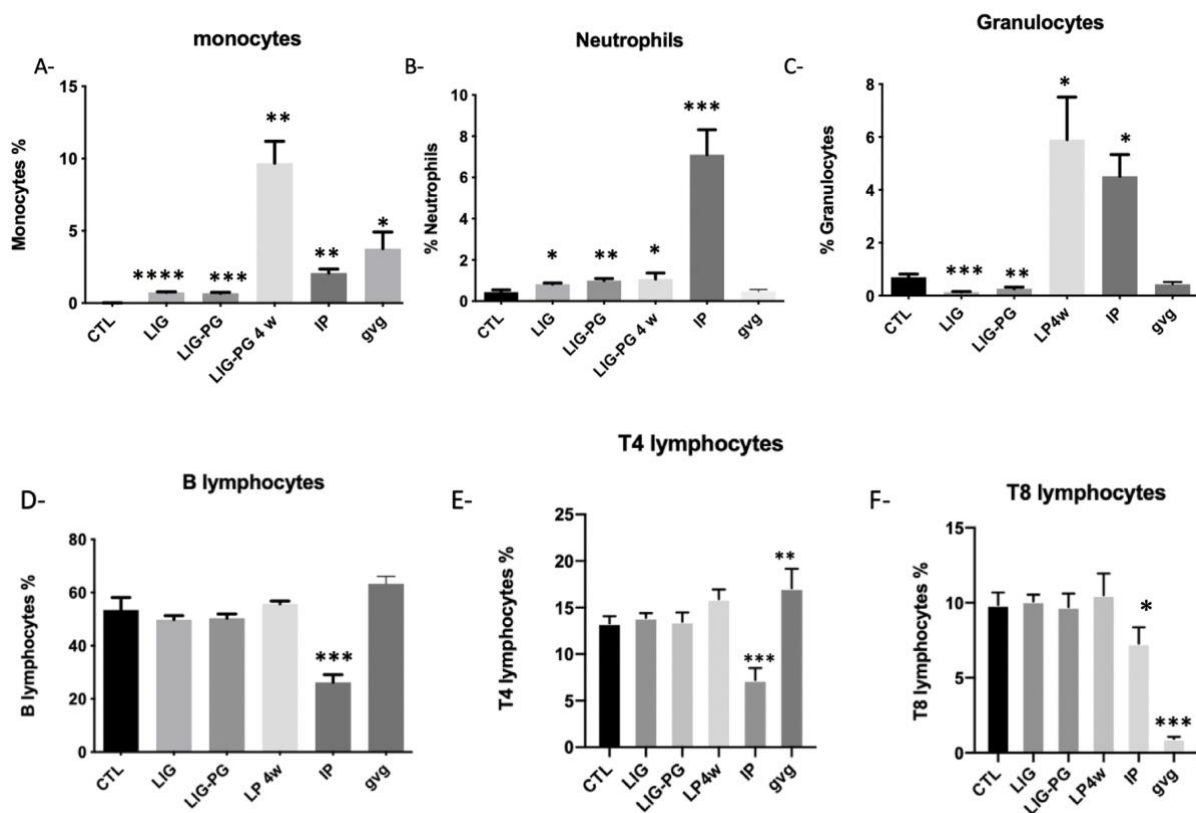


Fig 3: Spleen cell composition varies with the type of induction.

Leukocyte counts were measured by flow cytometry of the spleen cells from mice treated for 2 weeks by either gum ligature (LIG) with or without *P. Gingivalis* thread impregnation (LIG-PG), intraperitoneal *P. gingivalis* injection (IP) or oral gavage (gvg). LP4w: and IP enhanced monocytes and neutrophils. , LP4W: mice submitted to gum ligation for 4 weeks with a thread impregnated with *P.gingivalis*. CTL: untreated mice. Data are expressed as mean \pm SEM. n=5 ****: $p < 0.0001$, *** $p < 0.001$, ** $p < 0.004$ * $p < 0.01$, versus control.

4- Gum injury and *P. gingivalis* infection favor ROS accumulation in spleen tissue

Compared to control spleens, gum ligation alone was able to trigger a 5-fold ROS accumulation as assessed by histological staining with dihydroethidium. Addition of *P. gingivalis* in threads further doubled values of ROS (LIG-PG), up to 75% of the highest ROS value observed after IP treatment. Interestingly, PAD4 drastically prevented the effect of intraperitoneal *P. gingivalis*, suggesting that NETosis is key to ROS accumulation in the spleen.

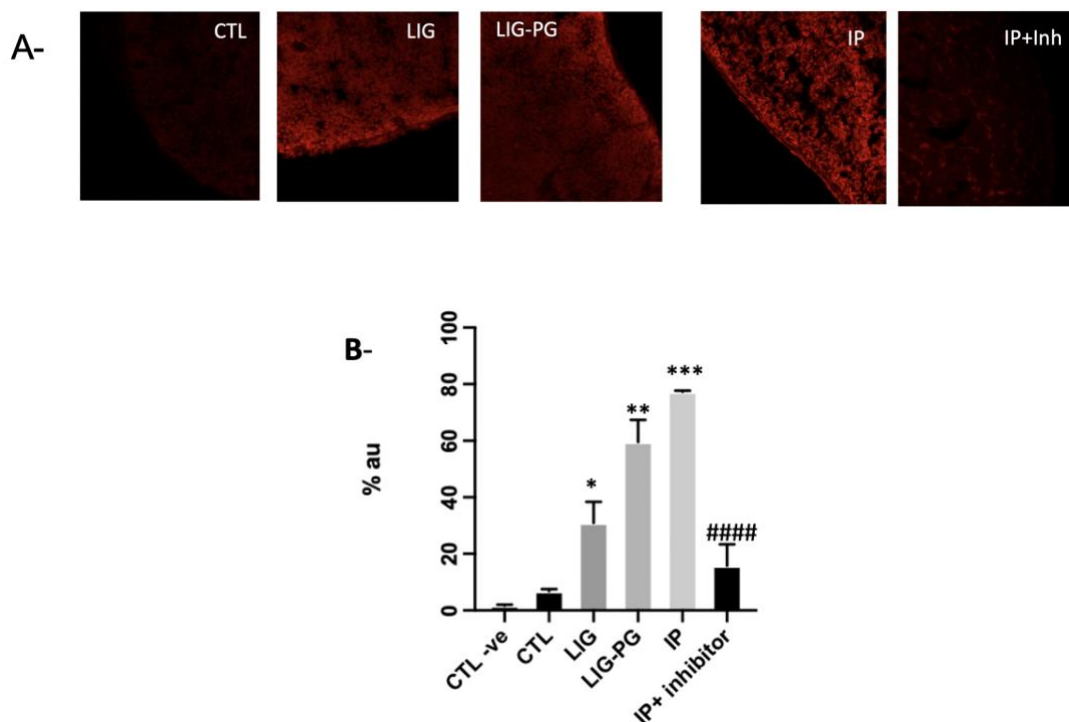


Fig 4: Upon gum injury and infection ROS accumulation increases in spleen tissue.

A: representative photographs of immuno-histological staining with the red fluorescent probe with DHE. CTL: untreated mice, IP: mice submitted to PG injection for 2 weeks, LIG: mice submitted to gum ligation for 2 weeks, LIG-PG : mice submitted to gum ligation for 2 weeks with a thread impregnated with *P.gingivalis*, IP+I: mice submitted to simultaneous *P.gingivalis* and PAD4 inhibitor

injection for 2 weeks. Data are expressed as mean \pm SEM. $n=5$ ***: $p<0.0001$, **: $p<0.001$, *: $p<0.03$. #: $p<0.0001$ vs CTL.

5- *P.gingivalis* enhances the pro-inflammatory response in spleen tissue

The activation of spleen cells was further characterized by assessment of the expression of VCAM-1, an inflammatory marker. In addition, tissue factor (TF) was assessed as an early indicator of leukocyte response to inflammation. As compared to control spleens, a 3-fold over-expression of VCAM-1 was observed in response to gum ligature (LIG), with or without *P.gingivalis*. IP injection of the pathogen did not induce higher VCAM-1 expression. Interestingly, TF was also overexpressed after 2 weeks of treatment, the highest value being observed with local gum injury combined to *P.gingivalis* soaked threads.

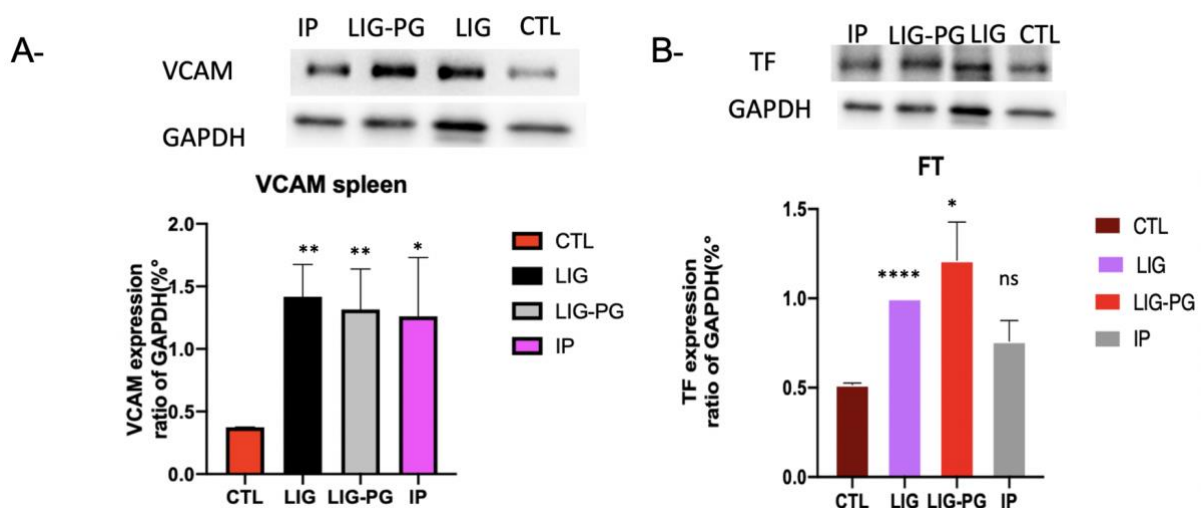


Fig5: Enhanced expression of VCAM-1 (A) and tissue factor (TF) in response to gum injury.

Upper panel: representative western blots. Lower panel: cumulative data. CTL: untreated mice, IP: mice submitted to *P. Gingivalis* injection for 2 weeks, LIG: mice submitted to gum ligation for 2 weeks, LIG-PG : mice submitted to gum ligation with a thread impregnated with *P.gingivalis* for 2 weeks.

*GAPDH: house-keeping protein. Data are expressed as mean± SEM. n=5 ****: p<0.0001, **: p<0.001, *: p<0.05 vs. CTL.*

Discussion

Neutrophils are key to the multiple spleen cell responses induced by *P. Gingivalis* gum insult

The present findings indicate that *P. gingivalis* is a strong inducer of the spleen response after only 2 weeks of treatment, highest values being observed when the pathogen is given by intraperitoneal injection. (figure 1)

While IP injection led to a drastic elevation after 2 to 4 weeks in spleen weight and cell count, they remained stable in individuals submitted to local gum ligature with soaked threads as compared to control animals. In all animal subsets cell viability did not differ from the baseline, suggesting that the above increase of weight was the consequence of either cell recruitment or cell proliferation. Interestingly, the simultaneous treatment by IP and a PAD 4 inhibitor that blunts histone citrullination lead to a significant reduction of the spleen weight and total cell count thereby pointing at the possible role of NETosis.

Analysis of the cell composition revealed that the gum insult, eventually combined to *P. gingivalis* local infection, was also able to significantly modify the spleen cell composition, mainly cells involved into naïve immunity. Although to a lesser extent than IP infection, increased neutrophil and monocyte counts were found in LIG and LIG-PG subsets while granulocytes were decreased after 2 weeks. (see figure 4) When treatment was extended to 4 weeks only

monocytes and granulocytes were strongly elevated in LIG-PG thereby underlining the different kinetics in cell proliferation and recruitment. Conversely to the IP infection, gum insult did not induce any count modification of the cell involved in adaptative immunity after 2 or 4 weeks.

Gum insult early promotes spleen responses driven by naïve immunity

To confirm the spleen cell modification after 2-weeks gum insults, we measured by western blot the expression of VCAM-1, an endothelial inflammatory marker and TF, induced at the plasma membrane of activated monocytes, neutrophils and endothelial cells in response to inflammatory and procoagulant mediators. Interestingly, gum insult combined or not to *P. gingivalis* led to a drastic and similar over-expression of both VCAM-1 and TF, that nearly reached the values observed after IP injection of *P. gingivalis*. (figure 5) In addition, ROS accumulation in the spleen also indirectly confirmed the active contribution of neutrophils and granulocytes after gum insults. Altogether, data from LIG and LIG-PG subsets strongly suggest a key role of monocytes and neutrophils in accordance with the flow cytometry cell analysis. (see figures 3 & 5). Nevertheless, the significant induction of splenocyte shedding assessed by prothrombinase assay or protein content was only detected in response to intraperitoneal *P. Gingivalis* infection. Interestingly, PAD4 was not efficient in the limitation of IP-driven SMV shedding, thereby suggesting that the release of MVs in the spleen in response to IP injection was not dependent on NET

extrusion after 2 weeks. Therefore, SMVs are most likely from another cell origin than neutrophils or released by non-extruding neutrophils in response to IP. The characterization of SMV cell origin would confirm the degree of activation of each contributing cell line.

Conclusion

Altogether data are highly suggestive of the strong and early contribution of the cells of naïve immunity in periodontitis and of a key role of neutrophils and of Netosis in the initiation and progression of periodontitis-driven spleen responses after 2 weeks of infection.

Complementary data

To further confirm the remote effects of gum insults described in the article, measurements have been initiated to detect

1) The properties of SMVs on coronary endothelial cells. The aim was to assess SMVs as possible mediators of a thrombotic tendency known to be associated with periodontitis in humans. For this purpose, we used a MV-mediated endothelial crosstalk model. The endpoint was the induction of endothelial senescence.

2) The heart inflammatory responses eventually driven by periodontitis by immunolabelling and western blot using heart lysates sampled from the different individuals that were analyzed in the article. We more particularly investigated markers of the endothelial inflammation (VCAM-I), the up-regulation of pro and anti-inflammatory cytokines and the expression of Gasdermin D, a recently identified contributor to the inflammosome.

Methods

Primary coronary endothelial cell culture

Primary coronary artery endothelial cells (ECs) were prepared from left coronary arteries of pig hearts, collected from local slaughterhouse (COPVIAL, Holtzheim, France) as described previously.⁷ Left coronary arteries were

dissected and cleaned of any adhesive conjunctive tissues then flushed with PBS. After debris removal and blood excess, cleaned coronary arteries were treated with Collagenase type I (Gibco, life technologies corporation, USA) solution at 1 mg/ml prepared in MCDB-131 medium (Gibco, life technologies limited, UK), supplemented with streptomycin (100 U/ml), penicillin (100 U/ml), fungizone (250 mg/ml), and L-glutamine (1 mM, all from Lonza, St Quentin en Yvelines, France) for 15 min at 37°C. Endothelial cells were then extracted into 50-mL falcon tubes by circular massage of arteries with frequent flushing with medium. The collected medium containing endothelial cells was then centrifuged (450g, 5min, at room temperature), supernatant was discarded and cells were re-suspended with complete MCDB-131 medium supplemented with 15% fetal bovine serum (FBS), penicillin (100 U/ml), streptomycin (100 U/ml), fungizone (250 mg/ml), and L-glutamine (1 mM). Endothelial cells of 4-5 different coronary arteries were cultured in adherent T25 flask in humidified incubator at 37 °C, with 5% CO₂. After 6 hours, cells were washed with PBS non-adherent cells removal and fresh complete medium was added. Thereafter, first passage ECs (P1ECs) were grown for 72 hours with medium changed every 48 hours.

Treatment of endothelial cells with SMVs

Following trypsinization (Trypsin, Gibco, Life Technologies SAS, St Aubin, France), P1 endothelial cells were seeded in 6-well plate at 65-75%

confluency and incubated with identical amounts of washed SMVs (30nM PhtdSer eq.) for 48 hours, P3 cells was our standard for senescence.

Measurement of Senescence-associated β -galactosidase activity

SA β -gal activity was measured by flow cytometry using the C12FDG fluorogenic cell permeable substrate. Endothelial cells were alkalinized (PH raised to 6) with chloroquine (300 μ molar) for 1 hour, followed by 1 hour incubation with C12FDG (33 μ molar), a fluorogenic substrate of SA β -gal. Cells were thereafter washed with ice cold PBS, harvested with trypsin and freshly analyzed using CellQuest software. (FACSscan, Becton Dickinson, San Jose, CA, USA). Light scattering parameters were set to eliminate dead cells and subcellular debris. The green C12-fluorescein signal was measured and SA β -gal activity estimated using the mean fluorescence intensity (MFI) of the cell population. Auto-fluorescence gains were determined in unlabeled cells and set at the first logarithmic decade.⁷

Western blot

Heart lysates (30 μ g) from the left ventricle were obtained by incubation in RIPA for 30 min on ice. SDS-PAGE electrophoresis was performed at 10% (Sodium dodecyl sulfate polyacrylamide gel electrophoresis) at 100 volts for 2 hours (Bio-Rad). After transfer onto a nitrocellulose membrane (Amersham GE Healthcare, USA) for 30 min at 25 V, the aspecific sites were saturated by 1h incubation the membranes in a TBS solution (Euromedex, Strasbourg)

containing 5% BSA and 0.1% of Tween 20. Membranes were then incubated overnight at 4°C with the primary antibodies directed against: VCAM-1 (1/1000; abcam, Cambridge, UK) and TF (Biomedica 11-4509). After washing, the secondary antibody was incubated for 1 h at room temperature (1/10000, anti-rabbit or anti-mouse immunoglobulin G, Cell Signaling Technology). The detection of the bands was carried out by chemiluminescence (Fisher, Bioblock Scientific) and the analysis of the optical density of each band performed by ImageQuant LAS 4000 imager (GE Healthcare). Optical densities are presented as a ratio, optical density of the band of interest to that of the GAPDH (1/10000; abcam Cambridge, UK) a maintenance protein.

VCAM (1/1000; abcam, Cambridge, UK) Gasdermin (1/2500; abcam, Cambridge, UK) TNF-alpha (1/1000; abcam, Cambridge, UK) , IL-6 (1/1000; abcam, Cambridge, UK), IL-10 (1/1000; abcam, Cambridge, UK).

Results

1) Complementary data to establish the proof of concept of endothelial damage induced by SMVs

SMVs induce the senescence of primary coronary endothelial cells

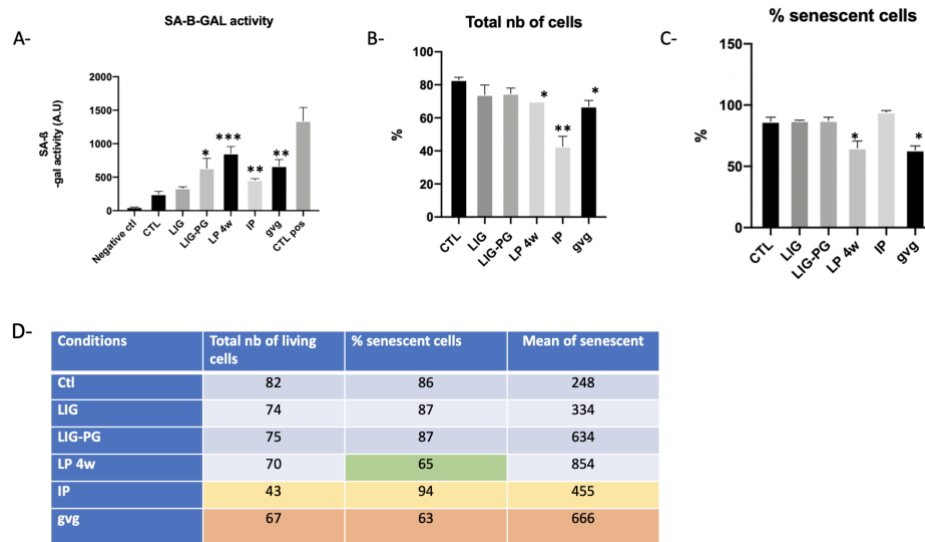


Fig 1: SMV generated in the presence of *P.gingivalis* induce endothelial senescence.

CTL: untreated mice, IP: mice submitted to PG injection for 2 weeks, LIG: mice submitted to gum ligation for 2 weeks, LIG-PG : mice submitted to gum ligation for 2 weeks with a thread impregnated with *P.gingivalis*, IP+I: mice submitted to PG injection for 2 weeks with injection PAD4 inhibitor simultaneously Data are expressed as mean \pm SEM. n=5 ***: $p < 0.0001$

2) Complementary data to establish the proof of a remote heart damage prompted by *P.gingivalis*

P. gingivalis induces inflammation in heart tissue

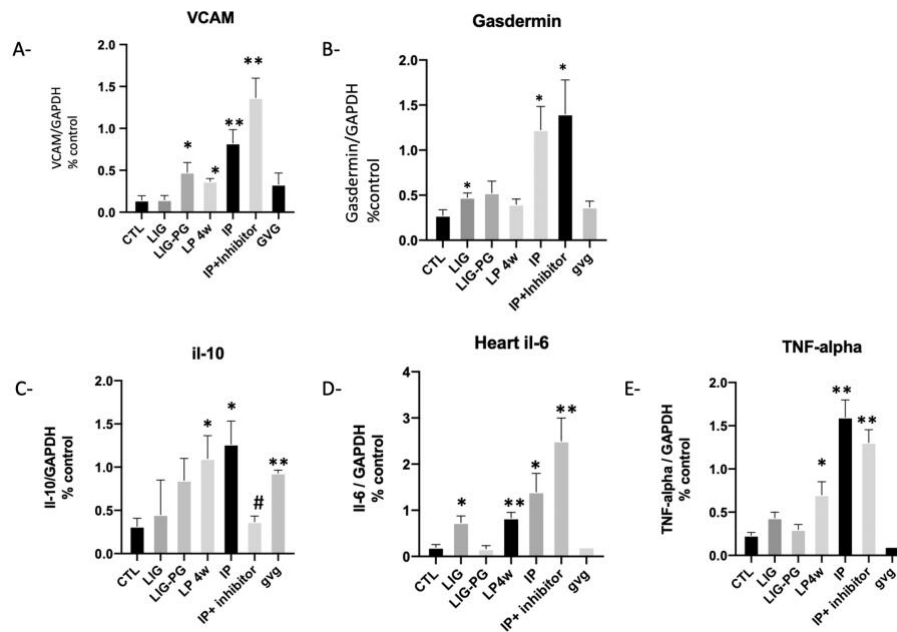


Fig: IP induces elevation of inflammatory markers in heart tissue: **VCAM** (IP: 0.8 ± 0.1 , CTL: 0.2 ± 0.05 , $p < 0.0001$), **Gasdermin** (IP: 1.2 ± 0.2 , CTL 0.2 ± 0.06 $p = 0.0009$), **TNF-alpha** (IP: 1.6 ± 0.2 , CTL: 0.2 ± 0.03 $p < 0.0001$), **IL-6** (IP 1.1 ± 0.6 , CTL 0.2 ± 0.05 $p < 0.001$), **IL-10** (IP: 1.2 ± 0.2 CTL 0.3 ± 0.09 , $p = 0.04$).

Discussion

Data clearly demonstrate that gum ligature with threads soaked in *P. gingivalis* induces high SMV-mediated endothelial senescence as compared to the SMV isolated from mice with IP infection. This observation points at an eventual new mechanism possibly contributing to thrombotic tendency through remote paracrine MV effects. Indeed, senescent endothelial cells are characterized by an atherothrombogenic profile.

Analysis of western blots of heart extracts indicated major changes of the inflammatory profile. In response to IP *P.gingivalis* injection, PAD-4 only down-regulated **IL-10** (IP+INH: 0.3 ± 0.06 , IP: 1.2 ± 0.2), suggesting the impact of netosis on anti-inflammatory responses. After 2 weeks-ligature, *P.gingivalis* soaked thread significantly upregulated **VCAM** and **Gasdermin** (LP: 0.5 ± 0.1 , $p < 0.0001$; LP: 0.6 ± 0.1 , $p < 0.001$ respectively; CTL: 0.2 ± 0.055), while LIG alone had no effect. A 4-weeks sustained treatment raised the expression of **VCAM** (LP4W: 0.4 ± 0.03 , CTL 0.2 ± 0.03 $p < 0.0001$), **TNF-alpha** (LP4W: 0.7 ± 0.1 , CTL 0.2 ± 0.03 $p < 0.0001$) and **IL-6** (LP4w: 0.8 ± 0.1 , CTL 0.2 ± 0.05 $p < 0.001$). Strikingly, only the IL-10 expression reached the peak values induced by IP (LP4w: 1.1 ± 0.2 , IP: 1.2 ± 0.2 vs CTL 0.3 ± 0.09 , $p = 0.04$), strongly suggesting a delayed anti-inflammatory effect prompted by *P.gingivalis*. Indeed, gavage led to elevated IL-10 already after 2 weeks (0.9 ± 0.03).

Interestingly, aside from the heart tissue responses after IP injection, mice submitted to gum insults showed a significant 2 folds elevation of VACM-I, suggesting a major endothelial insult (compared to 3 folds in the IP subset) Unfortunately, variations of cytokines (IL-6 & IL-10) were less informative owing to variability and the balance between pro and anti-inflammatory interleukines could not be investigated after 2 weeks. Nevertheless, the proinflammatory IL-6 was already elevated in response to ligature. Most probably the IL-10 assessment by western blot is highly sensitive to the kinetics of the proinflammatory responses. The role of Netosis could be shown by the reduced IL-10 expression in mice treated with IP and inhibitor. The model also shows that heart inflammation is a chronic on-going process since a prolonged 4-weeks treatment enhances the up-regulation of TNF-alpha, VCAM-I, IL-6 as compared to LIG-PG for 2 weeks.

Conclusion

Taken together, all data confirm the hypothesis of a remote effect of *P.gingivalis* contributing to the gum insult. They also bring new evidences in the relationships between the spleen and the heart also termed the cardiac splenic axis. Responses.

Future experiments

To further confirm the remote effects of MVs and of Netosis in the initiation and progression of *P.gingivalis*-mediated effects, the plasma concentration of NETs could be measured as well as the variations of cytokines and of circulating microvesicles of leukocyte origin. For this purpose, pre-analytical sampling has been achieved using individuals of the seven animal subsets experimental procedures were established according to the following methods. The aims were to examine and confirm the eventual Netosis effects in the IP treated mice, to identify remote mediators in the plasma. In addition, lymph nodes of the abdomen were also harvested to examine early remote effects by RT-PCR.

Preparation of preanalytical samples for anticipated experiments

Intraperitoneal (IP) liquid collection

After mice anesthesia using a combination of 100mg/kg ketamine and 10mg/kg xylazine, injection of 2 ml of salt solution (NaCl) into the peritoneal sac was performed followed by a massage to the hall abdominal cavity using a 2ml syringe. Then, peritoneum, intraperitoneal liquid was collected slowly liquid (approximately 1,7 ml might be collected) and stored at -80°C for long storage.

Plasma preparation

After IP liquid collection, mice were sacrificed. Rapidly the blood was collected from the mice's heart and harvested on 0.129 M Na citrate ratio: 9 volume

blood per 1vol anticoagulant. The tube was well mixed by inverting then centrifuged rapidly the at 13000g for 3 min at room temperature. Supernatant was collected in a new Eppendorf and centrifuged again at 13000g for 3 min at room temperature.

Platelet free plasma (PFP) was then collected by rapid upside-down inverting in a 1.5 ml Eppendorf and stored at -80°C .

After IP liquid and blood collection, the left part of the heart was isolated and stored at -80°C for long storage and the spleen was harvested after laparotomy.

Detection and quantification of NETs in the mice intraperitoneal liquid (IPL)

For comparative purposes, NETs will be characterized from the IPL of the different subsets and the and the activity of histones measured as a ratio of the NET length. After thawing, samples are centrifuged at 10,000g for 10 minutes. 50 μL of SN is recovered from washing. (SNL) and the pellet is suspended in 50 μL of PBS pH 7.4 or physiological solution. The obtained volumes are the separated into four 25 μL aliquots. 25 μl aliquot from the pellet and (SNL) are placed on slides, stained with 25 μL of DAPI or Hoetsch, incubated 10 min and then visualized under a fluorescence microscope. The remaining aliquot of each sample is used for elastase detection using the chromogenic substrate: MeOSuc-AAPV-pNA (Km 0.52 mM).

Dosage of cytokines in blood plasma

Cytokine assay was performed from blood samples collected during animal sacrifices. The assay of these cytokines was carried out using the Proteome Profiler Mouse Cytokine Array Kit, Panel A (R&D systems) consisting of profiling 40 different antibodies to mouse cytokines, chemokines, and acute phase proteins.

CXCL13/BLC/BCA-1	IL-5	M-CSF
C5a	IL-6	CCL2/JE/MCP-1
G-CSF	IL-7	CCL12/MCP-5
GM-CSF	IL-10	CXCL9/MIG
CCL1/I-309	IL-12 p70	CCL3/MIP-1 alpha
CCL11/Eotaxin	IL-13	CCL4/MIP-1 beta
ICAM-1	IL-16	CXCL2/MIP-2
IFN-gamma	IL-17	CCL5/RANTES
IL-1 alpha/IL-1F1	IL-23	CXCL12/SDF-1
IL-1 beta/IL-1F2	IL-27	CCL17/TARC
IL-1ra/IL-1F3	CXCL10/IP-10	TIMP-1
IL-2	CXCL11/I-TAC	TNF-alpha
IL-3	CXCL1/KC	TREM-1
IL-4		

The samples will be mixed with a cocktail of biotinylated detection antibodies, then incubated with the array membrane which is spotted in duplicate with capture antibodies to specific target proteins. After, captured proteins will be

visualized using chemiluminescent detection reagents. The signal produced will be proportional to the amount of analyte bound.

General discussion

In our study, we established the proof of concept of the impact of periodontitis on spleen and confirmed the interest of spleen in a C57BL6 murine model as a reliable and relevant source of MVs with no alternative method available for the procurement of large quantities of MVs. In addition, we confirmed that even after 2 weeks, the physio-pathological impact of any injury in the gum could be remotely sensed by the spleen, at much lower thresholds than those observed by intraperitoneal injection of the pathogen. (*El Itawi et al 2022*)

Interestingly, our standardized protocol for harvesting murine splenic microvesicles (SMVs) fits the unmet needs for the *in vivo* study of the control of SMV-mediated effects in engineered and transgenic mice.

Our findings indicate that *P. gingivalis* is a strong trigger for the shedding of pro-senescent spleen-derived microvesicles (SMVs) that were demonstrated to prompt senescence in primary coronary endothelial cells, on-line with our previous observation in the rat.^{4,7} Our data are in accordance with the cardiac splenic axis that has been proposed to explain the link between inflammation and athero-thrombogenicity and in particular the pericardiac inflammation occurring post myocardial infarction.^{227 229} However, the role of cardiac or splenic Tregs lymphocytes and their constitution remains to be evaluated.²²⁸

Nevertheless, measurement of IL-17 and of its receptor has been undertaken by western blot and by antibody chips using cardiac extracts from individuals of all subsets. Detailed analysis will be necessary to compare plasma and

tissue expression levels of all cytokines and more specifically of those involved in the control of the innate and adaptative immune response.

Used as relevant preclinical tools in our investigation, SMVs showed remote effects of local infection by *P. gingivalis* using multiple approaches. We showed significant variations between SMVs released from *P. gingivalis*-treated vs. untreated animals, already detectable after 2 weeks. We observed that these remote effects were associated with significant variations in weight, cell viability, and most importantly of the cell composition of the spleen. Indeed, *P. gingivalis* prompted neutrophil count raise as assessed by immunostaining just after splenocyte isolation (t0) in mice submitted to gum injury and suggested a remote action caused by chronic infection.

Interestingly, ROS accumulation during *P. gingivalis* infection was reversed by a Netosis inhibitor after reaching it highest raise in response to IP infection.

In the supernatant of 24 h splenocyte cultures, released SMVs were tripled when isolated from IP-injected mice only. However, the SMVs shed from all the conditions were able to alter primary endothelial cells to various degree, indicating on-going effects potentially noxious after a prolonged exposure. Indeed, the prosenescent features of SMVs shed from LIG-PG, LP4w, IP and gvg mice observed in coronary artery primary endothelial cells confirms their authentic role as biomarkers of a remote spleen activation by *P. gingivalis*.

At the heart level, *P.gingivalis* mediated pro-atherothrombotic and pro-inflammatory markers in left ventricular heart extracts. IP induced elevation of all inflammatory markers in heart tissue including VCAM, Gasdermin, TNF-alpha, IL-6, IL-10. The Netosis inhibitor PAD-4 only down-regulated IL-10 suggesting the impact of netosis on anti-inflammatory responses. After 2 weeks-ligature, *P.gingivalis* soaked thread significantly upregulated VCAM and Gasdermin while LIG alone had no effect. A 4-weeks sustained treatment (LP4w) raised the expression of VCAM, TNF-alpha, IL-6. Strikingly, only the IL-10 expression reached the peak values induced by IP, strongly suggesting a delayed anti-inflammatory effect prompted by *P.gingivalis* while gavage led to elevated IL-10 already after 2 weeks. This confirms that our model is suitable for the study of remote cardiac effects by *P.gingivalis* local infection. Moreover, low but sustained pathogen-induced periodontitis alter the balance of heart inflammatory mediators where the control of Netosis appears valuable to preserve or delay heart tissue inflammation.

In the present procedure, a 2-week duration induced variations in the splenocytes population, ROS accumulation, pro-senescent MVs shedding and heart inflammation. It is important to keep in mind that although the major drawback of the murine model is a small spleen weight as compared to rats, the present procedure was optimized for a murine model and suitable for further transgenic mice investigations.

Nevertheless, data confirm the model as suitable for the study of remote spleen and cardiac effects by *P.gingivalis* local or intraperitoneal infection.

Confirmation of our hypothesis of a remote action of periodontitis on spleen immune responses and noxious cardiac impact was obtained by examining spleen and cardiac tissues and the pro-senescent effect of SMVs on endothelial cells. Owing to pandemic, samples remain to be assessed. In particular, the plasma circulating mediators, like circulating fragments of NETs and their enzyme activities remain to be measured. To confirm the early impact on the cardiac outcome, other proteins like MMP or NLRP3 associated to cardiac inflammasome could be of interest as markers of heart tissue remodeling. Finally, the role of the periodontitis in the recently proposed spleen-cardiac axis could be explored in the lymph nodes. Indeed, IL-17 related regulatory events could not be explored at the protein level in spleen or MV extracts, but remain accessible by RT-PCR.

Conclusion

P.gingivalis-associated periodontitis induces spleen activation that seems to be an important source of MVs, eventually associated with heart inflammation and the shedding of deleterious procoagulant SMVs. Our data, although preliminary, show the feasibility of the evaluation of the noxious potency of circulating mediators such as MVs or NETs in individuals with periodontitis. Such results emphasize the need of periodontal management of patient at-risk. Moreover, the control of Netosis could be considered as an interesting strategy to preserve or delay the spleen inflammation.²³³

Annexe

Publications

1- Porphyromonas gingivalis triggers the shedding of inflammatory endothelial microvesicles that act as autocrine effectors of endothelial dysfunction.

Bugueno IM, Zobairi El-Ghazouani F, **El Itawi H**, Anglès-Cano E, Benkirane-Jessel, Toti F, Huck O. 2020 . Sci Rep **10**(1): 1778.

2- Ageing enhances the shedding of splenocyte microvesicles with endothelial pro-senescent effect that is prevented by a short-term intake of omega-3 PUFA EPA:DHA 6:1

A.W Qureishi, R.Altamimy, El Habhab Ali, **El Itawi Hanine**, M.A.Farooq, F.ZOBAIRI, H.Hassan, L.Amoura, M.Kassem, C.Auger, V.Schini-Kerth, F.Toti. Biochem Pharmacol. 2020;173:113734.

3- Significance of Neutrophil Microparticles in Ischaemia-Reperfusion: Pro-inflammatory Effectors of Endothelial Senescence and Vascular Dysfunction

El Habhab A, Altamimy R, Abbas M, Kassem M, Amoura L, Qureshi AW, **El Itawi H**, Kreutter G, Khemais-Benkhiat S, Zobairi F, Schini-Kerth VB, Kessler L, Toti F . J Cell Mol Med. 2020;24(13):7266-81.

1- Isolation of Splenic Microvesicles in a Murine Model of Intraperitoneal Bacterial Infection.

H. EL Itawi, Fareeha Batool, Céline Stutz, Abdul Wahid Qureshi, Fatiha El Zobairi, Olivier Huck, Florence Toti. (Journal of visualized experiments Jove. Accepted manuscript 18 March 2022) DOI: 10.3791/63480)

Scientific communications

Poster presentation

1- Peridental injury prompts remote spleen activation and the generation of spleen procoagulant microvesicles in a periodontitis murine model (International society for thrombosis and hemostasis ISTH – International online congress 17-23rd July 2021, granted a travel fellowship)

H. EL Itawi, S. Amissi, F. Batool, C. Stutz, F. El Ghazouani, A.B. Chaker, A.W. Qureshi, F. Moschovaki-Filippidou, C. Auger, E. Anglès-Cano, O. Huck, F. Toti

2- Remote spleen activation in murine periodontitis prompts the generation of procoagulant and pro-senescent spleen microvesicles associated with early heart inflammation (European molecular biology lab congress : engineering in vascular biology. Barcelona, Spain 9-11 May 2022)

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3-Impact of periodontal inflammation on the cardiac tissues in a murine model.

(International society for thrombosis and hemostasis ISTH congress. London 9-13 July 2021)

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Oral communication

Remote spleen activation after periodontal inflammation is mediated via netosis and prompts the generation of procoagulant microvesicles in an experimental murine model of periodontitis

Hanine El Itawi, Fatiha El Zobairi, Abdul Wahid Qureshi, Fareeha Batool, Céline Stutz, Ahmed Bey Chaker, Amissi Said, Cyril Auger, Olivier Huck, Florence Toti.

*1st place prize winner for the best presentation of the Doctoral school ED414
days - University of Strasbourg 2020-2021*

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Impact de l'inflammation parodontale sur l'axe splénique cardiaque : étude des Neutrophils Extracellular Traps (NETs) et des microvésicules spléniques comme médiateurs des réponses procoagulantes et inflammatoires.

Résumé

P.gingivalis (PG) induit la parodontite et est associée au risque cardiovasculaire. Les microvésicules (MV) sont des effecteurs pro-inflammatoires et coagulants libérés des membranes plasmiques. L'effet à distance de PG sur le cœur et la rate de souris est détecté par immuno-marquage, mesure de ROS, et émission de MVs splénocytaires (SMVs). Les lésions gingivales par fils (LIG) imbibés ou non de PG (LIG-PG) sont comparées au gavage (gvg) et à l'injection intrapéritonéale (IP). LIG et LIG-PG réduisent les granulocytes, doublent les monocytes et les neutrophiles spléniques, sans réponse adaptative. IP triple les monocytes, multiplie par 10 les neutrophiles, réduit par 2 lymphocytes T ou B. L'inhibiteur de PAD-4 réduit les ROS, suggérant une Nétose. In vitro, les SMVs de LIG-PG, IP et gvg induisent la sénescence endothéliale. Dans le cœur, VCAM, Gasdermin-D, IL-6 et TNF- α inflammatoires sont surexprimés pour IP et LIG-PG.

En conclusion, PG induit l'activation splénique et cardiaque à distance, l'émission de SMVs procoagulantes et -sénescents favorisant le risque cardiovasculaire.

Résumé en anglais

Periodontitis, mainly induced by *P.gingivalis* (PG) is associated with cardiovascular risk. Microvesicles (MVs) are pro-inflammatory and -coagulant effectors shed from plasma membranes. We evaluated the remote inflammatory impact of PG on heart and spleen tissue by immunostaining, ROS formation, and on endothelial senescence. In mice, ligature and/or PG gum injury by threads (LIG) soaked or not with PG (LP,LP 4w) were compared to oral gavage (gvg) and intraperitoneal injection (IP). LIG and LIG-PG reduced spleen granulocytes, doubled monocytes and neutrophils with no adaptative responses in 2-4 weeks. IP tripled monocytes with 10 folds neutrophil rise and half T or B lymphocytes. PAD-4 inhibitor decreased ROS, pointing at Netosis contribution. Splenocytes MVs (SMVs) raised in IP. In vitro, LIG-PG, IP and gvg SMVs induced coronary endothelial senescence. In heart extracts, pro-inflammatory VCAM, Gasdermin-D, IL-6, and TNF- α were only up-regulated in IP and LIG-PG. Anti-inflammatory IL-10 raised in IP.

Altogether, PG induces remote spleen and heart activation, the shedding of pro-coagulant and -senescent SMVs possibly favoring cardiovascular risk.