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HAL Id: hal-01681274
https://hal.uca.fr/hal-01681274
Submitted on 18 Jan 2018

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Unveiling and Characterizing Early Bilateral Interactions between Biofilm and the Mouse Innate Immune System

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Abstract

A very substantial progress has been made in our understanding of infectious diseases caused by invasive bacteria. Under their planktonic forms, bacteria transiently reside in the otherwise sterile mammal body tissues, as the physiological inflammation insures both their clearance and repair of any tissue damage. Yet, the bacteria prone to experience planktonic to biofilm developmental transition still need to be studied. Of note, sessile bacteria not only persist but also concur preventing the effectors and regulators of the physiological inflammation to operate. Thus, it is urgent to design biologically sound experimental approaches aimed to extract, at the earliest stage, immune signatures of mono-bacteria planktonic to biofilm developmental transition in vivo and ex vivo. Indeed, the transition is often the first event to which succeeds the “chronicization” process whereby classical bacteria-targeting therapies are no more efficacious. An in vivo model of micro-injection of Staphylococcus aureus planktonic or biofilm cells in the ear pinna dermis of laboratory transgenic mice with fluorescent immune cells is proposed. It allows visualizing, in real time, the range of the early interactions between the S. aureus and myeloid cell subsets- the resident macrophages and dendritic cells, the recruited neutrophil granulocytes/polymorphonuclear neutrophils, monocytes otherwise known to differentiate as macrophages or dendritic cells. One main objective is to extract contrasting immune signatures of the modulation of the physiological inflammation with respect to the two bacterial lifestyles.

Keywords: bacteria, biofilm, intravital imaging, macrophage/monocyte, mouse, polymorphonuclear neutrophil

INTRODUCTION

Most invasive bacteria display two different lifestyles: whereas the free-floating planktonic bacteria’ life style dominates, in some clinical settings, bacteria sensing hostile conditions adhere to biotic or abiotic surfaces and form biofilms (Moormeier and Bayles, 2017). The planktonic to biofilm/sessile lifestyle transition is associated with important metabolic changes and self-production of proteins-lipids-exopolysaccharides-rich as well as extracellular DNA-containing extracellular matrix (Costerton et al., 1999).
According to the National Institutes of Health, biofilms have an enormous impact on human medicine, accounting for over 80% of infectious processes in otherwise sterile tissue (s). Whereas the physiological inflammation is able to both clear invasive planktonic bacteria and to repair tissue damages insuring the return to tissue structural and functional homeostasis, this physiological inflammation does not operate in tissues experiencing sustained colonization by bacterial biofilms. Moreover, contrasting with planktonic bacteria that are cleared by commonly used antibiotics, provided that they do not harbor genetic resistance determinants, the majority of bacteria within the biofilms are resistant to these antibiotics (Lebeaux et al., 2014).

In this review, our present understanding of the professional phagocyte sensors of microbial agonists expected to operate over the in vivo planktonic to biofilm lifestyle switch is briefly introduced. Transiently invasive planktonic bacteria are usually cleared by myeloid cells of either the neutrophil granulocyte lineage or/and by mononuclear phagocytes. However, the bilateral interactions engaged or not between sessile bacteria and the myeloid cells are still poorly studied. Until now, most experimentalists have conducted in vitro studies with sessile bacteria, exposing them to either one or the other myeloid cell lineage or both (Watters et al., 2016). This review focuses on recent developments obtained in rodent models to characterize inflammatory responses against Staphylococcus aureus or Pseudomonas aeruginosa sessile bacteria. A new experimental approach combining the mouse ear pinna model and the intravital imaging approach is proposed to analyze these innate immune responses at the dynamic level.

THE PROFESSIONAL PHAGOCYTE SENSORS OF MICROBIAL AGONISTS EXPECTED TO OPERATE OVER THE IN VIVO PLANKTONIC TO BIOFILM LIFESTYLE SWITCH

The in vivo developmental transition from planktonic to sessile bacteria reflects a range of bilateral cross talks in the fluctuating dynamic tissue milieu colonized by the bacteria under study. At the earliest stage of this developmental transition, communications between key bacterial messengers as well as interactions between bacterial agonists and sensors displayed by the resident and recruited myeloid cells such as the professional phagocytes are initiated and renewed.

The Nucleotide-Based Second Messengers

The cyclic dinucleotides (c-di-NMPs) are recognized as Microbial Associated Molecular Patterns/MAMPs and induce a host type I interferon immune response prolonged by IFNγ production (Valle et al., 2013; Snyder et al., 2017). Moreover, the c-di-NMPs play a central role in many bacterial species during the lifestyle transition (Valle et al., 2013). Using the P. aeruginosa model organism, Valentini and Filloux (2016) showed that the bacteria use c-di-GMP as a checkpoint during the different steps of biofilm development. There is indeed a direct correlation between high levels of c-di-GMP in the bacteria and biofilm formation, and between low levels of c-di-GMP and motility (planktonic phenotype). The c-di-GMP second messenger is used by Escherichia coli and Salmonella enterica serovar Typhimurium over their planktonic to biofilm developmental transition (Allewell, 2016; Valentini and Filloux, 2016) whereas the c-di-AMP is used as a second messenger by other bacteria such as S. aureus (Corrigan et al., 2011).

The Guanosine tetraphosphate (ppGpp) and pentaphosphate (pppGpp), also called (p)ppGpp or alarmons are synthetized when bacteria are exposed to cells such as phagocytes in the infected tissue. Considered as bacterial signature of a so called stringent response, these alarmons represent intracellular signaling molecules known to participate to intracellular bacteria survival: Geiger et al. (2012) demonstrated that the stringent response is induced, in vitro, after S. aureus phagocytosis by neutrophil granulocytes or polymorphonuclears (PMN). The rapid (p)ppGpp synthesis leads to increased psm transcription and to participation of synthetized phenol soluble modulins (PSMs) concurring to bacteria survival after phagocytosis (Geiger et al., 2012). Depicted as pro-inflammatory agents, the PSMs also account for the bacteria escape from the transient intracellular niche, followed either by bacteria survival inside the cytosol or by lysis of the cell, all these rapid processes contributing to damages of the S. aureus-hosting tissues (Geiger et al., 2012; Peschel and Otto, 2013).

The Quorum Sensing Circuit and Its Additional Regulators

Quorum sensing (QS) is a cell-to-cell signaling process that allows bacteria to sense and process high cell densities. It involves the synthesis, release and accumulation of signaling molecules called auto-inducers (AIs) (Papenfort and Bassler, 2016). At high concentrations, AIs induce cellular signaling cascades that notably control biofilm formation. The QS system of S. aureus called accessory gene regulator (Agr) has been extensively studied (Paharik and Horswill, 2016). With other regulators, it constitutes a complex regulatory network that, at any moment, either modifies AGR activity itself, or its downstream signaling or metabolic pathways. At the early stage of S. aureus developmental transition from planktonic to biofilm lifestyle, the low Agr concentration allows the production of inter-bacteria/intercellular adhesins whereas toxins’ expression is repressed (Balasubramanian et al., 2016). Later, high levels of Agr induce biofilm structuration and dispersion by up-regulating the expression of the pro-inflammatory PSM molecules (Otto, 2008; Periasamy et al., 2012; Kavanagh and Horswill, 2016; Paharik and Horswill, 2016). Environmental factors also modulate the Agr function in S. aureus, with a well-described inhibitory effect of the reactive oxygen species (ROS) produced by innate immune cells (Kavanagh and Horswill, 2016).

Among other regulators that interact with the agr system at later stage of the biofilm development and maturation, the S. aureus exoprotein (Sae) two-component system promotes the synthesis and secretion of leucocidins and other virulence
determinants that actively participate to S. aureus survival after contact with PMN in vitro (Paharik and Horswill, 2016). Sae mutants have indeed a decreased capacity to resist to the PMN-cleaning functions after contact (Yarwood and Schlievert, 2003; Voyich et al., 2009; Paharik and Horswill, 2016).

RODENT MODELS TO STUDY INFLAMMATORY RESPONSES TO BIOFILMS IN VIVO

In rodent laboratory models, the most rapidly recruited cells are phagocytes, namely the PMN. Over any local disruption of mouse tissue homeostasis, PMN stored in the bone marrow egress into the blood vascular bed. Through chemoattractants and cytokines produced by tissue resident mast cells and macrophages (Teng et al., 2017), the PMN rapidly cross the microvessels endothelial cells, reaching the extracellular compartment colonized by invasive bacteria. They represent the first wave of innate immune cells to be recruited from the blood circulation. Most often, PMN efficiently kill and degrade invasive planktonic bacteria by using different antimicrobial strategies: phagocytosis, production of ROS and antimicrobial peptides, as well as cytotoxic components released from their subcellular distinct granules. More recently, neutrophil extracellular traps (NETs) have been observed and included as an additional strategy (Brinkmann et al., 2004). Among the in vivo models that allow characterization of the bilateral interactions co-engaged by PMN and sessile bacteria, we selected those relying on either P. aeruginosa or S. aureus (Table 1).

Of note, the features of the biofilm-colonized devices condition the interaction profiles: whereas in devices of hollow type (catheter, silicon splint) bacterial biofilms are protected from the immune cells, on solid devices (K-wire, pin), the bacterial biofilms are directly exposed to the different waves of immune cells. Depending on the model used, many other parameters operate (listed in Table 1). In most models, an intense and rapid accumulation of PMN is observed at the proximity of the biofilms (Wagner et al., 2003; Prabhakara et al., 2011a; Torre et al., 2015; Moser et al., 2017; Wang et al., 2017), the PMN representing the most abundant population of recruited cells. Using a non-invasive bioluminescence-based approach, Bernthal et al. (2011) showed that this recruitment is IL-1β dependent, as a 50% decrease in PMNs numbers was observed in the bacteria colonized knee joints of IL-1β deficient mice, as compared to wild-type mice. This PMN infiltration is increased when diabetic mice are treated with insulin in a bacteria-hosting wound, the latter incorporating actin and DNA from lysed PMN, which therefore contributes to the building of biofilms (Watters et al., 2014). Of note, a low PMN recruitment in the target tissues (Thurlow et al., 2011; Scherr et al., 2014; Secor et al., 2017) can be also operating: in particular was noticed an association between the reduced PMN recruitment and the production of Filamentous Pf-like bacteriophage (Pf phage) by P. aeruginosa (Secor et al., 2017). Taken globally, whatever the experimental conditions depicted in Table 1, there is a need to capture more comprehensive information documenting, at least at the earliest stages, the in vivo dynamic interactions between bacteria and PMN.

Could mature biofilms’ matrix components protect bacteria from activated PMN? PMN were indeed shown to be activated, in vitro, by bacterial DNA and polysaccharides components such as alginate, the measured outcome being an increase of their respiratory burst (Pedersen et al., 1990; Alvarez et al., 2006; Fuxman Bass et al., 2008; Jensen et al., 2010). In vivo, P. aeruginosa biofilm interactions with PMN lead to up regulation of the QS-dependent effectors such as rhamnolipids which cause PMN lysis (Alhede et al., 2014). This shedding specific property of rhamnolipids is described in mouse models relying upon the intraperitoneal implant of pre-colonized silicone device (Van Gennip et al., 2012) or on biofilm development in the respiratory tract (Bjarnsholt et al., 2005; Jakobsen et al., 2012). In these models, QS mutants are unable to produce rhamnolipids and are rapidly phagocytosed and cleared by PMN.

Monocytes/macrophages are other key actors recruited and sensing both the other inflammatory cells -e.g., PMN -as well as bacteria agonists. Under homeostatic conditions, circulating macrophage/monocytes qualified as classical/intermediate ones are continuously recruited from the blood and either mature into macrophages or remain as monocytes within tissues (Sprangers et al., 2016; Jakubzick et al., 2017). In the skin, long-lived resident macrophages are also present and maintain their population by self-renewal (Sprangers et al., 2016; Jakubzick et al., 2017). As for PMN, microbe-specific molecules participate to the rapid emigration of classical/intermediate monocytes in the extravascular space which contribute to the resolution of inflammation by recognizing and phagocytosing bacteria and dying cells, and by producing ROS and reactive nitrogen species (RNI) (Sprangers et al., 2016; Jakubzick et al., 2017; Kashem et al., 2017). Once PMNs experience apoptotic death, a second wave of monocytes qualified as non-classical monocytes contribute to the resolution of inflammation and repair of the disrupted tissue (Sprangers et al., 2016).

Only a few studies (Prabhakara et al., 2011a; Thurlow et al., 2011; Hanke et al., 2012, 2013; Scherr et al., 2015; Corrado et al., 2016; Silva-Santana et al., 2016; see Table 1) assess the complex recruitment waves and networks of both PMN and monocyte subsets. Of note, an early wave of monocyte recruitment is sometimes predominant, as compared to PMN recruitment (Thurlow et al., 2011). Two main studies were conducted to monitor the abundance and functional features of monocyte/macrophage recruitment in vivo at specific time points after contact with biofilms. The biofilms’ matrix components clearly modulate the functional properties of recruited cells. In a S. aureus pre-colonized catheter-based model, mobilized cells are mainly distant from the catheter and a non-significant proportion of F4/80+ macrophages are able to invade the biofilms. Cells present deeply into the biofilm rapidly die, therefore preventing phagocytosis of biofilm bacteria to be otherwise exerted by
<table>
<thead>
<tr>
<th>Organism</th>
<th>Biomedical device whenever it is implanted</th>
<th>Tissue(s) where are either inoculated bacteria or implanted a bacteria-free or loaded device</th>
<th>Either bacteria inoculation or bacteria-loaded device delivery mode</th>
<th>Inoculum dose (CFU)</th>
<th>Reference</th>
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</thead>
<tbody>
<tr>
<td><em>P. aeruginosa</em></td>
<td>Biofilm pre-colonized silicone implant</td>
<td>Lung (immobilized bacteria in alginate beads)</td>
<td>Intra-tracheal</td>
<td>6 × 10⁶ to 1,5 × 10⁷</td>
<td>Jensen et al., 2004; Bjarnsholt et al., 2005; Alhede et al., 2009; van Gennip et al., 2009; Jakobsen et al., 2012</td>
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<tr>
<td></td>
<td>Biofilm pre-colonized silicone implant</td>
<td>Oropharyngeal aspiration of a bacterial suspension</td>
<td>Oropharyngeal</td>
<td>1,5 × 10⁷</td>
<td>Secor et al., 2017</td>
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<tr>
<td></td>
<td></td>
<td>Implanted into the peritoneal cavity (hollow tubes)</td>
<td>Intraperitoneal</td>
<td></td>
<td>Van Gennip et al., 2012</td>
</tr>
<tr>
<td><em>S. aureus</em></td>
<td></td>
<td>Implanted into the peritoneal cavity (flat implant)</td>
<td>Intraperitoneal</td>
<td></td>
<td>Christensen et al., 2007</td>
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<tr>
<td><em>P. aeruginosa</em> and <em>S. aureus</em></td>
<td></td>
<td>Diabetic mouse-based model allowing systemic invasion outcome</td>
<td>Topical application of bacteria onto a peripheral wound</td>
<td>10⁴</td>
<td>Watts et al., 2013, 2014</td>
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<td><em>S. aureus</em></td>
<td>Un-colonized silicon splint</td>
<td>Chronically wounded diabetic mouse model</td>
<td>Dermal application of bacteria onto the wounded surface</td>
<td>10⁶</td>
<td>Guo et al., 2013</td>
</tr>
<tr>
<td><em>P. aeruginosa</em></td>
<td></td>
<td>Chronically wounded diabetic mouse model</td>
<td>Subcutaneous injection of bacteria immobilized in alginate beads beneath a thermal skin lesion</td>
<td>10⁶</td>
<td>Troshrub et al., 2013</td>
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<td><em>S. aureus</em></td>
<td></td>
<td>Air pouch model</td>
<td>Inoculation of bacteria in a single pouch</td>
<td>10⁶</td>
<td>Torre et al., 2015</td>
</tr>
<tr>
<td><em>S. aureus</em></td>
<td>Un-colonized orthopedic implant (K-wire)</td>
<td>Hematogenous model of septic arthritis initiated in murine knees</td>
<td>Intravenous</td>
<td>2 × 10⁶, 3 × 10⁷</td>
<td>Corrado et al., 2016</td>
</tr>
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<td></td>
<td></td>
<td>Un-colonized orthopedic implant (K-wire)</td>
<td>Inoculation of bacteria into the joint space containing the cut end of the implant</td>
<td>10³</td>
<td>Berendts and Tarkowski, 1997</td>
</tr>
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<td></td>
<td></td>
<td>Un-colonized catheter inserted in a pouch</td>
<td>Intradermal inoculation of bacteria at proximity of the pouch containing the catheter</td>
<td>5 × 10⁵</td>
<td>Bernthal et al., 2011; Heim et al., 2014; Scherr et al., 2015; Pribaz et al., 2012; Niska et al., 2012; Vidiak and Kielian, 2016</td>
</tr>
<tr>
<td><em>P. aeruginosa</em></td>
<td>Un-colonized catheter</td>
<td>Catheter-related model</td>
<td>Intradermal inoculation of bacteria into the catheter lumen</td>
<td>10⁴</td>
<td>Hanke et al., 2012, 2013</td>
</tr>
<tr>
<td></td>
<td>Un-colonized catheter</td>
<td>Catheter-related model</td>
<td>Intradermal inoculation of bacteria into the catheter lumen</td>
<td>5 × 10⁵</td>
<td>Thurbow et al., 2011</td>
</tr>
<tr>
<td></td>
<td>Un-colonized orthopedic implant (K-wire)</td>
<td>Hematogenous implant-related bacteria colonization</td>
<td>Intravenous (tail vein)</td>
<td>10⁴ to 10⁶</td>
<td>Sheils et al., 2015</td>
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<td></td>
<td>Pre-colonized flat stainless steel wire</td>
<td>Orthopedic biofilm model</td>
<td>Tibial implant</td>
<td></td>
<td>Wang et al., 2017</td>
</tr>
<tr>
<td></td>
<td>Pre-colonized pin</td>
<td>Prosthetic implant model</td>
<td>Tibial implant</td>
<td>3 × 10⁵</td>
<td>Nashi et al., 2015</td>
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<tr>
<td><em>P. aeruginosa</em></td>
<td>Un-colonized polyethylene catheter</td>
<td>Ascending pyelonephritis model</td>
<td>Inoculation of bacteria into the bladder</td>
<td>5 × 10⁵</td>
<td>Prabhakara et al., 2011,a,b</td>
</tr>
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</table>

**TABLE 1 | Rodent models to study inflammatory responses to biofilms in vivo.**
macrophages (Thurlow et al., 2011). A significant reduction of pro-inflammatory cytokines (IL-1β, TNF...) and chemokines (CXC12, CCL2) production at the boundary of the biofilm-colonized tissue is also observed, associated with a reduced Nitric Oxide synthase (iNOS) induction and an increased arginase-1 expression. The authors conclude to a macrophage polarization toward a counter-inflammatory activated M2 phenotype and to fibrosis with MyD88- signaling as a major effector pathway regulating these two phenomena (Thurlow et al., 2011; Hanke and Kielian, 2012; Hanke et al., 2012). In a lung experiencing colonization with phage Pf- producing P. aeruginosa, Secor et al. (2017) also documented a M2 polarization profile. Taken globally, it appears that the macrophage M2 polarization and fibrosis do concur prolonging bacteria biofilm persistence, although the universal character of such responses remains to be assessed.

THE MOUSE EAR PINNA DERMIS IMAGED BY INTRA-VITAL CONFOCAL MICROSCOPY AT STEADY AND NOT STEADY STATE

Intra-vital microscopy is increasingly used in different biomedical research fields to study dynamic processes at the cellular level in their specific tissue environment. Compared to classical methods such as ex vivo histology or flow cytometry, intra-vital confocal microscopy live imaging allows dynamic interactions to be captured once fluorescent reporters are expressed by both the microbes and the laboratory mouse cell lineages with which are engaged, more or less durably, dynamic interactions.

Several skin-related models were described in the literature to study the immunobiology of biofilm infections by using classical approaches (Table 1). In these models, the biofilm-loaded cutaneous sites were the back or the flank of animals, which represent unsuitable sites for intravitral microscopy of cutaneous innate immune responses.

The ear pinnae is one of the most studied appendage in which are delivered microorganisms, enabling the observation of the early and either transient or prolonged dynamic interactions with resident or recruited myeloid cells (Amino et al., 2006, 2007; Peters et al., 2008; Ng et al., 2011; Sumaria et al., 2011; Jain and Weninger, 2013; Tavares et al., 2013; Carneiro et al., 2017). As an imaging site, the ear presents several technical advantages such as the accessibility of the tissue, easy and fast protocols of preparation to perform imaging experiments and obtain reproducible results, and the possibility of imaging for long periods of time in blocks of 20–40 min (Li et al., 2012).

The mouse ear pinnae infection model, inflammatory responses against biofilms could be analyzed for the first time at the dynamic level in the tissue environment. The Figure 1 shows the schematic workflow of methods proposed to characterize and compare the innate immune responses against S. aureus planktonic and sessile bacteria. Transgenic mice with fluorescent immune cells visible in the skin such as Lysozyme-EGFP (circulating PMNs and monocytes, dermal macrophages), CD11c-EYFP (dermal dendritic cells, epidermal laengerhans cells) and Mcpt5-Cre+R26Y+ (dermal mast cells) mouse strains have been selected (Faust et al., 2000; Lindquist et al., 2004; Dudeck et al., 2011). The conditions to prepare bacteria inoculum will be set up. The planktonic inoculum will be obtained from an overnight culture of fluorescent S. aureus Lyo-S2 strain in Trypticase Soja broth (Marquié et al., 2015). Biofilms will be generated from a planktonic culture incubated at 37°C under static conditions. After 24 h of incubation, biofilms will be gently collected (A). The first series of experiments will be performed.
FIGURE 1 | The three steps’ workflow proposed for extracting, post either *Staphylococcus aureus* planktonic or biofilm delivery, specific immune signatures displayed by mouse myeloid cells. (A) Inoculum preparation in vitro. (B) Inoculum micro-injection in the ear pinna of mouse (10^7 UFC of either planktonic or sessile bacteria). (C1a) Real time imaging of the ear pinna of a LysM-EGFP transgenic mouse harboring fluorescent phagocytes and fluorescent *S. aureus* bacteria by confocal microscopy. (C1b) Massive recruitment of GFP+ cells post-injection in the upper dermis of the ear pinna of a mouse inoculated with *S. aureus* sessile or planktonic bacteria. (C2), (C3), (C4) Quantitative analyses in the ear pinna and the auricular lymph node to determine (C2) the phenotype of recruited cells, (C3) the cytokine levels and (C4) the bacteria counts.

CONCLUSION

The objective of the review was to highlight the requirement of developing new *in vivo* models to analyze, at the early stage of infection, the dynamics of innate immune responses against *S. aureus* planktonic or sessile bacteria. A new experimental approach in the field combining the mouse ear pinna model and the intravital imaging approach is proposed. The long term
objects are to use this model as a pre-clinical model to test necessary new therapeutic approaches targeting the host immune system, as proposed initially by Hanke et al. (2013).

AUTHOR CONTRIBUTIONS

CF: intellectual contribution to the work; EB: intellectual contribution to the work; GM: substantial, direct and intellectual contribution to the work; PG: substantial, direct and major intellectual contribution to the work—corresponding author. All authors listed approved the work for publication.

ACKNOWLEDGMENT

The authors wish to acknowledge the contribution of Caroline Vachias at the Confocal Microscopy Facility ICCF (Imagerie Confocale Clermont-Ferrand) at Université Clermont Auvergne.

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**Conflict of Interest Statement:** The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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