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Biological activities of non-enzymatic oxygenated metabolites of polyunsaturated fatty acids (NEO-PUFAs) derived from EPA and DHA: New anti-arrhythmic compounds?

Jean-Marie Galano^{b,1}, Jérôme Roy^{a,1}, Thierry Durand^b, Jetty Chung-Yung Lee^c, Jean-Yves Le Guennec^{a,*}, Camille Oger^b, Marie Demion^a

^a Université de Montpellier, CNRS, Inserm, PhyMedExp, Montpellier, France

^b Université de Montpellier, CNRS, IBMM, Montpellier, France

^c School of Biological Sciences, The University of Hong-Kong, Hong Kong

ABSTRACT

Keywords:

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Arrhythmias

ω 3 Polyunsaturated fatty acids (ω 3 PUFAs) have several biological properties including anti-arrhythmic effects. However, there are some evidences that it is not solely ω 3 PUFAs *per se* that are biologically active but the non-enzymatic oxygenated metabolites of polyunsaturated fatty acids (NEO-PUFAs) like isoprostanes and neuroprostanes. Recent question arises how these molecules take part in physiological homeostasis, show biological bioactivities and anti-inflammatory properties. Furthermore, they are involved in the circulations of childbirth, by inducing the closure of the *ductus arteriosus*. In addition, oxidative stress which can be beneficial for the heart in given environmental conditions such as the presence of ω 3 PUFAs on the site of the stress and the signaling pathways involved are also explained in this review.

1. Introduction

The role of omega-3 polyunsaturated fatty acids (ω 3 PUFAs) on cardiac disease has been controversial for several decades. Numerous studies have been covered in recent years to elucidate if the ω 3 PUFAs have a direct protective effect in cardiac disease (For review see Saravanan et al., 2010; Roy and Le Guennec, 2017). Recently, a new hypothesis has been proposed that involves oxidative stress, and the resulting non-enzymatic oxidation of ω 3 PUFAs that can generate bioactive metabolites having cardioprotective properties. Isoprostanooids derived from ω 6 and ω 3 PUFAs are known biomarkers of oxidative stress in plants and mammals however, in recent studies, some of these derivatives have been shown to hold biological effects. For example, non-enzymatic metabolites of eicosapentaenoic acid (NEO-EPA) and non-enzymatic metabolites of docosahexaenoic acid (NEO-DHA) are responsible of anti-inflammatory properties of EPA and DHA. In this review, we describe known biological activities of these NEO-PUFAs with a particular highlight on their cardioprotective effects and anti-arrhythmic properties. A mechanism of action is proposed on how the ω 3 NEO-PUFAs released take part in the prevention of

arrhythmias following an ischemic-reperfusion episode. A short description on the underlying biological effects of ω 6 NEO-PUFAs is also noted in this review.

1.1. ω 3 PUFAs and cardiac disease

The cardioprotective effects of ω 3 PUFAs have been known since the mid-70's (Bang et al., 1976). The intake of fatty fish such as mackerel or tuna was associated with lower risk of cardiac arrhythmias including sudden cardiac death (Burr et al., 1989; Siscovick et al., 1995; Albert et al., 2002) and arrhythmic coronary heart disease (Mozaffarian et al., 2003). Administration of Omacor[®], a mixture of 850 mg of eicosapentaenoic acid (C20:5 ω 3, EPA) and docosahexaenoic acid (C22:6 ω 3, DHA) the two major PUFAs of fatty fish, decreased the incidence of sudden cardiac death in a secondary prevention study of myocardial infarction (GISSI, 1999). Interestingly, in this large randomized clinical trial, the number of myocardial events was not reduced by ω 3 PUFAs supplementation but was more effective in reducing the incidence of sudden cardiac death. In fact, sudden cardiac death with consecutive ventricular fibrillation is the major consequence of myocardial

* Corresponding author. Inserm 1046-UMR 9214 CNRS PHYMEDEX, Physiologie et Médecine Expérimentale du Coeur et des Muscles CHU Arnaud de Villeneuve, Bâtiment Crastes de Paulet, 371 avenue du doyen Gaston Giraud, 34295 MONTPELLIER Cedex 5, France.

E-mail address: jean-yves.le-guennec@inserm.fr (J.-Y. Le Guennec).

¹ These authors contributed equally to this work.

infarction (Hinkle and Thaler, 1982; Leaf and Hallaq, 1992; Bayes de Luna et al., 1989; Greene, 1990). Recently, the science advisory board of the American Heart Association, Siscovick et al. (2017) carefully analyzed studies of large randomized clinical trials and concluded that among all potential targeted cardiac diseases and cardiac events, only cardiac death was decreased by ω 3 PUFA intake. Thereafter, the scientific community concluded that the most probable positive effect of ω 3 PUFAs supplementation is by preventing fatal arrhythmias.

1.2. Anti-arrhythmic effects of ω 3 PUFAs

The precise mechanisms responsible for the anti-arrhythmic properties of PUFAs remain unclear. Intravenous infusion of DHA emulsion in dogs tended to slow heart rate, shortened the corrected QT interval (QTc) at rest and significantly prevented fatal ischemia-induced ventricular arrhythmias (Billman et al., 1999). This experiment confirmed previous reports on the prevention of ischemia-induced ventricular arrhythmias in dogs (Billman et al., 1994) and marmosets (McLennan et al., 1992) by PUFAs. In humans, the consumption of tuna or other fatty fish was associated with a significant slowing of heart rate and reduced likelihood of prolonged QT; the two electrophysiological parameters that can participate in anti-arrhythmic effects of ω 3 PUFAs (Mozaffarian et al., 2006). Interestingly, in accordance to Billman et al. (1999), a pilot study on ten patients who were at high risk of sudden cardiac death (Schrepf et al., 2004) showed that the induction of sustained tachycardia was significantly decreased after infusion of a solution containing ω 3 PUFAs. This indicates that the effect of ω 3 PUFAs acting as anti-arrhythmic agents was viable but it also may need an ischemic period to occur. During myocardial infarction, oxidative stress is induced that contributes to arrhythmias leading to sudden cardiac death (Downey, 1990; Fukuda et al., 2005). Such an abrupt imbalance of the redox status can lead to the oxidation of proteins (Davies, 1987), nucleic acids (Dizdaroglu, 1992) and lipids (Burton et al., 1990). It is widely acknowledged that some of these oxidized products of macromolecules in part could trigger arrhythmias (Tse et al., 2016). For example, Fukuda et al. (2005) showed that an isoketal, E₂-IsoK originating from the non-enzymatic oxidation of arachidonic acid (C20:4 ω 6, AA) can form adducts with the sodium channel protein Na_v1.5, perturbing its activity in a pro-arrhythmic way.

1.3. Effect of ω 3 PUFAs in cell models

Experiments performed on isolated cardiac cells suggest that ω 3 PUFAs have direct electrophysiological effects (Leaf et al., 2008; Moreno et al., 2012). In a study using isolated cardiac cells of rabbits with heart failure and isolated cells from human heart at the final stage of heart failure (Den Ruijter et al., 2008), the authors showed that the prevention of arrhythmias by ω 3 PUFAs (EPA and DHA) was due to reduced diastolic calcium and lower sensitivity of cardiac cells induced by adrenaline. EPA and DHA, the two major ω 3 PUFAs found in fatty fishes, hyperpolarized the resting membrane potential and shortened the duration of the action potential (Leaf et al., 2008; Den Ruijter et al., 2008) by modulating the ionic channel activity. An inhibition of the fast sodium current (I_{Na}) was observed in some reports (Xiao et al., 1995; Leifert et al., 1999) and moreover, the ultrafast activation delayed the outward potassium current (I_{KUR}) (Honoré et al., 1994), the inwardly-rectifying rapidly-activated potassium current (I_{KR}) (Guizy et al., 2005), the L-type calcium inward current (I_{CaL}) (Xiao et al., 1997; Verkerk et al., 2006), and the Na⁺-Ca²⁺ exchange current (I_{NCX}) (Xiao et al., 2004; Ander et al., 2007) of the membrane. It is also known that ω 3 PUFAs blocked the transient outward potassium current (I_{TO}) (Bogdanov et al., 1998; Macleod et al., 1998). It should be noted that, to the best of our knowledge, the ionic current(s) involved in the hyperpolarization induced by ω 3 PUFAs has not been clearly identified.

In contrast, it has been shown that NEO-DHA and not DHA *per se*, were active on cardiac ionic channels such as I_{TO} and I_{SS} (Judé et al.,

2003). The authors demonstrated this effect by using low concentration of H₂O₂ (1 μ M) to favor the oxidation of DHA or α -tocopherol (1 μ M) as positive control, and found that the modulatory effects of ω 3 PUFAs on cardiac ionic channels were due to NEO-PUFA. Roy et al. (2015) further confirmed this hypothesis in isolated ventricular cells. The authors observed that the anti-arrhythmic potential of DHA was potentiated by pro-oxidants and conversely prevented by anti-oxidants. Another study that showed the possible role of NEO-PUFA in preventing or curing arrhythmias was by Zhao et al. (2012) who showed that in rabbit ventricular cells, early depolarizations induced by high dose of H₂O₂ (200 μ M) were inhibited by DHA (10 μ M) whereas ROS production by cardiac cells was not changed. In the presence of such concentration of H₂O₂, the 10 μ M of DHA in the solution is very likely to oxidize completely suggesting that the anti-arrhythmic effects are not due to DHA itself but due to NEO-DHA generated from DHA oxidation.

2. Oxygenated metabolites of ω 3 PUFAs

PUFAs are vulnerable substrates for enzymatic and non-enzymatic oxidative transformations. Collectively, these metabolites formed are known as oxylipins. The oxidative transformations are due to the presence of multiple double bonds in their structures, and more so in the presence of two double bonds surrounding a methylene group (-CH=CH-CH₂-CH=CH-). Such configuration creates weak methylene C-H bond and readily allow H-abstraction by heme (cyclooxygenases) or non-heme (lipoxygenases) enzymes, iron-containing enzymes (enzymatic transformation) or free radical species (non-enzymatic transformation). Enzymatic H-abstraction of the substrate is very specific with regard to the position of the methylene bond whereas the abstraction is random for non-enzymatic oxidative transformations and consequently the ensuing product profile is more complex and more so, when the number of double bonds in the PUFA increases. Of note, the radical mechanisms following H-abstraction are the same for enzymatic and non-enzymatic oxidation. For example, in Fig. 1A, the H-atom of AA is abstracted at the 13th position by cyclooxygenases or 15-lipoxygenase (15-LOX) or by ROS. The resulting carbon radical (compound A), in the presence of oxygen, further proceeds to form a peroxy radical (compound B) which react with another molecule of PUFA (AA for example) to produce hydroperoxide products i.e. 15(S)-hydroperoxyicosatetraenoic acid (15(S)-HpETE via 15-LOX) or racemic 15-HpETE (via ROS) and another carbon-centred radical (compound A), hence ensuing the propagation step needed for auto-oxidation processes. In the case of enzymatic processes, it is the production of hydroperoxide that oxidizes the heme or non-heme iron-containing enzymes and further pursues the enzymatic auto-oxidation.

Another fate of peroxy radical B is the formation of an endoperoxide carbon centred radical (compound C) which then proceeds through a cyclization step to form the cyclopentane ring followed by final oxygenation to produce G₂-IsoP or PGG₂. This second consecutive 5-*exo*-trig cyclization of compound C follows the models of Stanley and Pryor, and of Funk and Porter (structures C¹ and C²) which are the origin of the main structural differences between prostaglandins (PG) and Isoprostanes (IsoPs) e.g. 1,2 lateral chains relationship is predominantly *cis* configuration for IsoP, while the enzymatic 3D constrain model (structure C³) prefers the *trans* configuration only. Finally, the reduction of the peroxide and endoperoxide groups gives the isoprostanooids 15-F_{2t}-IsoP and 15-F_{2c}-IsoP that is considered a large part of the oxylipins.

Neuroprostanes (NeuroPs) is derived from DHA and the formation does not involve cyclooxygenases and instead inhibits them (Ringbom et al., 2001). Consequently, NeuroPs only exist via a non-enzymatic process (Roberts et al., 1998), and independent from enzymatic oxidation. Therefore, these are very much unique metabolites of DHA. As described in Fig. 1B, eight different series of NeuroP can be generated via free radical mechanism.

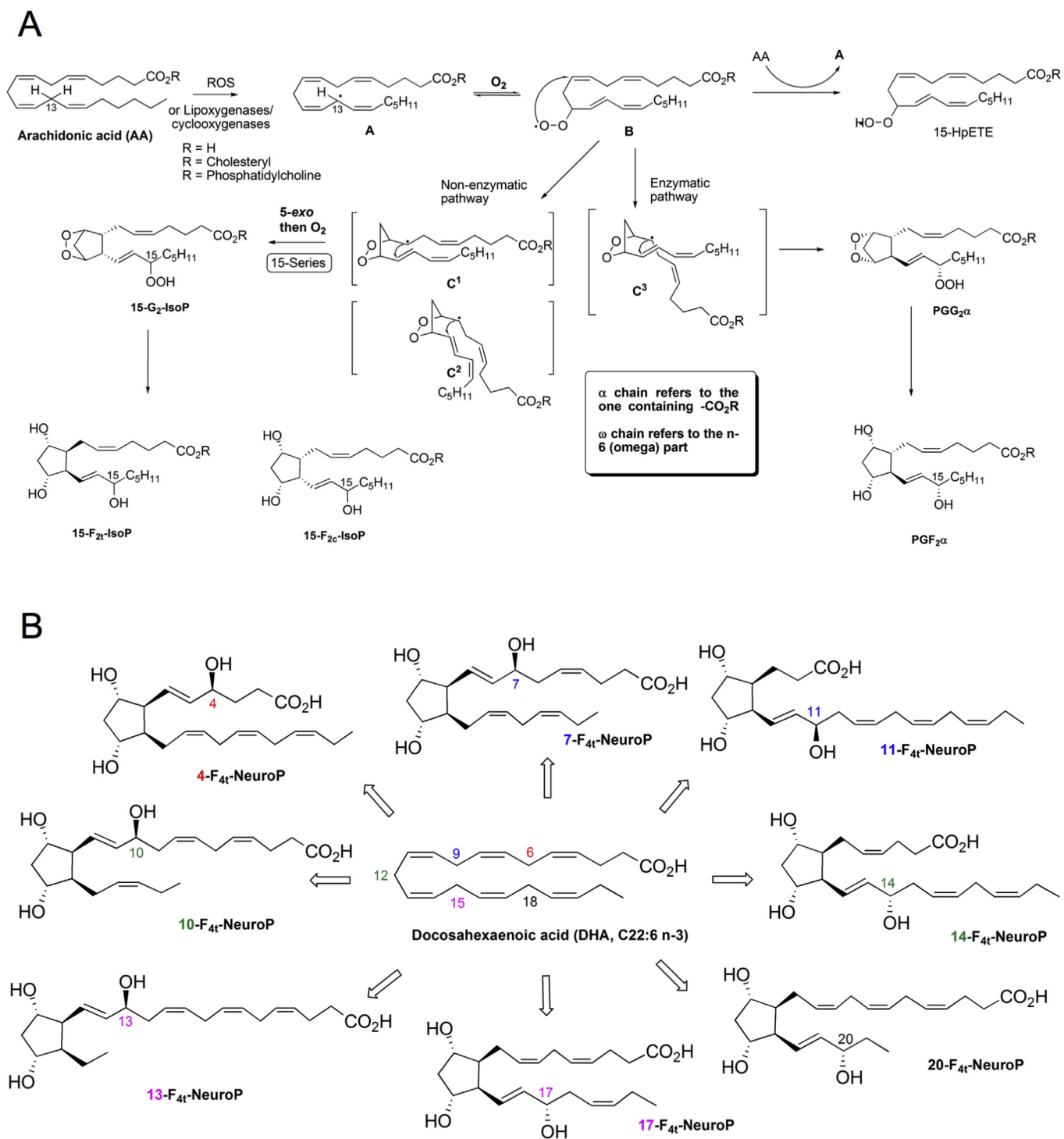


Fig. 1. Chemistry of isoprostanoids. **A)** Biosynthesis of prostanooids and isoprostanoids (only the 15 series of isoprostanoids are displayed). **B)** Representation of the eight possible neuroprostanes formed from DHA non-enzymatic peroxidation.

3. Biological activities of NEO-PUFAs

3.1. Physiological roles of NEO-PUFAs in non-cardiac functions

NEO-PUFAs are considered as biomarkers of oxidative stress (Van't Erve et al., 2017) but recent studies showed them to exert physiological functions. A remarkable point to notice about isoprostanes (IsoPs) and other NEO-PUFAs is that, they are often assumed to be inherently deleterious (Chen et al., 2013; Njie-Mbye et al., 2013; Bauer et al., 2014; Gauthier et al., 2014; Spinelli et al., 2014) particularly, F₂-IsoPs from

AA. However, F₃-IsoPs from EPA is considered to be biologically inactive, but high consumption of fish elevated blood F₃-IsoPs and suppressed F₂-IsoPs leading to cardioprotection in Canadian Inuit population (Alkazemi et al., 2016). The authors explain the cardioprotection afforded by ω₃ PUFAs in fish was due to competition between ω₃ PUFAs and AA in the phospholipids leading to decreased plasma concentration of deleterious F₂-IsoPs. Nevertheless, a careful analysis of the literature suggests that it is not so simple (Fig. 2).

In the resolution of inflammation, it appears more and more obvious that NEO-PUFAs from ω₃ PUFAs are likely to play a unique role that is

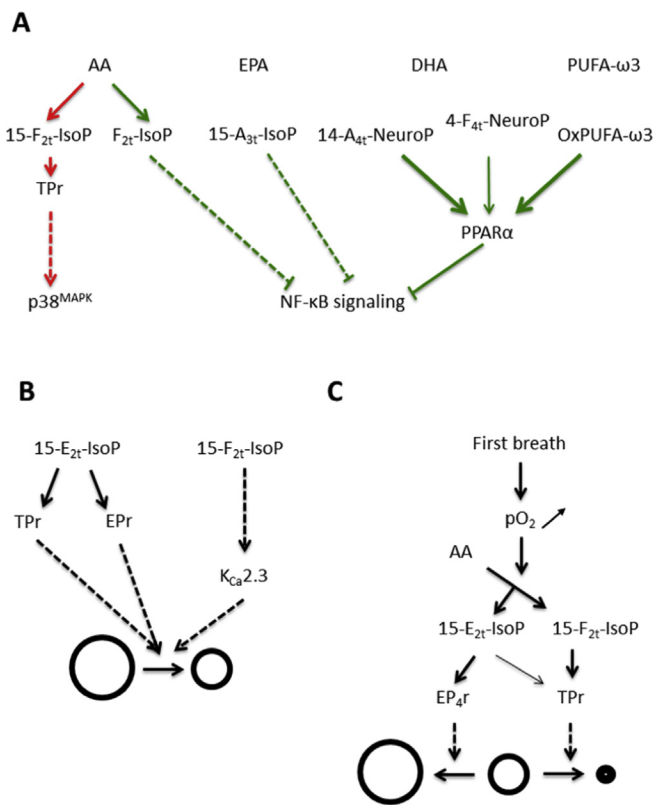


Fig. 2. Known signaling pathways of IsoP and NeuroP from arachidonic acid (AA), eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA). Dotted lines suggest that there are unknown intermediate pathways while the others can be direct. **A)** Anti- and pro-inflammatory effects of IsoPs and NeuroPs. The red lines indicate pathways involved in pro-inflammatory situations while those in green indicate the anti-inflammatory pathways. **B)** Signaling pathways involved in the vasoconstrictive properties of IsoPs. TP and EP are prostanoid receptors of T and E type respectively. $K_{Ca2.3}$, potassium channel activated by intracellular calcium. When activated, the channel induces the depolarization of the smooth muscle cell membrane leading to vasoconstriction. **C)** Signaling pathways involved in the closure of the *ductus arteriosus* at birth. During the first breathe, the blood pO_2 increases that lead to the production of IsoPs like 15-E_{2t}-IsoP and 15-F_{2t}-IsoP and interact with the prostanoid receptors EP_{4r} and TPPr. The activation of EP_{4r} produces a dilatation of the *ductus arteriosus* while the activation of TPPr is vasoconstrictive. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

at least comparable to anti-inflammatory resolvin E, which are metabolites of EPA released through enzymatic oxidation. Evidently, increased consumption of $\omega 3$ PUFAs reduced chronic inflammation and the incidence of consecutive disorders such as atherosclerosis (Allaire et al., 2016; Gladine et al., 2014; Calder, 2015). Sethi's group (Sethi et al., 1996, 2002; Mishra et al., 2004) first corroborated that oxidized EPA and DHA and not native EPA or DHA possessed anti-inflammatory properties. The same authors further confirmed that EPA and DHA need to be oxidized to activate PPAR α and in turn, could inhibit NF- κ B activation, a transcription factor regulating the expression of pro-inflammatory molecules to activate endothelial cells for binding to monocytes (Sigal, 2006). Thereafter, it has been shown that NEO-PUFAs were able to form ligands with PPAR α as well as PPAR γ (Itoh et al., 2008).

Regardless to Sethi's group observation, it is of interest to note Brooks et al. (2011) report. The group identified that 15-A_{3t}-IsoP, another NEO-EPA, was also a potent anti-inflammatory molecule by inhibiting NF- κ B in macrophages. More recently, a comparison of the putative anti-inflammatory effects of protectin (NPD1 and PDX, metabolites of enzymatic oxidation of DHA) and neuroprostanes (14-A_{4t}-

NeuroP and 4-F_{4t}-NeuroP, NEO-DHA) on human macrophages were performed for the first time (Bosviel et al., 2017). The authors showed that the most active metabolite to reduce the levels of cytokines IL-6 and TNF- α through activation of PPAR γ and not PPAR α , was 14-A_{4t}-NeuroP. However, 4-F_{4t}-NeuroP activated PPAR γ albeit with less potency. The authors concluded that, depending on the concentration of the metabolites, protectins and neuroprostanes have similar potency and likely to have complementary anti-inflammatory properties. Moreover, it should be mentioned that 14-A_{4t}-NeuroP was indeed previously discovered to be anti-inflammatory via the inhibition of the NF- κ B pathway (Musiek et al., 2008).

Leitinger et al. (2001) found that 15-F_{2t}-IsoP (also known as 8-iso-PGF_{2 α}), a NEO-AA, stimulated human endothelial cells-monocytes interaction independently and not through NF- κ B pathway. It is of interest the finding by Kumar et al. (2005) who showed that the properties of NEO-AA depended on the type of vascular system. In large vessels such as aorta and umbilical vein, 15-F_{2t}-IsoP was found to be pro-inflammatory through the stimulation of endothelial cell-monocytes interaction whereas in the microvasculature, the primary site of inflammation, showed exactly the opposite effect. The group explained the effect may occur through two different pathways. One pathway involves a TP receptor and the other one, an unknown receptor. Similar inhibition of NF- κ B and monocyte-endothelial cell adhesion was also observed in porcine pulmonary arteries by another neuroprostane, A₄/J₄ NeuroP (Majkova et al., 2011). To date, the receptors involved and the associated signaling pathways have not been elucidated. Moreover, F₂-IsoPs showed to increase cell proliferation and endothelin-1 release through an unknown receptor coupled to a phosphoinositide pathway (Yura et al., 1999). Such effect was observed in the development of a hepatorenal syndrome that is characterized by intense vasoconstriction.

Beside the anti-inflammatory properties of NEO-PUFAs, another physiological role of these compounds emerged: regulation of vascular tone (Cracowski and Durand, 2006). A thromboxane A₂ (TXA₂) mimetic, U-46619, and an IsoP, 15-E_{2t}-IsoP (noted as 8-isoPGE₂ in the report) showed to regulate the human placental vascular tone and resistance (Hausermann and St-Louis, 2011). This role appeared to be important since the placenta was devoid of autonomic innervation and nitric oxide (NO) regulation was inefficient. The effects of both metabolites of AA, enzymatic (TXA₂) and non-enzymatic (15-E_{2t}-IsoP), were mediated through prostanoid receptors, TP and EP respectively.

Angiotensin II (AngII) is a potent constrictor of the aorta and mesenteric arteries. Pfister et al. (2011) showed that AngII-induced vasoconstriction of these vessels was partly due to the production of superoxide and in turn, generated a F₂-IsoP that is not 15-F_{2t}-IsoP. Interestingly, this finding was also mentioned in vascular disease where the production of superoxide is a physiological event. For example, it has been shown to occur in β -adrenergic receptor activation and recognized that the production of superoxide is needed for the physiological activation of the β -adrenergic signaling pathways (Andersson et al., 2011; Llano-Diez et al., 2016) and probably, the same applies to the AngII pathway (Pfister et al., 2011). Gauthier et al. (2014) also found that 15-F_{2t}-IsoP can induce the constriction of middle cerebral arteries through the inhibition of $K_{Ca2.3}$ potassium channels. However, the authors did not investigate whether this inhibition is consecutive to any prostanoid receptors.

The most interesting physiological role of isoprostanes is its participation in the closure of the *ductus arteriosus* of newborn. The *ductus arteriosus* is a vascular shunt between pulmonary artery and the aorta that remains open during fetal life, and constricts in the hours after birth. This closure allows the redirection of blood flow from the fetal gas exchange organ to the placenta and to the newly inflated lungs. The *ductus arteriosus* closure is mediated in part by increased oxygen tension that can activate ionic channels and the withdrawal of vasodilatory prostaglandins. Van der Sterren and Villamor (2011) and Chen et al. (2012) showed that 15-E_{2t}-IsoP and 15-F_{2t}-IsoP were potent vasoconstrictors of the *ductus arteriosus* in chicken and mouse, and the TP

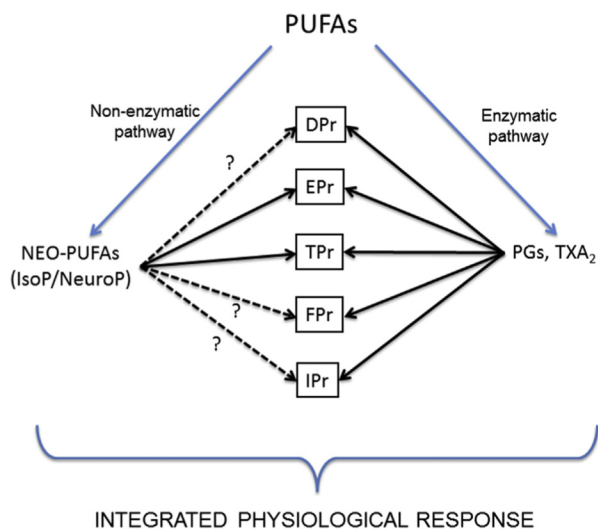


Fig. 3. NEO-PUFAs can activate prostanoid receptors of prostaglandins and thromboxane A₂. This has been shown for EPr and TPr (plain lines) but not studied for the other receptors (dotted lines). The cross-talk between the three kinds of stimulators: NEO-PUFAs, enzymatic metabolites and prostanoid receptors needs to be determined to understand the physiological response.

receptors were responsible to mediate these effects. They proposed that the sharp transition from the relatively low oxygen intrauterine environment to a higher oxygen extrauterine environment exposes the newborn to an oxidative challenge. This induces the production of IsoPs that participates to the *ductus arteriosus* closure and the separation of the two blood circulations. These findings are of interest since they showed that a change in environmental pO₂ can be signaled for NEO-AA to “read” and subsequently produce IsoPs in response to physiological reaction. [Chen et al. \(2012\)](#) also showed that 15-E_{2t}-IsoP can activate EP_{4r} that evokes the relaxation of *ductus arteriosus* where EP_{4r} are predominant from mid-gestation and shift the TP receptor expression predominantly at gestation term.

IsoPs derived from AA and EPA have been shown to interact with some selectivity with prostanoid receptors like TP and EP concomitantly with enzymatically formed metabolites suggesting

important physiological interactions between those enzymatic and non-enzymatic metabolites of PUFAs ([Jamil et al., 2012, 2014](#); [Njie-Mbye et al., 2013](#); [Bosviel et al., 2017](#)) (Fig. 3).

3.2. NEO-PUFAs and arrhythmias

Numerous reports on cardiac anti-arrhythmic effect by DHA and EPA, especially following a cardiac stroke are found (for reviews see [Siscovick et al., 2017](#)). Based on the work of [Judé et al. \(2003\)](#), the question was left open on whether DHA (and EPA) or NEO-DHA (and NEO-EPA) exerted anti-arrhythmic properties. To answer the question, [Roy et al. \(2015\)](#) tested the anti-arrhythmic properties of DHA in different oxidative environments (with or without 1 μM H₂O₂ or α-tocopherol) in isolated cardiac cell model and arrhythmic mice model. In both models, the group found that DHA needs to be oxidized to exert anti-arrhythmic property. Natural F_{4t}-NeuroPs that was chemically synthesized were tested, and it was found 4(RS)-4-F_{4t}-NeuroP (4-F_{4t}-NeuroP) was the most active anti-arrhythmic molecule with IC₅₀ approximately 100 nM. In certain condition, the type 2 sarcoplasmic reticulum (SR) calcium channel ryanodine receptor (RyR2), does not close perfectly leading to calcium leak from the SR and consequently cause arrhythmias ([Marks, 2001](#); [Beccera et al., 2016](#)). This calcium in turn activates the sodium-calcium exchange that produces an arrhythmogenic inward current (I_{TT}). The leaky behavior of RyR2 was due to abnormal phosphorylation, S-nitrosylation and/or carbonylation leading to uncoupling of RyR2 with the regulatory protein FKBP12.6 ([Fauconnier et al., 2010](#)). In the presence of 4-F_{4t}-NeuroP, phosphorylation, S-nitrosylation and carbonylation were reduced and arrhythmic events were lessened (Fig. 4).

This study underlines the role played by a specific NEO-PUFA, here a NEO-DHA, on cardiac arrhythmias as the other NeuroPs tested by [Roy et al. \(2015\)](#) had lower activity. However, it is not clear whether 4-F_{4t}-NeuroP interacts directly with the RyR2 or with receptors, such as prostanoid receptors, that are responsible to reduce post-translational modifications ([Narumiya et al., 1999](#)). This discovery can explain some contradictory results (for a review on this topic, see [Billman, 2013](#)) obtained with ω3 PUFAs and opened a new field in the search for new endogenous anti-arrhythmic molecules.

Indeed, in animal and cell experiments, most of the studies on anti-arrhythmic effects by ω3 PUFAs have been performed without taking

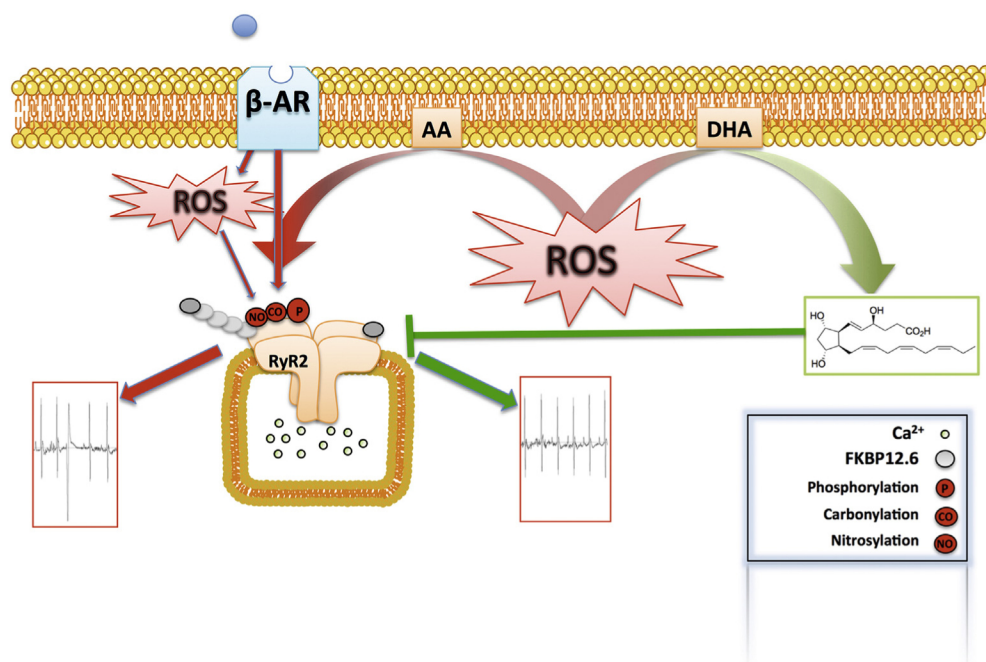


Fig. 4. Schematic diagram explaining signaling pathways involved in the anti-arrhythmic effects of 4(RS)-4-F_{4t}-NeuroP. Sympathetic activation and ROS peroxidize molecules like arachidonic acid that will carbonylate, S-nitrosylate and phosphorylate the RyR2 calcium channel inducing a destabilization of the complex RyR2-FKBP12.6. Subsequently, the channel complex becomes leaky and provoke arrhythmias. The 4(RS)-4-F_{4t}-NeuroP, prevent/reduce carbonylation/S-nitrosylation/phosphorylation of the RyR2, and prevent the destabilization of RyR2/FKBP12.6 complex hence reduce calcium leakage from the sarcoplasmic reticulum and thus arrhythmias.

Extracellular [H ₂ O ₂] (μM)	Physiological		Pathophysiological	
	0.01	10	100	1000
Cellular responses	<ul style="list-style-type: none"> - Proliferation - Stabilization of the RyR - Anti-inflammatory ? 		<ul style="list-style-type: none"> - Proliferation - growth arrest and adaptation - cell death 	

Yang (2006).

into account the development of PUFA peroxidation. Some experiments in dog and humans were designed to test the direct effects of ω3 PUFAs by intravenously injecting an emulsion of EPA and DHA (Billman et al., 1999; Schrepf et al., 2004; Den Ruijter et al., 2008). It is very likely that the emulsion of ω3 PUFAs auto-oxidized to NEO-PUFAs *in vivo* in such experimental conditions, and accounted for the observed effects. However, the quality of the emulsion should be eminent as ω3 PUFAs are prone to peroxidation and may be loaded with NEO-PUFA therefore, precautions must be taken in preparing emulsion of oils containing ω3 PUFAs, including supplemental pills which has been underlined recently (Albert et al., 2015).

4. Oxidative stress or oxidative signal?

The increasing number of publications on the biological effects of NEO-PUFAs like F₄-NeuroPs should decipher the question on its physiological and not pathophysiological role of oxidative stress in diseases. Classically, oxidative stress is understood as disequilibrium between oxidants and antioxidants that create excessive ROS. ROS is often used as a generic term describing deleterious molecules that can oxidize proteins, lipids and nucleic acids resulting in disastrous consequences in most of the time. This dogma leads to ignore papers that described the importance of ROS in regulating cardiac function of the β-adrenergic signaling pathway. The inotropic response observed with β-stimulation is due to the production of ROS by mitochondria (Andersson et al., 2011). Acutely, this is beneficial for the heart, and chronically it could become deleterious. However, in some cases, like in the metabolic syndrome, there is no production of ROS with the β-stimulation suggesting an adaptation to avoid a potentiation of the chronic oxidative stress (Llano-Diez et al., 2016). Knowing the importance of the autonomic nervous system in the prevention/triggering of arrhythmias (Champéroux et al., 2015), the beneficial and deleterious effects of ROS when the sympathetic system is activated needs to be more precisely defined. Therefore oxidative stress should be advocated as an event where a transient or permanent perturbation in the ROS balance-state generates physiological consequences within the cell, for which the precise outcome depends on ROS targets and concentrations. ROS refers to four molecules mainly, superoxide, hydrogen peroxide, peroxynitrite and hydroxyl radicals. Among them, one in particular, hydrogen peroxide (H₂O₂) is the product of superoxide dismutase (SOD) and NADPH oxidases (NOX), and metabolized in water by catalases and peroxidases and thereof enzymatically regulated (see Stone and Yang, 2006). The intracellular physiological concentration of H₂O₂ can vary from 0.001 to 0.7 μM in response to a signal (Stone and Yang, 2006). It has been shown to retard aging by oxidizing peroxiredoxins giving a new role for H₂O₂ signaling in proteostasis and lifespan control (Hanzén et al., 2016). It is of important to note that the oxidation of proteins by H₂O₂ is an intermediate step in the physiological signaling (Rhee et al., 2018). In the light of this review, it is proposed that IsoPs and NeuroPs are intermediate lipid mediators in H₂O₂ physiological signaling pathway suggesting that such oxylipins do matter as such as other oxylipins including the eicosanoids.

H₂O₂ is produced in high concentrations by macrophages (respiratory burst) to kill bacteria but it is also a metabolite of the superoxide anion via superoxide dismutase (SOD). H₂O₂ is also produced in wound at low concentrations. Its removal slows down the healing

Fig. 5. Cellular response to external H₂O₂. Depending on the concentration of H₂O₂ in the environment surrounding cells, the response of the cells can be physiological (below 10 μM) or pathophysiological (above 10 μM). A “?” is put after *anti-inflammatory* since there are no direct evidence of a link between H₂O₂ and the anti-inflammatory properties of ω3 PUFAs even if it is known that anti-inflammatory IsoPs must be produced in such conditions. Adapted from Stone and

process suggesting that it is necessary for healing to efficiently take place (Roy et al., 2006; Loo et al., 2012). Consequently, a mild oxidative stress involving H₂O₂ could be a participating signal for physiological cellular homeostasis. This proposal is not completely new since Stone and Yang (2006) proposed that H₂O₂ could be a signaling messenger that stimulates biological responses and activates specific biochemical pathways. However, the role as a messenger occurs only at micromolar concentrations range. Indeed the authors proposed that intracellular concentrations of H₂O₂ up to 1 μM (occurring when the extracellular concentration is 10 times higher, 10 μM) lead to physiological cellular responses like proliferation (Stone and Yang, 2006; Roy et al., 2017). This implies that up to 10 μM, H₂O₂ is physiological and the reactions it provokes are normal. The deleterious effects occur at higher concentrations that correspond to the oxidative stress *per se* (Fig. 5).

In the heart, this hypothesis needs to be specifically addressed by using mice conditionally knock-out for superoxide dismutase and/or NADPH oxidase in order to evaluate their cardiac response to myocardial infarction as well as the regulation of the cardiac cycle by sympathetic activation. The same kind of experiments could be performed on mice over-expressing superoxide dismutase and/or NADPH oxidase or catalase. Mice over-expressing SOD1 have been developed and studied a decade ago (Thireau et al., 2008), but this animal model was not conditional and above all, the consequences of a myocardial infarction after cardiac cell membrane PUFAs enrichment have not been studied. At least, it must be underlined that they have a cardiac phenotype reproducing some aspects of the cardiac phenotype found in patients having Down syndrome.

5. Summary and perspectives

In the light of the recent knowledge about the physiological role of H₂O₂ and NEO-PUFAs, we propose that the anti-arrhythmic effects of ω3 PUFAs present in phospholipids (Friedli and Freigang, 2017) are due to their oxidation by H₂O₂ produced consecutively to the cardiac infarct that in turn metabolized to NEO-PUFAs such as F₃-IsoPs and F₄-NeuroPs. These NEO-PUFAs will subsequently reverse or prevent the phosphorylation and carbonylation of RyR2, stabilizing its interaction with FKBP12.6 and normalizing the channel function and thus stopping arrhythmias (Fig. 4).

There are probably some other roles of the NEO-PUFAs but the research field has only opened recently and an easier access to the signaling molecules will help to advance in the understanding of their physiological role. Fully understanding the role of NEO-PUFAs will clarify their interaction with enzymatic eicosanoids such as prostaglandins and enable to fine-tune the mechanistic action of ω3 PUFAs.

References

Alkazemi, D., Jackson 2nd, R.L., Chan, H.M., Kubow, S., 2016. Increased F3-isoprostanates in the Canadian inuit population could be cardioprotective by limiting F2-isoprostanate production. *J. Clin. Endocrinol. Metabol.* 101 (9), 3264–3271.

- Allaire, J., Couture, P., Leclerc, M., Charest, A., Marin, J., Lepine, M.-C., Talbot, D., Tchernof, A., Lamarche, B., 2016. A randomized, crossover, head-to-head comparison of eicosapentaenoic acid and docosahexaenoic acid supplementation to reduce inflammation markers in men and women: the comparing EPA to DHA (compared) study. *Am. J. Clin. Nutr.* 104, 280–287.
- Albert, B.B., Derraik, J.G., Cameron-Smith, D., Hofman, P.L., Tumanov, S., Villas-Boas, S.G., Garg, M.L., Cutfield, W.S., 2015. Fish oil supplements in New-Zealand are highly oxidized and do not meet label content of n-3 PUFA. *Sci. Rep.* 5 7928.
- Albert, C.M., Campos, H., Stampfer, M.J., Ridker, P.M., Manson, J.E., Willett, W.C., Ma, J., 2002. Blood levels of long-chain n-3 fatty acids and the risk of sudden death. *N. Engl. J. Med.* 346, 1113–1118.
- Ander, B.P., Hurtado, C., Raposo, C.S., Maddaford, P.G., Deniset, J.F., Hryshko, L.V., Pierce, G.N., Lukas, A., 2007. Differential sensitivities of the NCX1.1 and NCX1.3 isoforms of the Na-Ca2 exchanger to alpha-linolenic acid. *Cardiovasc. Res.* 73, 395–403.
- Andersson, D., Fauconnier, J., Yamad, T., Lacampagne, A., Zhang, S.-H., Katz, A., Westerblad, H., 2011. Mitochondrial production of reactive oxygen species contributes to the β -adrenergic stimulation of mouse cardiomyocytes. *J. Physiol.* 589.7, 1791–1801.
- Bang, H.O., Dyerberg, J., Hjörne, N., 1976. The composition of food consumed by Greenland Eskimos. *Acta Medicine Scandinavia* 200, 69–73.
- Bauer, J., Ripperger, A., Frantz, S., Ergün, S., Schwedhelm, E., Benndorf, R.A., 2014. Pathophysiology of isoprostanes in the cardiovascular system: implications of isoprostanes-mediated thromboxane A₂ receptor activation. *Br. J. Pharmacol.* 171, 3115–3131.
- Bayes de Luna, A., Coumel, P., LeClercq, J.F., 1989. Ambulatory sudden cardiac death: mechanisms of production of fatal arrhythmia on the basis of data from 157 cases. *Am. Heart J.* 117, 151–159.
- Beccera, R., Román, B., Di Carlo, M.N., Mariangelo, J.L., Salas, M., Sanchez, G., Donoso, P., Schinella, G.R., Vittone, L., Wehrens, X.H., Mundiña-Weilenmann, C., Said, M., 2016. Reversible redox modifications of ryanodine receptor ameliorate ventricular arrhythmias in the ischemic-perfused heart. *Am. J. Physiol. Heart Circ. Physiol.* 311, H713–H724.
- Billman, G.E., Hallaq, H., Leaf, A., 1994. Prevention of ischemia-induced ventricular fibrillation by omega 3 fatty acids. *Proc. Natl. Acad. Sci. U. S. A.* 91, 4427–4430.
- Billman, G.E., Kang, J.X., Leaf, A., 1999. Prevention of sudden cardiac death by dietary pure omega-3 polyunsaturated fatty acids in dogs. *Circulation* 99, 2452–2457.
- Billman, G., 2013. The effects of poly-unsaturated fatty acids on cardiac rhythm: a critical reassessment. *Pharmacology and Therapy* 140, 53–80.
- Bogdanov, K.Y., Spurgeon, H.A., Vinogradova, T.M., Lakatta, E.G., 1998. Modulation of the transient outward current in adult rat ventricular myocytes by polyunsaturated fatty acids. *Am. J. Physiol. Heart Circ. Physiol.* 274 (2), H571–H579.
- Bosviel, R., Joulard-Cubizolles, L., Chinetti-Gbaguidi, G., Bayle, D., Copin, C., Hennuyer, N., Duplan, I., Staels, B., Zanoni, G., Porta, A., Balas, L., Galano, J.-M., Oger, C., Mazur, A., Durand, T., Gladine, C., 2017. DHA-derived oxylipins, neuroprostanes and protectins, differentially and dose-dependently modulate the inflammatory response in human macrophages: putative mechanisms through PPAR activation. *Free Radic. Biol. Med.* 103, 146–154.
- Brooks, J., Musiek, E., Koestner, T., Stankowski, J., Howard, J., Brunoldi, E., Porta, A., Zanoni, G., Vidari, G., Morrow, J., Milne, G., McLaughlin, B., 2011. The fatty acid oxidation product 15-A3t-Isoprostane is a potent inhibitor of NF κ B transcription and macrophage transformation. *J. Neurochem.* 119 (3), 604–617.
- Burr, M.L., Fehily, A.M., Gilbert, J.F., Rogers, S., Holliday, R.M., Sweetnam, P.M., Elwood, P.C., Deadman, N.M., 1989. Effects of changes in fat, fish, and fibre intakes on death and myocardial reinfarction: diet and reinfarction trial (DART). *Lancet* 2, 757–761.
- Burton, K.P., Morris, A.G., Massey, K.D., Buja, L.M., Hagler, H.K., 1990. Free radicals alter ionic levels and membrane phospholipids in cultured rat ventricular myocytes. *J. Mol. Cell. Cardiol.* 22, 1035–1047.
- Calder, P.C., 2015. Marine omega-3 fatty acids and inflammatory processes: effects, mechanisms and clinical relevance. *Biochim. Biophys. Acta* 1851, 469–484.
- Champéroux, P., Thireau, J., Judé, S., Laigot-Barbé, C., Maurin, A., Sola, M.L., Fowler, J.S.L., Richard, S., Le Guennec, J.-Y., 2015. Short-term variability in QT interval and ventricular arrhythmias induced by dofetilide are dependent on high-frequency autonomic oscillations. *Br. J. Pharmacol.* 172, 2878–2891.
- Chen, J.-X., O'Mara, P.W., Poole, S.D., Brown, N., Ehinger, N.J., Slaughter, J.C., Paria, B.C., Aschner, J.L., Reese, J., 2012. Isoprostanes as physiological mediators of transition to newborn life: novel mechanisms regulating patency of the term and preterm ductus arteriosus. *Pediatr. Res.* 72 (2), 122–128.
- Chen, S.-P., Chung, Y.-T., Liu, T.-Y., Wang, Y.-F., Fuh, J.-L., Wang, S.-J., 2013. Oxidative stress and increased formation of vasoconstricting F2-isoprostanes in patients with reversible cerebral vasoconstriction syndrome. *Free Radic. Biol. Med.* 61, 243–248.
- Cracowski, J.-L., Durand, T., 2006. Cardiovascular pharmacology and physiology of the isoprostanes. *Fund. Clin. Pharmacol.* 20 (5), 417–427.
- Davies, K.J.A., 1987. Protein damage and degradation by oxygen radicals: I. General aspects. *J. Biol. Chem.* 262, 9895–9990.
- Den Ruijter, H.M., Berecki, G., Verkerk, A.O., Bakker, D., Baartsheer, A., Schumacher, C.A., Belterman, C.N.W., de Jonge, N., Fiolet, J.W.T., Broower, I.A., Coronel, R., 2008. Acute administration of fish oil inhibits triggered activity in isolated myocytes from rabbits and patients with heart failure. *Circulation* 117, 536–544.
- Dizdaroglu, M., 1992. Oxidative damage to DNA in mammalian chromatin. *Mutat. Res.* 275, 331–342.
- Downey, A.K., 1990. Free radicals and their involvement during long-term myocardial ischemia and reperfusion. *Annu. Rev. Physiol.* 52, 487–504.
- Fauconnier, J., Thireau, J., Reiken, S., Cassan, C., Richard, S., Matecki, S., Marks, A.R., Lacampagne, A., 2010. Leaky RyR2 triggers ventricular arrhythmias in Duchenne muscular dystrophy. *Proc. Natl. Acad. Sci. U. S. A.* 107 (4), 1559–1564.
- Friedli, O., Freigang, S., 2017. Cyclopentone-containing oxidized phospholipids and their isoprostanes as pro-resolving mediators of inflammation. *Biochim. Biophys. Acta* 1862, 382–392.
- Fukuda, K., Davies, S., Nakajima, T., Ong, B., Kupersmidt, S., Fessel, J., Amarnath, V., Mark, E., Anderson, A., Boyden, P., Viswanathan, P., Roberts, L., Balsler, J., 2005. Oxidative mediated lipid peroxidation recapitulates proarrhythmic effects on cardiac sodium channels. *Circ. Res.* 97, 1262–1269.
- Gauthier, K., Campbell, W., McNeish, A., 2014. Regulation of KCa2.3 and endothelium-dependent hyperpolarization (EDH) in the rat middle cerebral artery: the role of lipoxigenase metabolites and isoprostanes. *PeerJ* 2http://dx.doi.org/10.7717/peerj.414. e414.
- GISSI (Gruppo Italiano per lo Studio della Sopravvivenza nell'Infarto miocardico), 1999. Dietary supplementation with n-3 polyunsaturated fatty acids and vitamin E after myocardial infarction: results of the GISSI-Prevenzione trial. *Lancet* 354, 447–455.
- Gladine, C., Newman, J.W., Durand, T., Pedersen, T.L., Galano, J.-M., Demougéot, C., Berdeaux, O., Pujos-Guillot, E., Mazur, A., Comte, B., 2014. Lipid profiling following intake of the omega 3 fatty acid DHA identifies the peroxidized metabolites F₄-neuroprostanes as the best predictors of atherosclerosis prevention. *PLoS One* 9 (2) e89393.
- Greene, H.L., 1990. Sudden arrhythmic cardiac death: mechanisms, resuscitation and classification: the Seattle perspective. *Am. J. Cardiol.* 65, 4B–12B.
- Guizy, M., Arias, C., David, M., Gonzalez, T., Valenzuela, C., 2005. ω -3 and ω -6 polyunsaturated fatty acids block HERG channels. *Am. J. Physiol. Cell Physiol.* 289, C1251–C1260.
- Hanzén, S., Vielfort, K., Yang, J., Roger, F., Andersson, V., Zamarbide-Forés, S., Andersson, R., Malm, L., Palais, G., Biteau, B., Liu, B., Toledano, M.B., Molin, M., Nyström, T., 2016. Lifespan control by redox-dependent recruitment of chaperones to misfolded proteins. *Cell* 166, 140–151.
- Hausermann, L., St-Louis, J., 2011. Thromboxane and isoprostanes share the same prostanoïd receptors to increase human placental tone. *Placenta* 32, 941–948.
- Hinkle, L.E.J., Thaler, H.T., 1982. Clinical classification of cardiac deaths. *Circulation* 65, 457–464.
- Honoré, E., Barhanin, J., Attali, B., Lesage, F., Lazdunski, M., 1994. External blockade of the major cardiac delayed-rectifier KC channel (Kv1.5) by polyunsaturated fatty acids. *Proc. Natl. Acad. Sci. U. S. A.* 91, 1937–1941.
- Itoh, T., Fairall, K., Amin, K., Inaba, A., Szanto, B.L., Balint, L., Nagy, K., Yamamoto, K., Schwabe, J.W.R., 2008. Structural basis for the activation of PPAR γ by oxidized fatty acids. *Nat. Struct. Mol. Biol.* 15, 924–931.
- Jamil, J., Wright, A., Harrison, N., Kegey, E., Flowers, A.F., Flyod, N.J., Kotera, C., Guy, A., Galano, J.-M., Durand, T., Njie-Mbye, Y.F., Ohia, S.E., Opere, C.A., 2012. Role of [³H]D-aspartate release by the 5-F_{2t}-Isoprostane and its epimer in isolated bovine retina. *Neurochem. Res.* 37, 574–582.
- Jamil, J., Bankhele, P., Salvi, A., Mannix, J.E., Oger, C., Guy, A., Galano, J.-M., Durand, T., Njie-Mbye, Y.F., Ohia, S.E., Opere, C.A., 2014. Role of the non-enzymatic metabolite of eicosapentaenoic acid 5-epi-5F_{3t}-isoprostane in the regulation of [(3)H]D-aspartate release in isolated bovine retina. *Neurochem. Res.* 39 (12), 2360–2369.
- Judé, S., Bedut, S., Roger, S., Pinault, M., Champeroux, P., White, E., Le Guennec, J.-Y., 2003. Peroxidation of docosahexaenoic acid is responsible for its effects on I_{TO} and I_{SS} in rat ventricular myocytes. *Br. J. Pharmacol.* 139, 816–822.
- Kumar, A., Kingdon, E., Norman, J., 2005. The isoprostanes 8-iso-PGF₂ α suppresses monocytes adhesion to human microvascular endothelial cells via two independent mechanisms. *FASEB (Fed. Am. Soc. Exp. Biol.) J.* 19 (3), 443–445.
- Leaf, A., Hallaq, H.A., 1992. The role of nutrition in the functioning of the cardiovascular system. *Nutr. Rev.* 50 (12), 402–406.
- Leaf, A., Kang, J.X., Xiao, Y.-F., 2008. Fish oil fatty acids as cardiovascular drugs. *Curr. Vasc. Pharmacol.* 6, 1–12.
- Leifert, W., McMurchie, E., Saint, D., 1999. Inhibition of cardiac sodium currents in adult rat myocytes by n-3 polyunsaturated fatty acids. *J. Physiol.* 520, 3671–3679.
- Leitinger, N., Huber, J., Rizza, C., Mechtcheriakova, D., Bochkov, V., Koshelnick, Y., Berlinger, J.A., Binder, B.R., 2001. The isoprostanes 8-iso-(PGF₂ α) stimulates endothelial cells to bind monocytes: differences from thromboxane-mediated endothelial activation. *FASEB (Fed. Am. Soc. Exp. Biol.) J.* 15 (7), 1254–1256.
- Llano-Diez, M., Sinclair, J., Yamada, T., Zong, M., Fauconnier, J., Zhang, S.-Y., Katz, A., Jardemark, K., Westerblad, H., Andersson, C., Lanner, J., 2016. The role of reactive oxygen species in β -adrenergic signaling in cardiomyocytes from mice with the metabolic syndrome. *PLoS One*. http://dx.doi.org/10.1371/journal.pone.0167090.
- Loo, A.E.K., Wong, Y.T., Ho, R., Wasser, M., Du, T., Ng, W.T., Halliwell, B., 2012. Effects of hydrogen peroxide on wound healing in mice in relation to oxidative damage. *PLoS One* 7 (11) e49215.
- Macleod, J.C., Macknight, A.D., Rodrigo, G.C., 1998. The electrical and mechanical response of adult Guinea pig and rat ventricular myocytes to omega-3 polyunsaturated fatty acids. *Eur. J. Pharmacol.* 356, 261–270.
- Marks, A., 2001. Ryanodine receptors/calcium-released channels in heart failure and sudden cardiac death. *J. Mol. Cell. Cardiol.* 33 (4), 615–624.
- McLennan, P.L., Bridle, T.M., Abeywardena, M.Y., Charnock, J.S., 1992. Dietary lipid modulation of ventricular fibrillation threshold in the marmoset monkey. *Heart* J. 123, 1555–1561.
- Majkova, Z., Layne, J., Sunkara, M., Morris, A.J., Toborek, M., Hennig, B., 2011. Omega-3 fatty acid oxidation products prevent vascular endothelial cell activation by coplanar polychlorinated biphenyls. *Toxicol. Appl. Pharmacol.* 251 (1), 41–49.
- Mishra, A., Chaudhary, A., Sethi, S., 2004. Oxidized omega-3 fatty acids inhibit NF- κ B activation via a PPAR α -dependent pathway. *Arterioscler. Thromb. Vasc. Biol.* 24, 1621–1627.
- Moreno, C., Macías, A., Prieto, A., Cruz, A., González, T., Valenzuela, C., 2012. Effects of n3 polyunsaturated fatty acids on cardiac ion channels. *Front. Physiol.* 3, 245.

- Mozaffarian, D., Lemaitre, R.N., Kuller, L.H., Burke, G.L., Tracy, R.P., Siscovick, D.S., 2003. Cardiac benefits of fish consumption may depend on the type of fish meal consumed: the Cardiovascular Health Study. *Cardiovascular Health Study. Circulation* 107, 1372–1377.
- Mozaffarian, D., Prineas, R.J., Stein, P.K., Siscovick, D.S., 2006. Dietary fish and n-3 fatty acid intake and cardiac electrocardiographic parameters in humans. *J. Am. Coll. Cardiol.* 48, 478–484.
- Musiek, E., Brooks, J., Joo, M., Brunoldi, E., Porta, A., Zanoni, G., Vidari, G., Blackwell, T., Montine, T., Milne, G., McLaughlin, B., Morrow, J., 2008. Electrophilic cyclopentenone neuroprostanes are anti-inflammatory mediators formed from the peroxidation of the ω -3 polyunsaturated fatty acid docosahexaenoic acid. *J. Biol. Chem.* 283 (29), 19927–19935.
- Narumiya, S., Sugimoto, Y., Ushikubi, F., 1999. Prostanoid receptors: structures, properties and functions. *Physiol. Rev.* 79 (4), 1193–1226.
- Njie-Mbye, Y.F., Kulkarni-Chitnis, M., Opere, C.A., Barrett, A., Ohia, S., 2013. Lipid peroxidation: pathophysiological and pharmacological implications in the eye. *Front. Physiol.* 4, 366.
- Pfister, S., Nithipatikom, K., Campbell, W., 2011. Role of superoxide and thromboxane receptors in acute angiotensin II-induced vasoconstriction of rabbit vessels. *Am. J. Physiol. Cell Physiol.* 300, H2064–H2071.
- Rhee, S.G., Woo, H.A., Kang, D., 2018. The role of peroxiredoxins in the transduction of the H₂O₂ signals. *Antioxidants Redox Signal.* 28 (7). <https://doi.org/10.1089/ars.2017.7167>.
- Ringbom, T., Huss, U., Stenholm, A., Flock, S., Skattebol, L., Perera, P., Bohlin, L., 2001. Cox-2 inhibitory effects of naturally occurring and modified fatty acids. *J. Nat. Prod.* 64 (6), 745–749.
- Roberts II, L.J., Montine, T.J., Markesbery, W.R., Tapper, A.R., Hardy, P., Chemtob, S., Dettbarn, W.D., Morrow, J.D., 1998. Formation of isoprostanol-like compounds (neuroprostanes) in vivo from docosahexaenoic acid. *J. Biol. Chem.* 273 (2), 13605–13612.
- Roy, J., Oger, C., Thireau, J., Roussel, J., Mercier-Touzet, O., Faure, D., Pinot, E., Farah, C., Tabert, D.F., Cristol, J.-P., Lee, J.C.Y., Lacampagne, A., Galano, J.-M., Durand, T., Le Guennec, J.-Y., 2015. Nonenzymatic lipid mediators, neuroprostanes, exert the anti-arrhythmic properties of docosahexaenoic acid. *Free Radical Biol. Med.* 86, 269–278.
- Roy, J., Le Guennec, J.-Y., 2017. Cardioprotective effects of omega 3 fatty acids: origin of the variability. *J. Muscle Res. Cell Motil.* 38, 25–30.
- Roy, J., Galano, J.M., Durand, T., Le Guennec, J.-Y., Lee, J.-C.-Y., 2017. Physiological role of ROS as promoters of natural defences. *FASEB (Fed. Am. Soc. Exp. Biol.) J* 10.1096.
- Roy, S., Khanna, S., Nallu, K., Hunt, T.K., Sen, C.K., 2006. Dermal wound healing is subject to redox control. *Mol. Ther.* 13, 211–220.
- Saravanan, P., Davidson, N.C., Schmidt, E.B., Calder, P.C., 2010. Cardiovascular effects of marine omega-3 fatty acids. *Lancet* 376 (9740), 540–550.
- Schrepf, R., Limmert, T., Claus-Weber, P., Theisen, K., Sellmayer, K., 2004. Immediate effect of n-3 fatty acid infusion on the induction of sustained ventricular tachycardia. *Lancet* 363, 1441–1442.
- Sethi, S., Eastman, A.Y., Eaton, J.W., 1996. Inhibition of phagocyte-endothelium interactions by oxidized fatty acids: a natural anti-inflammatory mechanism? *J. Lab. Clin. Med.* 128, 27–38.
- Sethi, S., Ziouzenkova, O., Ni, H., Wagner, D.D., Plutzky, J., Mayadas, T.N., 2002. Oxidized omega-3 fatty acids in fish oil inhibit leukocyte-endothelial interactions through activation of PPAR α . *Blood* 100, 1340–1346.
- Sigal, L.H., 2006. Basic science for the clinician 39: NF-kappaB function, activation, control and consequences. *J. Clin. Rheumatol.: Practical Rep. Rheum. Musculoskel. Dis.* 12, 207–211.
- Siscovick, D.S., Raghunathan, T.E., King, I., Weinmann, S., Wicklund, K.G., Albright, J., Bovbjerg, V., Arbogast, P., Smith, H., Kushi, L.H., 1995. Dietary intake and cell membrane levels of long-chain n-3 polyunsaturated fatty acids and the risk of primary cardiac arrest. *J. Am. Med. Assoc.* 274, 1363–1367.
- Siscovick, D.S., Barringer, T.A., Fretts, A.M., Wu, J.H.Y., Lichtenstein, A.H., Costello, R.B., Kris-Etherton, P.M., Jacobson, T.A., Engler, M.B., Alger, H.M., Appel, L.J., Mozaffarian, D., 2017. Omega-3 polyunsaturated fatty acid (fish oil) supplementation and the prevention of clinical cardiovascular disease. A science advisory from the American Heart Association. *Circulation* 135 (15), e867–e884.
- Spinelli, S.L., Lannan, K.L., Casey, A.E., Croasdel, A., Curran, T.M., Henrichs, K.F., Pollock, S.J., Milne, G.A., Refaai, M.A., Francis, C.W., Phipps, R.P., Blumberg, N., 2014. Isoprostanol and isofuran lipid mediators accumulate in stored red blood cell concentrates and influence platelet function *in vitro*. *Transfusion* 54 (6), 1569–1579.
- Stone, J.R., Yang, S., 2006. Hydrogen peroxide: a signaling messenger. *Antioxidants Redox Signal.* 8 (3–4), 243–270.
- Thireau, J., Poisson, D., Zhang, B.L., Gillet, L., Le Pêcheur, M., Andrès, C., London, J., Babuty, D., 2008. Increased heart rate variability in mice overexpressing the Cu/Zn superoxide dismutase. *Free Radical Biol. Med.* 45 (4), 396–403.
- Tse, G., Yan, B., Chan, Y., Tian, X., Huang, Y., 2016. Reactive oxygen species, endoplasmic reticulum stress and mitochondrial dysfunction: the link with cardiac arrhythmogenesis. *Front. Physiol.* <http://dx.doi.org/10.3389/fphys.2016.00313>.
- Van der Sterren, S., Villamor, E., 2011. Contractile effects of 15-E_{2t}-isoprostane and 15-F_{2t}-isoprostane on chicken embryo ductus arteriosus. *Comp. Biochem. Physiol., A* 159, 436–444.
- Van't Erve, T.J., Kadiiska, M.B., London, S.J., Mason, R.P., 2017. Classifying oxidative stress by F₂-isoprostane levels across human diseases: a meta-analysis. *Redox Biol.* 12, 582–599.
- Verkerk, A.O., van Ginneken, A.C., Berecki, G., Den Ruijter, H.M., Schumacher, C.A., Veldkamp, M.W., Baartscheer, A., Casini, S., Opthof, T., Hovenier, R., Fiolet, J.W., Zock, P.L., Coronel, R., 2006. Incorporated sarcolemmal fish oil fatty acids shorten pig ventricular action potentials. *Cardiovasc. Res.* 70, 509–520.
- Xiao, Y.F., Ke, Q., Chen, Y., Morgan, J.P., Leaf, A., 2004. Inhibitory effect of n-3 fish oil fatty acids on cardiac Na⁺/Ca²⁺ exchange currents in HEK293t cells. *BBRC (Biochem. Biophys. Res. Commun.)* 321 (1), 116–123.
- Xiao, Y.F., Gomez, A.M., Morgan, J.P., Lederer, W.J., Leaf, A., 1997. Suppression of voltage-gated L-type Ca²⁺ currents by polyunsaturated fatty acids in adult and neonatal rat ventricular myocytes. *Proc. Natl. Acad. Sci. U. S. A.* 94, 4182–4187.
- Xiao, Y.F., Kang, J.X., Morgan, J.P., Leaf, A., 1995. Blocking effects of polyunsaturated fatty acids on Na⁺ channels of neonatal rat ventricular myocytes. *Proc. Natl. Acad. Sci. U. S. A.* 92 (24), 11000–11004.
- Yura, T., Fukunaga, M., Khan, R., Nassar, G.N., Badr, K.F., Montero, A., 1999. Free-radical-generated F₂-isoprostane stimulates cell proliferation and endothelin-1 expression on endothelial cells. *Kidney Int* 56 (2), 471–478.
- Zhao, Z., Wen, H., Fefelova, N., Allen, C., Guillaume, N., Xiao, D., Huang, C., Zang, W., Gwathmey, J.K., Xie, L.-H., 2012. Docosahexaenoic Acid reduces the incidence of early afterdepolarizations caused by oxidative stress in rabbit ventricular myocytes. *Front. Physiol.* 3, 252.