The Discovery of Nitro-Fatty Acids as Products of Metabolic and Inflammatory Reactions and Mediators of Adaptive Cell Signaling

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Abstract

Foundational advances in eicosanoid signaling, the free radical biology of oxygen and nitric oxide and mass spectrometry all converged to enable the discovery of nitrated unsaturated fatty acids. Due to the unique biochemical characteristics of fatty acid nitroalkenes, these species undergo rapid and reversible Michael addition of biological nucleophiles such as cysteine, leading to the post-translational modification of low molecular weight and protein thiols. This capability has led to the present understanding that nitro-fatty acid reaction with the alkylation-sensitive cysteine proteome leads to physiologically-beneficial alterations in transcriptional regulatory protein function, gene expression and in vivo rodent model responses to metabolic and inflammatory stress. These findings motivated the preclinical and clinical development of nitro-fatty acids as new drug candidates for treating acute and chronic metabolic and inflammatory disorders.

Keywords

Introduction

Three foundational discoveries helped direct us down the experimental pathway leading to the discovery of fatty acid nitroalkene derivatives (nitro-fatty acids, NO$_2$-FA)

Prostaglandins and leukotrienes were identified as unsaturated fatty acid oxygenation products that mediate receptor-dependent regulation of inflammation, metabolism, and

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vascular function (1). Prior to this discovery, fatty acids and complex lipids were typically viewed as sources of metabolic energy and structural constituents of membranes, rather than as substrates for signaling mediator biosynthesis. At about the same time, seminal discoveries that led to the fields of free radical biology and redox signaling were being made. Specifically, the generation of superoxide ($O_2^{\cdot-}$), hydrogen peroxide (H_2O_2) and other oxygen-derived species was identified in microbes, plants, fish and mammals, along with the existence of small molecule and enzymatic antioxidant networks that regulate cell levels of these oxidizing species (2). This led to the rapid acceptance of "reactive oxygen species" as mediators of xenobiotic toxicity and host defense and later, as cell signaling mediators. Finally, the free radical gas nitric oxide ($^{\cdot}$NO) was identified as a product of nitric oxide synthase-catalyzed arginine oxidative deamination and the roles of $^{\cdot}$NO as a mediator of endothelial-dependent vascular relaxation and neurotransmission were described (3). With this critical perspective in mind, we discovered that convergent reactions of unsaturated fatty acids and reactive species derived from oxygen, nitric oxide and nitrite (NO_2^-) yield a family of chemically-reactive products that mediate pleiotropic metabolic and anti-inflammatory signaling actions. Moreover, synthetic homologs of NO_2-FA may have pharmacologic utility, as present data indicates oral bioavailability, good pharmacokinetics, signaling pathway engagement and a promising safety profile in model systems and humans. There were a number of critical steps that had to be taken and pitfalls to overcome in this process of discovery:

1. Overcoming an initial bias that $^{\cdot}$NO-derived reactive species primarily mediated pro-inflammatory and pathogenic oxidation and nitration reactions

We had discovered that the toxicity of $O_2^{\cdot-}$ and $^{\cdot}$NO could be transduced by peroxynitrite ($ONOO^-$), the product of their radical-radical reaction, and by the product of $ONOO^-$ and carbon dioxide (CO_2) reaction, nitrosoperoxocarbonate ($ONOOCO_2$). These nitrogen oxides can react directly or rapidly undergo homolytic scission (as $ONOOH$) to yield nitrogen dioxide ($^{\cdot}$NO$_2$), hydroxyl radical ($^{\cdot}$OH) and, in the case of $ONOOCO_2$, carbonate radical ($CO_3^{\cdot-}$)(4–7). We also had discovered that the neutrophil-derived heme protein myeloperoxidase (MPO), upon degranulation and reaction with H_2O_2, catalytically consumes $^{\cdot}$NO and further oxidizes NO_2^- to the nitrating species nitrogen dioxide ($^{\cdot}$NO$_2$)(8–10). Because of the facile ability of MPO to generate $^{\cdot}$NO$_2$ during inflammatory responses and the unique ability of MPO to become anatomically "locked" in place by high affinity glycosaminoglycan binding, we also discovered a strong spatial co-distribution between MPO and nitrated biomolecules (11,12). More recently, we demonstrated that during $^{\cdot}$NO autooxidation, NO_2^- directly participates in fatty acid nitration reactions at neutral pH via the formation of symmetrical dinitrogen trioxide ($ONONO$)(13). These reactions, all operative in cell and murine models of inflammation and clinical observations, support the physiological relevance of these diverse mechanisms of nitro-oxidative stress (13,14).

2. How we overcame bias and preconceived notions

In testing the concept that $^{\cdot}NO$ exacerbates oxidative inflammatory responses in more biologically-relevant model systems, we evaluated biochemical, cellular and *in vivo* responses to the co-generation of $O_2^{\cdot-}$, H_2O_2 and $^{\cdot}NO$. It was first observed that $^{\cdot}NO$ more potently inhibited the oxidation of membranes and plasma lipoproteins than α-tocopherol (15,16). We then extended these studies to more biological model systems by showing that elevated rates of $^{\cdot}NO$ biosynthesis or the introduction of $^{\cdot}NO$ donors led to protection of pulmonary and vascular cells having elevated rates of $O_2^{\cdot-}$ and H_2O_2 generation. Similarly, rodents inhaling 95% oxygen (thus enhancing rates of pulmonary $O_2^{\cdot-}$ and H_2O_2 generation) were protected from pulmonary oxygen toxicity by the introduction of 8 ppm $^{\cdot}NO$, a concentration of inhaled $^{\cdot}NO$ that is within the range of that used clinically to treat pulmonary hypertension (17–19). In these studies, anti-inflammatory, antioxidant and tissue-protective responses prevailed that were contrary to dogma at the time regarding the biochemical effects of $^{\cdot}NO$ during oxidative inflammatory reactions (20).

3. New perspective was gained regarding the tissue-protective and anti-inflammatory actions of $^{\cdot}NO$ during oxidative-stress

The antioxidant actions of $^{\cdot}NO$ were first ascribed to its kinetically rapid reaction with lipid peroxyl radicals, thus terminating autocatalytic free radical-mediated chain propagation reactions (15,16,21). It had become apparent that, *depending on concentration and the nature of the local free radical milieu, the reactions of $^{\cdot}NO$ could promote both pro-inflammatory and anti-inflammatory responses.* This was exemplified in a biochemical reaction system where rates of $^{\cdot}NO$ introduction and enzymatic $O_2^{\cdot-}$ and H_2O_2 generation were varied inversely (15). The continuous variation of the $^{\cdot}NO/O_2^{\cdot-}$ ratios showed that when $^{\cdot}NO$ concentrations exceeded those of $O_2^{\cdot-}$ and consequent $ONOO^-/ONOOH$ formation, lipid peroxidation was inhibited. The HPLC-MS/MS analysis of the different reaction conditions in this study also gave the first mass spectra showing the nitration of unsaturated fatty acids by oxidative inflammatory conditions. Further studies of linoleic acid reaction with $ONOO^-$, $\cdot NO_2$, NO_2^+ or $NO_2^-/HONO$ also revealed both linoleate oxidation and nitration products (22,23). Previously, photochemical air pollution-related studies of gaseous nitrogen dioxide ($\cdot NO_2$) reaction with fatty acids and phospholipids had also shown the formation of nitration products (24–26). Prior to appreciating that NO_2-FA induce cell signaling responses via the PTM of nucleophilic protein targets, additional understanding of the chemical reactions that led to unsaturated fatty acid nitration was acquired (27–30). The fact that nitroalkene-containing hydrocarbons, released at high pressure by a termite soldier gland, act as a termite chemical warfare armament for establishing turf domain also suggested that fatty acid nitroalkenes might have some unique reactivities (31).

4. Nitric oxide and its secondary products were observed to regulate lipid signaling by modulating the enzymatically-catalyzed oxygenation of unsaturated fatty acids

The small molecular radius, lipophilicity and free radical character of ·NO all contribute to the broad range of actions that both ·NO and its secondary nitrogen oxides will exert on the oxidative generation of bioactive unsaturated fatty acid products. These effects have been extensively reviewed and include the regulation of the gene expression and changes in the catalytic activities and oxygenated lipid product profiles of cyclooxygenase-1 and -2, multiple lipoxygenases, CYP450s and soluble epoxide hydrolase (32–34). When catalyzing fatty acid oxidation, cyclooxygenase-1 and -2 and lipoxygenases were observed to catalytically consume ·NO and impair downstream cGMP-dependent signaling actions (10,35–37). Moreover, electrophilic NO_2-FA species inhibit cyclooxygenase and lipoxygenase catalysis and gene expression (38,39). These observations affirmed to us that there is a very strong and diverse array of biochemical linkages between lipid and ·NO signaling.

5. The organic synthesis of nitro-oleic, nitro-linoleic and nitro-arachidonic acid provided the key to unlocking the analytical, biochemical and pharmacological characteristics of nitro-fatty acids

The characterization of nitration products of unsaturated fatty acids in model system reactions prioritized the first NO_2-FA to be synthesized. This was first accomplished by a selenium-catalyzed nitration reaction that gave mixed regioisomers of linoleic and oleic acid nitroalkenes (40–42). Later, the synthesis of specific nitro-oleic acid regioisomers by the Henry nitro-aldol reaction further facilitated the discovery of the pleiotropic signaling actions of NO_2-FA and the definition of structure-function relationships in the responses of signaling networks to different fatty acid nitroalkene derivatives (43–49). Moreover, these synthetic approaches allowed the synthesis of isotopically-labeled NO_2-FA (^{13}C, ^{15}N and ^{18}O), permitting the development of HPLC-based isotopic dilution mass spectrometry methods. Overall, these capabilities and reagents were crucial for defining the endogenous generation, tissue levels, metabolism, and signaling actions of this new class of mediators (22,43,44,50–54). Nonetheless, some mistakes and incorrect assumptions were made in early studies of the structure and concentrations of NO_2-FA species in biological systems (15,50). These analytical challenges were similar to the those faced in other studies of electrophilic fatty acid derivatives, for example 15-deoxyprostaglandin J_2 (15d-PGJ$_2$), 4-hydroxy-2-nonenal and α,β-unsaturated fatty acid ketone derivatives, when trying to establish their endogenous tissue and plasma levels, with net tissue concentrations of these species still remaining controversial. The later development of improved sample preparation, chromatographic separations, and more refined mass spectrometric analyses improved NO_2-FA structural and concentration determinations (51,55–63). Also, better understanding of the bond scission mechanisms operative in mass spectrometer-based fragmentation studies permitted the definition of NO_2-conjugated linoleic acid as the principal nitrated fatty acid regioisomer present in cellular models of inflammation, and endogenously in both animal

models and humans (13,14,55–57,64). The availability of solid analytical approaches and critical reagents for studying lipid nitroalkene pharmacology were crucial for obtaining consistent results between investigators and labs focused on defining the mechanisms of NO_2-FA generation, metabolism and how these species impact cell and organ function. As discussed in the translational chapter of this series, these goals were accomplished in parallel with the acquisition of intellectual property protection, studies of NO_2-FA actions in preclinical models of inflammatory and metabolic diseases and the attainment of investment for supporting new drug development activities. Importantly, freely sharing reagents, standards, analytical expertise and ideas with colleagues was crucial for correcting mistakes, improving methods, replicating results and advancing understanding.

6. Critical issues and novel insights regarding the unique nature of NO_2-FA as endogenous mediators and new drug candidates

Do NO_2-FA generate ·NO?

We initially viewed that NO_2-FA might serve as an endogenous reserve of ·NO that would be formed by metabolic and inflammatory reactions, and that after decay or metabolism would subsequently mediate cGMP-dependent vascular relaxation. To this extent, we and others have documented very low stoichiometric levels of ·NO release by NO_2-FA under aqueous conditions (40,44,65–70). While the mechanism of ·NO release is still a matter of debate (via a modified Nef reaction or a rearrangement to a nitrite ester and N-O bond homolysis), these potential reactions are inhibited in membranes and in the presence of plasma constituents such as protein and lipoproteins (44,65,70). Further lines of evidence coming from more biologically relevant systems such as rodent model and clinical studies also do not support the occurrence of ·NO-mediated, cGMP-dependent signaling actions of NO_2-FA. For example, acute intravenous infusion of low to high concentrations of NO_2-FA does not affect blood pressure or heart rate in rodents, dogs and humans (71). Still, there are other biochemical and cellular studies that still suggest that fatty acid nitroalkenes yield ·NO. We view that additional experimental evidence is needed, that must be supported by the reactions of ^{15}N-labeled NO_2-FA and the subsequent detection of $^{15}NO_2^-$ and/or· ^{15}NO. These approaches are important for eliminating the confounding effects of adventitious NO_2^-, contamination and the concomitant modulation of cellular or *in vivo* sources of ·NO generation. In the latter regard, NO_2-FA a) induce endothelial nitric oxide synthase gene expression and catalytic activity and b) promote the upregulation of multiple antioxidant mechanisms that will "preserve" ·NO by limiting its oxidative inactivation and the subsequent generation of secondary nitrogen oxides.(72)

NO_2-FA displays a unique pharmacology that is dissimilar from ·NO

In the early 2000s, two cell biological studies documented non-cGMP-dependent inhibition of platelet and neutrophil function by nitro-linoleic acid (73,74). This work significantly transformed our understanding of the mechanisms accounting for the potential signaling actions NO_2-FA signaling. Both of these studies revealed that, in the absence of cytotoxicity, NO_2-FA induced novel anti-inflammatory signaling actions at very low concentrations. This data affirmed that there were effects of NO_2-FA on calcium homeostasis and cAMP/adenyl

cyclase signaling that occurred in the absence of transcriptional responses and reactions that could be attributable to ·NO/cGMP.

Michael acceptor properties – a crucial mechanism of action underlying NO$_2$-FA signaling

The cGMP-independent signaling actions of NO$_2$-FA pointed to non-canonical signaling actions being defined by the nitroalkene group of NO$_2$-FA. This functionality confers unique electrophilic character to the β-carbon of nitro-activated alkenes. *The –NO$_2$ substituent is one of the most electron-withdrawing moieties in chemistry, thus when bonded to an alkene it promotes a kinetically rapid and reversible NO$_2$-FA Michael addition with cysteine (Cys), a reaction that induces the post-translational modification (PTM) of proteins and potentially alters target protein structure and function* (59,75,76). These biochemical characteristics (*kinetically rapid and reversible*) differentiate NO$_2$-FA from most other endogenous signaling electrophiles such as cyclopentanone prostaglandins and aldehydic lipid oxidation products (e.g., 15d-PGJ$_2$ and 4-hydroxy-2-nonenal). These non-nitrated lipid electrophiles, while potentially abundant, react slowly with nucleophiles, do not readily β-eliminate and can form irreversible Schiff's base products. Unlike fatty acid cyclopentenone and lipid aldehyde derivatives, NO$_2$-FA will not accumulate as thiol addition products or promote toxicity at low concentrations. The irreversible reaction of many Michael adducts under biological conditions can be a main cause of cell toxicity (77). Current model systems, preclinical pharmacokinetics and toxicology studies and Phase 1 safety evaluation in healthy and obese individuals continue to support that NO$_2$-FA such as 10-nitro-oleic acid is safe in humans at pharmacologically-active doses. A single exception to this generalization comes from the topical application of NO$_2$-FA in a model of allergic contact dermatitis. While oral and subcutaneous NO$_2$-FA administration inhibits dermal responses to hapten-induced inflammation, the topical administration of solvated NO$_2$-FA results in a sustained neutrophil-dependent inflammation (78,79). Even though the inflammatory milieu of psoriasis in humans actually increases dermal production and levels of NO$_2$-FA, it appears that the high local epithelial concentrations that would result from dermal administration of solvated NO$_2$-FA induces pro-inflammatory responses.

NO$_2$-FA detection approaches evolved in response to new understanding of NO$_2$-FA electrophilic character and metabolism

HPLC-MS/MS was crucial for resolving and detecting fatty acids having NO$_2$ substituents. Early bioanalysis of NO$_2$-FA was occasionally complicated by acid-catalyzed nitration occurring by the formation of nitrous acid from the protonation of NO$_2^-$ to nitrous acid (HNO$_2$) during lipid extractions and de-esterification reactions, leading to further generation of NO$_2$-FA. We learned that one could control for this artifact by including ^{15}NO$_2^-$ during tissue handling and extractions, with the formation of ^{15}NO$_2$-FA indicating unwanted processing-induced nitration. Upon realizing that these species were electrophilic, new strategies were developed for "fishing out" protein-adducted NO$_2$-FA for MS-based structural and quantitative analysis. Three techniques have been particularly revealing. The first involves addition of a high concentration of β-mercaptoethanol to cell preparations and tissue homogenates to force the β-elimination of adducted NO$_2$-FA and reaction with excess β-mercaptoethanol, yielding higher molecular weight adducts that would yield a fragment ion of m/z 78. A second approach is the addition of HgCl$_2$ to biological fluid or tissue

samples. Since NO_2-FA form reversible adducts with thiols, after an "off reaction" (β-elimination of NO_2-FA from a thiol) Hg will react with the free thiol formed by NO_2-FA dissociation, resulting in the inhibition of subsequent thiol reactions. Overall, this results in a net increase in detectable "free" NO_2-FA and still-electrophilic NO_2-FA metabolites. The chemistry of this reaction has not been studied in depth and direct interactions of Hg with the NO_2-FA adduct should not be excluded. Applying this approach to healthy human urine, the Hg-induced NO_2-FA displacement strategy increases detectable "free" NO_2-FA levels by 10–20 fold (57). More recently, the clinical administration of ^{15}N-labeled nitrite and nitrate has convincingly shown that fatty acid nitration occurs in humans during digestion (Fig. 1) (80,81). This observation in turn motivated the proposal that the cardiovascular benefits of a Mediterranean-like diet, rich in both vegetable-derived NO_2^- and NO_3^- and marine or olive oil-derived unsaturated fatty acids, could be (in part) ascribed to increased NO_2-FA generation and the downstream elevation of vasoactive and anti-inflammatory lipid mediators (82).

In intracellular environments, where the concentration of low molecular weight and protein thiols can exceed 15 mM, the concentration of free NO_2-FA is expected to be below 1% of total available NO_2-FA, given the calculated equilibrium constants (83). This underscores the need to identify the specific protein targets of these bioactive electrophilic lipids. While biotin derivatives of the carboxylate of NO_2-FA were initially used, these suffer from increased bulkiness, the intrinsic problem of esterase cleavage and disruption of potential CoA ester formation, potentially impairing detection and altering intracellular distribution and pharmacokinetics. To address this, ω-terminal azido derivatives of NO_2-FA were synthesized for click chemistry-based definition of protein targets. Finally, NO_2-FA alkylation increases HPLC retention times of modified peptides, allowing for more facile target identification and providing an alternative mass spectrometry-based approach for target protein determinations (84).

NO_2-FA reaction with the cysteine proteome regulates protein expression by the electrophile-responsive genome

Affinity labeling and mass spectrometry studies have identified susceptible NO_2-FA protein targets and now focus has been placed on understanding the biochemical and cellular consequences of NO_2-FA-protein reactions. Current perspective holds that *transient post-translational modification (PTM) of hyperreactive protein thiols by NO_2-FA modulates signaling pathways involved in cell proliferation and inflammatory responses*(85). This occurs as a result of the alkylation of functionally-significant Cys residues in transcriptional regulatory proteins, including the Kelch-like ECH-associated protein-1 (Keap1) regulator of nuclear factor (erythroid-derived-2)-like 2 (Nrf2) signaling, the nuclear lipid receptor peroxisome proliferator-activated receptor γ (PPARγ), heat shock factor-1 (HSF-1) and NF-κB (48,86,87). Of relevance to the anti-inflammatory actions of NO_2-FA is the potent and multifaceted inhibition of NF-κB-mediated signaling, as demonstrated in diverse cell and murine models of cancer, metabolic syndrome, cardiopulmonary disease and both acute and chronic renal disease (87–90). Unbiased gene expression response studies in human vascular endothelial and smooth muscle cells affirm the broad and pleiotropic modulation of adaptive cell responses by NO_2-FA that would be anticipated from the PTM of key transcriptional

regulatory proteins (91,92). Functional enrichment analysis of differentially expressed genes reveals multiple cellular processes will be affected, including cell proliferation, lipid metabolism, antioxidant and inflammatory-related gene expression responses.

NO$_2$-FA esterification in complex lipids

Since the initial demonstration of increased cholesterol nitrolinoleate levels in post-prandial human plasma, further advances related to the characterization and quantitation of esterified NO$_2$-FA have been scarce (53,61). These analyses are complicated by the instability of NO$_2$-FA in most hydrolysis conditions, ion suppression by native complex lipids during direct mass spectrometric analysis and the complexity of the different molecular species expected from various esters of NO$_2$-FA in phospholipids, glycerides and sterols. Fortunately, recent advances in the detection and characterization of esterified NO$_2$-FA have been made. While phospholipid analysis has not yet been translated into *in vivo* measurements, the presence of NO$_2$-FA containing triglycerides has been reported in animal models supplemented with NO$_2$-FA (93,94). Of importance, triglycerides are an important storage depot and distribution mechanism for remote organ deposition of NO$_2$-FA. In this regard, the hydrophobic environment of membranes, lipid droplets, and lipoproteins abrogates any nitroalkene reactivity with thiols, even those present in small molecules such as β-mercaptoethanol, cysteine and glutathione. In addition to these accessibility limitations for Michael addition by esterified NO$_2$-FA, current data indicates that NO$_2$-FA also do not add to thiolates in organic solvents, supporting that acid-base chemistry for NO$_2$-FAnucleophile reactivity.

7. Conclusions

The study of interactions between ·NO-derived species and lipid peroxidation intermediates motivated the discovery of a functionally unique class of endogenous mediators (lipid nitroalkenes). The unique biochemical qualities of the electrophilic nitroalkene substituent prompted the evaluation of downstream signaling responses, the acquisition of better understanding of the pharmacokinetics and potential toxicity of orally and intravenouslyadministered NO$_2$-FA and the in vivo testing of NO$_2$-FA pharmacology in preclinical models of metabolic and inflammatory disease. Moreover, the detection of fatty acid nitroalkenes in plants and their linkage with plant stress responses expands the scope of actions of this class of mediators. These data, reinforced by the observation that NO$_2$-FA are endogenously-generated during digestion, inflammatory responses and metabolic stress, has motivated their evaluation as therapeutic agents for treating pathogenic cell proliferation, metabolic and inflammatory-related diseases in humans.

Acknowledgments

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Highlights

- The discovery of nitro-fatty acids (NO_2-FA) was motivated by new insight into the biochemistry of nitration reactions and the signaling actions of oxidized fatty acids.

- Four main areas of discovery supported the notion that NO_2-FA serve as mediators of physiological homeostasis and in pure form as pharmacologically-active agents:

  - The reversible reaction of electrophilic nitro-fatty acids with cysteine and the central role of this reaction in modulating key signaling and gene expression responses.

  - The identification of conjugated diene-containing fatty acids such as conjugated linoleic acid as main substrate for nitration.

  - The digestive and inflammatory formation of NO_2-FA in humans and rodents.

  - The protective anti-inflammatory and anti-fibrotic actions of NO_2-FA in a wide range of preclinical animal models of metabolic and inflammatory disease.
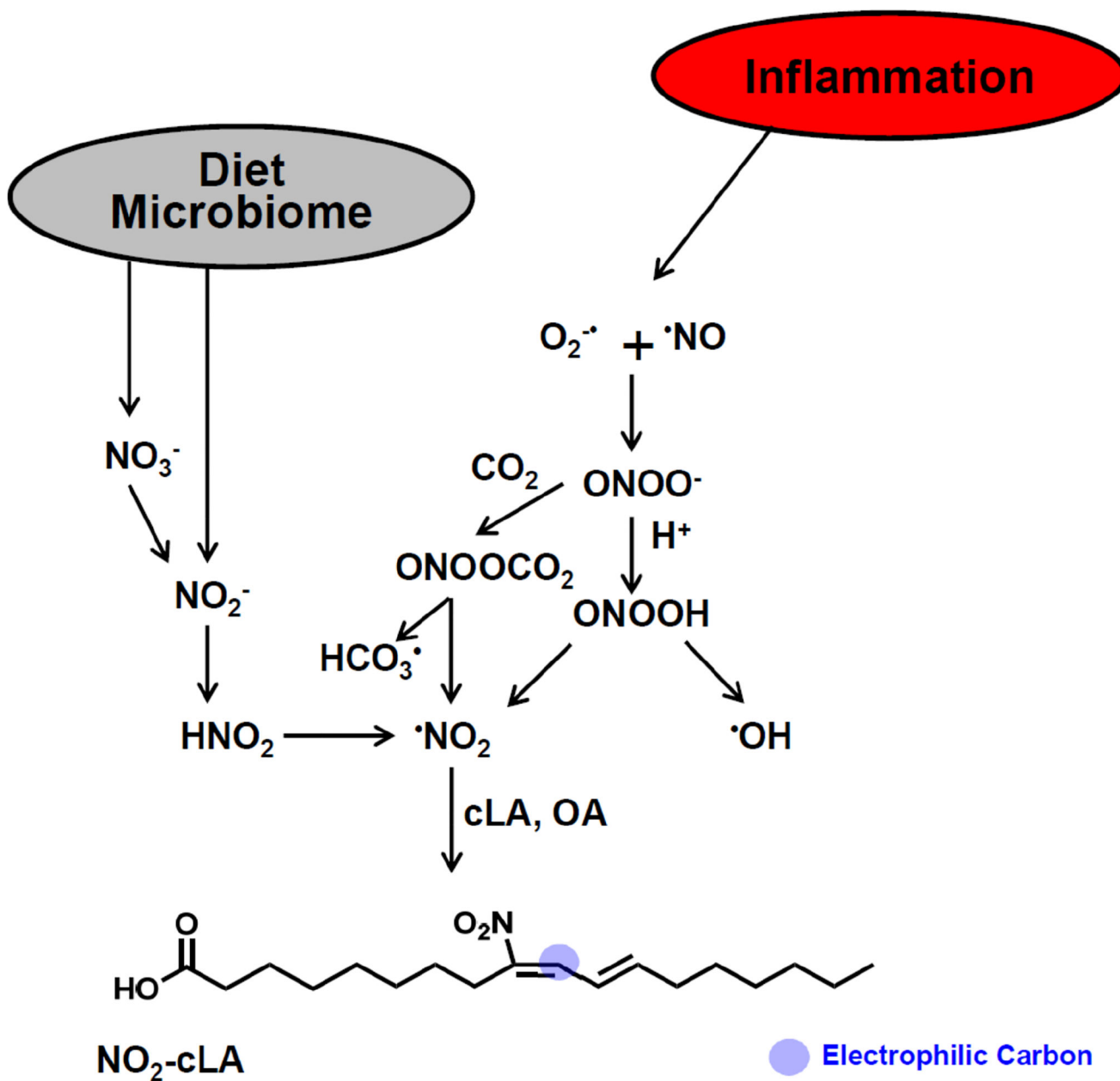
Figure 1. Fatty acid nitration is induced by nitrite and nitric oxide dependent mechanisms
The concentrations of nitrogen oxide precursors for nitrogen dioxide generation and levels of readily-nitrated unsaturated fatty acids such as conjugated linoleic acid will impact rates of formation and tissue concentrations of fatty acid nitroalkene derivatives.