

An Introduction to Reactive Oxygen Species

Measurement of ROS in Cells

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Abstract

Reactive Oxygen Species (ROS) have long been known to be a component of the killing response of immune cells to microbial invasion. Recent evidence has shown that ROS play a key role as a messenger in normal cell signal transduction and cell cycling. These reactive molecules are formed by a number of different mechanisms and can be detected by various techniques. Here we briefly describe the biology behind some of these molecules and the means for their detection.

Introduction

Reactive Oxygen Species (ROS) is a phrase used to describe a number of reactive molecules and free radicals derived from molecular oxygen. The production of oxygen based radicals is the bane to all aerobic species. These molecules, produced as byproducts during the mitochondrial electron transport of aerobic respiration or by oxidoreductase enzymes and metal catalyzed oxidation, have the potential to cause a number of deleterious events. It was originally thought that only phagocytic cells were responsible for ROS production as their part in host cell defense mechanisms. Recent work has demonstrated that ROS have a role in cell signaling, including; apoptosis; gene expression; and the activation of cell signaling cascades [1]. It should be noted that ROS can serve as both intra- and inter-cellular messengers.

Types of Reactive Oxygen Species

Most reactive oxygen species are generated as by-products during mitochondrial electron transport. In addition ROS are formed as necessary intermediates of metal catalyzed oxidation reactions. Atomic oxygen has two unpaired electrons in separate orbitals in its outer electron shell. This electron structure makes oxygen susceptible to radical formation. The sequential reduction of oxygen through the addition of electrons leads to the formation of a number of ROS including: superoxide; hydrogen peroxide; hydroxyl radical; hydroxyl ion; and nitric oxide. (Figure 1).

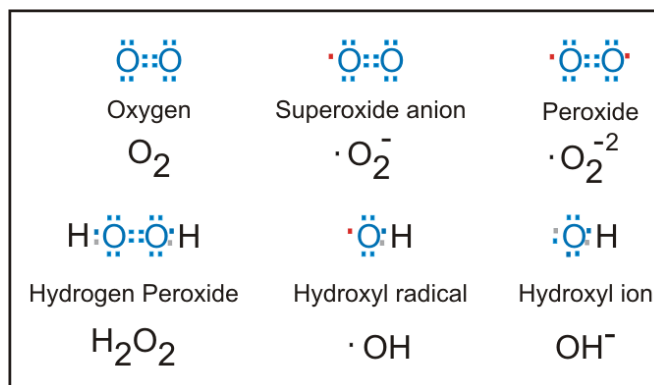
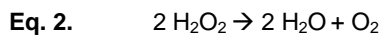
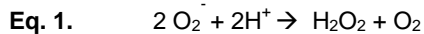


Figure 1. Electron structures of common reactive oxygen species. Each structure is provided with its name and chemical formula. The \bullet designates an unpaired electron.

Cellular Defense against ROS

Detoxification of reactive oxygen species is paramount to the survival of all aerobic life forms. As such a number of defense mechanisms have evolved to meet this need and provide a balance between production and removal of ROS. An imbalance toward the pro-oxidative state is often referred to as "Oxidative stress".

Cells have a variety of defense mechanisms to ameliorate the harmful effects of ROS. Superoxide dismutase (SOD) catalyzes the conversion of two superoxide anions into a molecule of hydrogen peroxide (H_2O_2) and oxygen (O_2) [3] (Eq. 1). In the peroxisomes of eukaryotic cells, the enzyme catalase converts H_2O_2 to water and oxygen, and thus completes the detoxification initiated by SOD (Eq. 2). Glutathione peroxidase is a group of enzymes containing selenium, which also catalyze the degradation of hydrogen peroxide, as well as organic peroxides to alcohols.



There are a number of non-enzymatic small molecule antioxidants that play a role in detoxification. Glutathione may be the most important intra-cellular defense against the deleterious effects of reactive oxygen species. This tripeptide (glutamyl-cysteinyl-glycine) provides an exposed sulphhydryl group, which serves as an abundant target for attack. Reactions with ROS molecules oxidize glutathione, but the reduced form is regenerated in a redox by an NADPH-dependent reductase. Vitamin C or ascorbic acid is a water soluble molecule capable of reducing ROS, while vitamin E (α -tocopherol) is a lipid soluble molecule that has been suggested as playing a similar role in membranes.

The ratio of the oxidized form of glutathione (GSSG) and the reduced form (GSH) is a dynamic indicator of the oxidative stress of an organism [2].

Reaction to Oxidative Stress

The effect of reactive oxygen species on cellular processes is a function of the strength and duration of exposure, as well as the context of the exposure. The typical cellular response to stress is to leave the cell cycle and enter into G_0 . With continued exposure and/or high levels of ROS, apoptosis mechanisms are triggered. In cycling cells, p21 is activated in response to stress, such as oxidants or oxidative stress and blocks cell cycle progression [4]. Likewise p27 production leads to G_1 arrest of cells. In cycling cells, p53 and p21 respond to oxidants by inducing the dephosphorylation of retinoblastoma (RB). Exposure to oxidants such as H_2O_2 or nitric oxide also results in dephosphorylation of RB that is independent of p53 or p21. In either case cells are arrested in S-phase. Expression of p27 is controlled in part by the Foxo transcription factors, which are known to control the expression of genes involved in cell cycle progression, metabolism and oxidative stress response [5]. For example, mitogenic stimulation by the PI3K/Akt pathway maintains Foxo3a in the cytoplasm, but in the absence of stimulation Foxo3a enters the nucleus and up-regulates genes for oxidant metabolism and cell cycle arrest, such as p27 [5]. Under some conditions Foxo3a can directly activate *bim* gene expression and promote apoptosis. [6]. Thus, Foxo3a promotes cell survival of cycling cells under oxidative stress by enabling a stress response, but induces cell death when conditions warrant. Noncycling cells, such as neurons, also have coping mechanisms to oxidative stress that involve Foxo3a. Foxo3a induces expression of the manganese form of SOD in response to oxidative stress [7].

Regulation of ROS production

Phagocytic Cells

The stimulated production of reactive oxygen species by phagocytic cells was originally called "the respiratory burst" due to the increased consumption of oxygen by these cells [8]. This process is catalyzed by the action of NADPH oxidase, a multicomponent membrane bound enzyme complex, and is necessary for the bactericidal action of phagocytes [8].

While several enzymes are recognized as being able to produce ROS moieties, NADPH oxidase is the most significant [9]. NADPH oxidase activity is controlled by a complex regulatory system that involves the G-protein Rac [10] (Figure 2).

In resting cells a membrane embedded heterodimer of two polypeptides (p22-*phox* and gp91-*phox*), which also contains two heme groups as well as a FAD group, enables the transfer of electrons from cytosolic NADPH across the membrane to molecular oxygen without NADPH oxidase activity [9].

It is believed that the charge compensation occurs when gp91-phox polypeptide also acts as an H⁺ ion channel. Upon stimulation, a number of polypeptides (p47-phox, p67-phox and p40phox) translocates to the inner face of the plasma membrane to form a fully active enzyme complex that possesses NADPH oxidase activity. A similar process is believed to take place in non phagocytic cells as well [11].

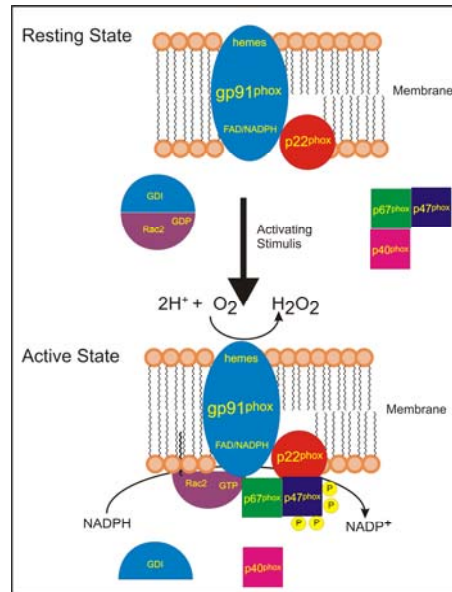


Figure 2. Schematic illustration of the activation of NADPH Oxidase.

Signal Transduction

Reactive oxygen species have a role in a number of cellular processes. High levels of ROS, which can lead to cellular damage, oxidative stress and DNA damage, can elicit either cell survival or apoptosis mechanisms depending on severity and duration of exposure. Nitric oxide (•NO) has been shown to serve as a cell-to-cell messenger, being responsible for such effects as decreasing blood pressure [12]. Intra-cellularly, ROS species, in conjunction with antioxidant enzymes, are believed to play a role in turning enzymes on and off by redox signaling in a manner akin to that of the cAMP second messenger system [12]. Examples include superoxide anion, hydrogen peroxide. The steady state level of •O₂⁻ is estimated to be so low, however that its activity is spatially limited. Hydrogen peroxide (H₂O₂) is normally unreactive with thiols in the absence of catalyzing agents (e.g. enzymes, multivalent metals etc.), it does react with thiolate anion (S⁻), to form sulfenic acid, which in turn ionizes to form sulfenate (SO⁻). This intermediate can be reversed by the action of glutathione [13].

Mitogenic signaling begins at the cell surface with the ligand-dependent activation of receptor tyrosine kinases, which activate important MAP kinase cascades necessary for proliferation. These cascades lead to the generation of H₂O₂ from several enzyme catalysts, including the NADPH oxidases [14]. It has been estimated that the production of H₂O₂ at nanomolar levels is required for proliferation in response to growth factors [15]. Hydrogen peroxide interacts with both the SOS-Ras-Raf-ERK and PI3K/Akt pathways through several mechanisms and in a dose-dependant manner (Figure 3). It has been suggested that small increases of H₂O₂, as a result of Nox1 expression result in increased reentry into the cell cycle, while sustained high levels of H₂O₂ lead to cell arrest and eventual apoptosis after prolonged arrest.

Peroxidoxins serve as important regulators of H₂O₂ and mitogenic signaling. These thiol-dependent peroxidases are activated and recruited to receptors as part of mitogenic stimulation and serve to limit the effect of ROS-associated stimulation on downstream targets of the mitogen cascade [16]. (Figure 3).

Cell Cycle Control: Redox signaling

As cells proliferate, they move through a coordinated process of cell growth, DNA duplication and mitosis referred to as the cell cycle. The cell cycle is a tightly regulated process with several checkpoints. Each one of these checkpoints is regulated by proteins and protein complexes that are influenced by the oxidative state of the cell. The relationship between the Redox state and cell cycle control is described in great detail in a review by Heintz and Burhans [5].

In multi-cellular animals most of the cells are not replicating and have withdrawn from the cell cycle either temporarily or permanently via terminal differentiation. The exit of G_0 and entry into G_1 in response to extracellular growth factors is controlled by oxidants. Redox-dependent signaling pathways promote the expression of Cyclin D1 [17], the key protein for re-entry into the cell cycle. As such, cyclin D1 expression has been reported to be a marker for successful mitogenic stimulation [15]. The key regulatory point in G_1 is the restriction point (or R point), where cells become committed to entry into S-phase. At the R point, the retinoblastoma (pRB) protein becomes phosphorylated by Cyclin D/CDK complexes. Interestingly enough studies have shown that there is a redox potential of approximately -207 mV for pRB phosphorylation, above which cells pRB is dephosphorylated and cells cease cycling [18]. It has been noted that in synchronized cells the production of ROS increases during the cell cycle, with peak levels occurring in the G_2/M phase [19]

Reactive oxygen species play a role in apoptosis. NF- κ B, which is a collective term to describe the Rel family of transcription factors, inhibits apoptosis by upregulating several antiapoptotic genes [17]. Conversely, the c-Jun N-terminal kinase (JNK) promotes apoptosis when activated for prolonged periods [20]. Prolonged activation has been shown to be caused by exposure to ROS directly as well as by inactivating JNK inhibitors such as MAP Kinase phosphatases [20]. Suppression of TNF- α -induced ROS accumulation seems to be the mechanism by which NF- κ B downregulates JNK activation.

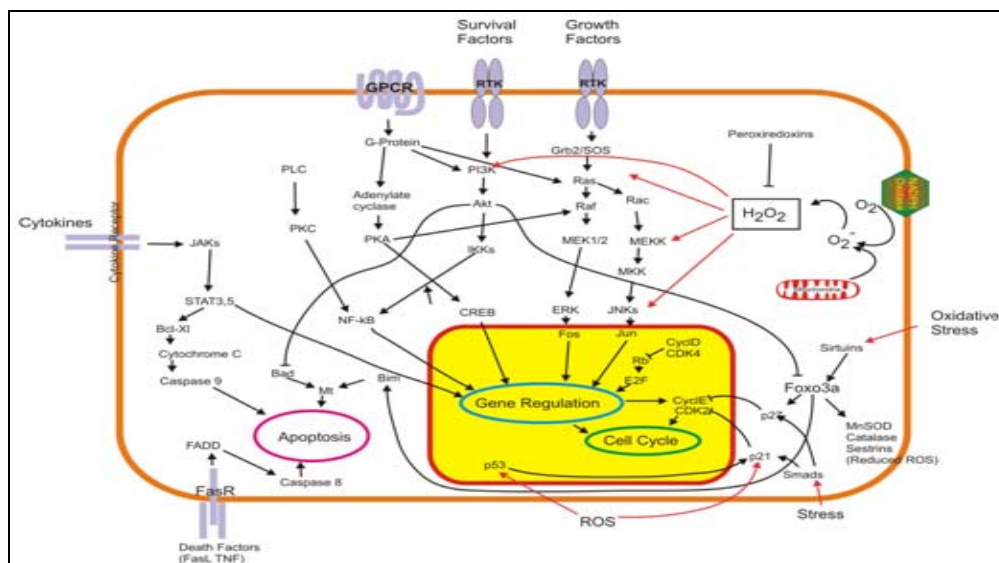


Figure 3. Schematic Illustration of Reported Interactions of ROS and Mitogenic Cascades.

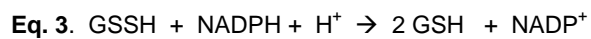
Measuring Reactive Oxygen Species

The measurement of reactive oxygen species is dependent on the analytic target along with the reactive oxygen species in question. At the cellular level, specific ROS can be individually assessed from tissue culture, while at the animal level typically the effects of oxidative stress are measured from blood product (e.g. serum or plasma) or from urine samples.

Oxidative stress

Glutathione is the most significant non enzymatic oxidant defense mechanism. It exists in relatively large amounts (mM levels) and serves to detoxify peroxides and regenerate a number of important antioxidants (e.g. α -tocopherol and ascorbic acid) [21].

Reduced glutathione (GSH) is regenerated from its oxidized form (GSSH) by the action of an NADPH dependent reductase (Eq. 3).



Due to the rapid nature of the reduction of GSSH relative to its synthesis or secretion, the ratio of GSH to GSSH is a good indicator of oxidative stress within cells. GSH and GSSH levels can be determined by HPLC [22], capillary electrophoresis [23], or biochemically in microplates [24].

Several different assays have been designed to measure glutathione in samples. By using a luciferin derivative in conjunction with glutathione S-transferase enzyme the amount of GSH would be proportional to the luminescent signal generated when luciferase is added in a subsequent step [25]. Total glutathione can be determined colorimetrically by reacting GSH with DTNB (Ellman's reagent) in the presence of glutathione reductase. Glutathione reductase reduces GSSH to GSH, which then reacts with DTNB to produce a yellow colored 5-thio-2-nitrobenzoic acid (TNB), which absorbs at 412 nm.

Lipid peroxidation is one of the most widely used indicators of free radical formation, a key indicator of oxidative stress. Unsaturated fatty acids such as those present in cellular membranes are a common target for free radicals. Reactions typically occur as a chain reaction where a free radical will capture a hydrogen moiety from an unsaturated carbon to form water. This leaves an unpaired electron on the fatty acid that is then capable of capturing oxygen, forming a peroxy radical (Figure 4). Lipid peroxides are unstable and decompose to form a complex series of compounds, which include reactive carbonyl compounds, such as malondialdehyde (MDA).

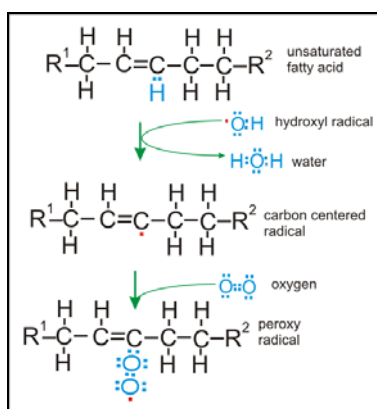


Figure 4. Illustration of lipid peroxidation

Measurement of lipid peroxidation has historically relied on the detection of thiobarbituric acid (TBA) reactive compounds such as malondialdehyde generated from the decomposition of lipid peroxidation products [25]. While this method is controversial in that it is quite sensitive, but not necessarily specific to MDA, it remains the most widely used means to determine lipid peroxidation. This reaction, which takes place under acidic conditions at 90-100°C, results in an adduct that can be measured colorimetrically at 532 nm or by fluorescence using a 530 nm excitation wavelength and a 550 nm emission wavelength [26] (Figure 5). A number of commercial assay kits are available for this assay using absorbance or fluorescence detection technologies.

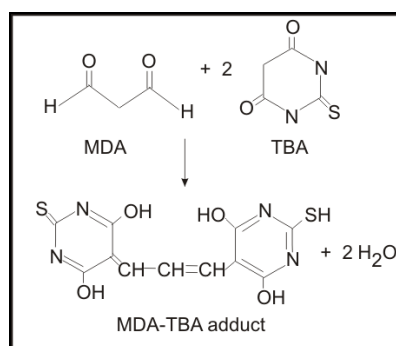


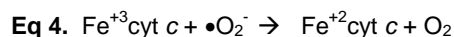
Figure 5. MDA-TBA adduct formation

The formation of F₂-like prostanoid derivatives of arachidonic acid, termed F₂-isoprostanes (IsoP) has been shown to be specific for lipid peroxidation [27]. Unlike the TBA assay, measurement of IsoP appears to be specific to lipid peroxides, they are stable and are not produced by any enzymatic pathway making interpretation easier.

There have been a number of commercial ELISA kits developed for IsoPs, but interfering agents in samples requires partial purification of samples prior to running the assay. The only reliable means for detection is through the use of GC/MS, which makes it expensive and limits throughput [28].

Superoxide

Superoxide detection is based on the interaction of superoxide with some other compound to create a measurable result. The reduction of ferricytochrome c to ferrocyanochrome c has been used in a number of situations to assess the rate of superoxide formation [29]. (Eq 4)



While not completely specific for superoxide this reaction can be monitored colorimetrically at 550 nm. The addition of enzyme inhibitors such as CN⁻ or scavengers of reactive species such as catalase can minimize any reoxidation.

Aconitase catalyzes the conversion of citrate to isocitrate. Superoxide inactivates this enzyme by oxidizing the Fe (II) moiety from its cubane {4Fe-4S} cluster. Thus superoxide concentrations can be estimated by the degree of enzyme inactivation. The activity of the enzyme can be monitored by following the conversion of 20 mM isocitrate to cis-aconitate using absorbance at 240 nm. A coupled assay where the aconitase product, isocitrate is then converted to α -ketoglutarate by NADP⁺ dependent isocitrate dehydrogenase can also be used. In this reaction the production of NADPH can be monitored colorimetrically at 340 nm [21].

Chemiluminescent reactions have been used for their potential increase in sensitivity over absorbance-based detection methods. The most widely used chemiluminescent substrate is Lucigenin, but this compound has a propensity for redox cycling, which has raised doubts about its use in determining quantitative rates of superoxide production [30]. The use of low concentrations of this compound has been suggested as a means to minimize this problem. Coelenterazine has also been used as a chemiluminescent substrate. This lipophilic compound does not redox cycle and is brighter than Lucigenin. It is not however completely specific towards superoxide, as the presence of peroxynitrite will result in chemiluminescence [31].

Hydrocyanine dyes are fluorogenic sensors for superoxide and hydroxyl radical. These dyes are synthesized by reducing the iminium cation of the cyanine (Cy) dyes with sodium borohydride. While weakly fluorescent, upon oxidation their fluorescence intensity increases 100 fold. In addition to being fluorescent, oxidation also converts the molecule from being membrane permeable to an ionic impermeable moiety [32]. The most characterized of these probes are Hydro-Cy3 and Hydro-Cy5.

Hydrogen Peroxide

Hydrogen peroxide (H₂O₂) is the most important ROS in regards to mitogenic stimulation or cell cycle regulation. There are a number of fluorogenic substrates, which serve as hydrogen donors that have been used in conjunction with horseradish peroxidase (HRP) enzyme to produce intensely fluorescent products [21]. While the list is quite extensive, the more commonly used substrates include diacetyldichloro-fluorescein [33], homovanillic acid [34], and Amplex[®] Red [35]. In these examples, increasing amounts of H₂O₂ form increasing amounts of fluorescent product. For example, Amplex Red is oxidized by hydrogen peroxide in the presence of HRP and in doing so converted to resorufin [35]. Unlike Amplex Red, resorufin is a highly colored compound that can be detected colorimetrically at 570 nm or by fluorescence using excitation of 570 nm and emission of 585 nm [36].

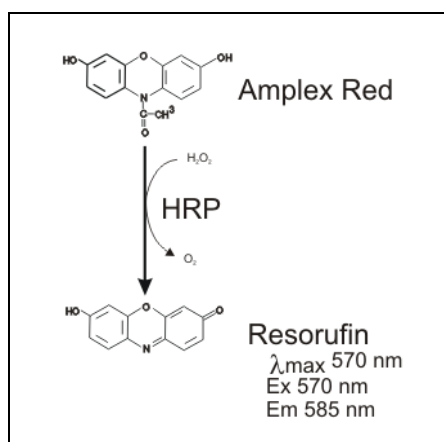


Figure 6. Conversion of Amplex Red to resorufin by HRP using H₂O₂.

Homovanillic acid dimerizes when oxidized by hydrogen peroxide through horseradish peroxidase catalysis. As with Amplex red, homovanillic acid monomer is non-fluorescent, but as a dimer, it possesses a peak excitation wavelength of 315 nm, with an emission wavelength of 425 nm (Figure 7). Care should be taken when using this compound to assess hydrogen peroxide production. The near UV nature of the excitation and emission wavelengths for fluorescence measurements make this compound prone to inordinate background signal, particularly when polystyrene microplates are used. Several peroxidase-like metalloporphyrins have been shown to be catalytic for the reaction in addition to HRP [37].

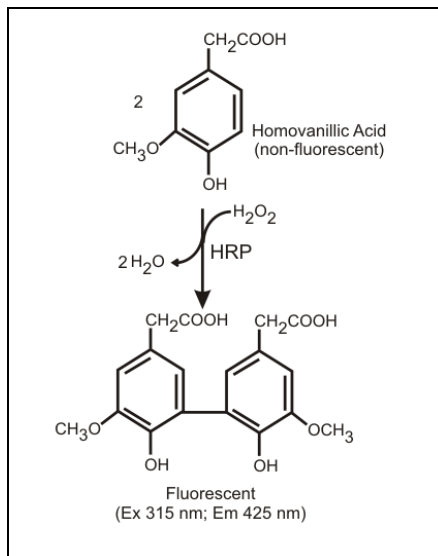


Figure 7. Dimerization of homovanillic acid by the action of HRP and hydrogen peroxide.

A number of colorimetric substrates such as tetramethylbenzidine (TMB) and phenol red have also been used in conjunction with HRP to measure hydrogen peroxide concentrations. In general colorimetric means are less sensitive than fluorescent detection methods, but instrumentation costs are significantly lower than those required for fluorescence based measurements when using tube based or microplate based detection methodologies.

There are a number of issues that one should be aware of when using HRP catalyzed substrates to quantitate hydrogen peroxide. Cellular compounds such as thiols can serve as a substrate for HRP. Endogenous catalase activity can artificially reduce the amount of H₂O₂ present. Cellular components can affect the fluorescent signal depending on the excitation and emission wavelengths, as with homovanillic dimer, while other wavelengths may suffer from signal quenching.

Tarpley *et al.* summarized the utility of HRP-linked assays quite succinctly by stating that the method(s) are quite useful for the quantification of H₂O₂ levels "... cultured cells, organ cultures and isolated buffer perfused tissue preparations. However these methods are not suitable for determinations of H₂O₂ in plasma, or serum because many reducing agents are present in extracellular fluid..."[21].

The oxidation of 2'-7' dichlorofluorescein (H₂DCF) to 2'-7' dichlorofluorescein (DCF) has been used quite extensively for the quantitation of H₂O₂. The diacetate form, H₂DCFDA and its acetomethyl ester H₂DCFDA-AM are taken up by cells where non specific cellular esterases act upon it to cleave off the lipophilic groups, resulting in a charged compound believed to be trapped inside the cell. Oxidation of H₂DCF by ROS converts the molecule to 2', 7' dichlorodihydrofluorescein (DCF), which is highly fluorescent (Figure 8). The reported wavelengths for the measurement of DCF fluorescence are 498 nm for excitation and 522 nm for emission.

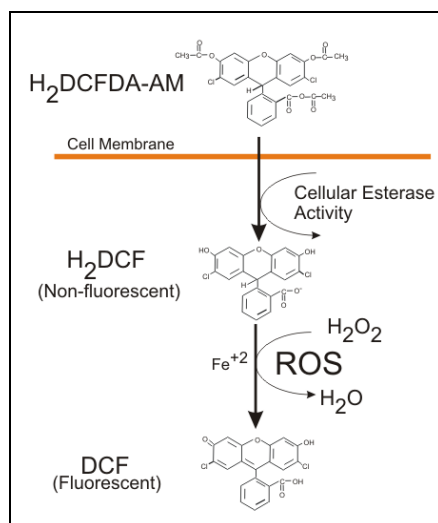


Figure 8 . Formation of fluorescent Compound DCF by ROS.

Originally, DCF was thought to be specific for hydrogen peroxide, but recent evidence has shown that other ROS such as nitrate and hypochlorous acid can oxidize H_2DCF [18]. Most importantly is the fact that H_2O_2 -dependent oxidation of H_2DCF requires ferrous iron [38]. In addition, as H_2DCF is no longer ionic it is not precluded from migrating out of the cell and accumulating in the media, where it is free to interact with oxidants.

In order to address the weaknesses of DCF fluorescence several new fluorescent probes have been developed. Two such probes are Peroxy Green 1 (PG1) and Peroxy Crimson 1 (PC1). These boronate-based H_2O_2 probes have been reported to have high selectivity, membrane permeability, along with visible-wavelength excitation and emission wavelengths [38]. Reacting with hydrogen peroxide, results in a 10-fold and 40-fold increase in fluorescence for PG1 and PC1, respectively. PG1 features an excitation wavelength of 460 nm with emission maxima at 510 nm (Figure 9). PC1 demonstrates improved characteristics of red-shifted excitation and larger Stokes shift which reduces auto-fluorescence (excitation: 480 nm; emission: 584 nm) [39].

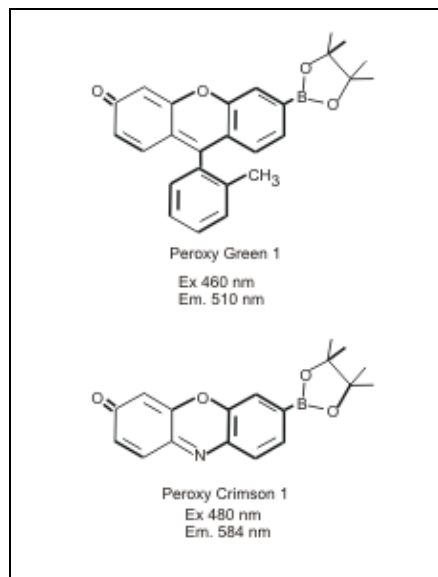


Figure 9. Structure of Peroxy Green 1 and Peroxy Crimson 1.

These molecules exhibit a direct reaction with hydrogen peroxide not observed with H_2DCF . In addition these molecules are unreactive towards high-valent metal-oxo species derived from heme-proteins and H_2O_2 . DCFH normally exhibits a greater response to this combination than it does towards H_2O_2 .

Calcein-acetoxymethylester (Calcein-AM) has also been reported as a detector to intracellular oxidative activity [40]. Calcein-AM is a fluorogenic cell permeable compound that is converted by intracellular esterases into the cell impermeant anion calcein, which is fluorescent. Historically intracellular calcein production has been used in both microscopy and fluorometry as an indicator of viable cells. In regards to the detection of ROS, the kinetics of ROS reaction are favorable relative to esterase conversion to calcein.

The ROS-oxidized product of Calcein AM has been shown to be chemically distinct from Calcein-AM through this larger chromatography [40], but it still retains the ability to cross cell membranes and has similar spectral properties to the fluorescent calcein. Thus it is important to keep the compound in the media rather than washing it away after cell loading, which is typically performed when using the compound for cell viability. Removal of the dye results in movement of the reacted compound back out of the cell on a concentration gradient. The physical properties of Calcein AM are also different from either Calcein-AM or Calcein as the dye tends to aggregate and form intensely fluorescent localizations within the cell. While this dye has possibilities with confocal microscopy where cellular localization is possible, the inability to distinguish spectrally between ROS reacted calcein-AM and the esterase reacted product makes the use of this dye in microplates problematic.

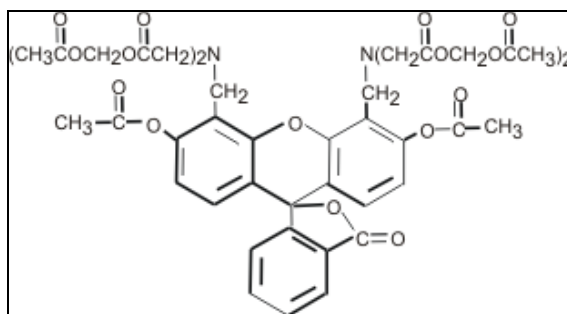


Figure 10. Calcein-AM structure.

Nitric Oxide

The free radical nitric oxide ($\bullet\text{NO}$) is produced by a number of different cell types with a variety of biological functions. Nitric oxide is a product of the oxidation of L-arginine to L-citrulline in a two step process catalyzed by the enzyme nitric oxide synthase (NOS). Two major isoforms of nitric oxide synthase have been identified. The constitutive isoform found in neurons and endothelial cells, produces very low amounts of nitric oxide in a calcium- and calmodulin-dependent fashion. $\bullet\text{NO}$ activates soluble guanylate cyclase in target cells, resulting in increased levels of cGMP, which in turn facilitates neuronal transmission and vascular relaxation, and inhibits platelet aggregation [41].

The inducible isoform, found in macrophages, fibroblasts, and hepatocytes, produces $\bullet\text{NO}$ in relatively large amounts in response to inflammatory or mitogenic stimuli and acts in a host defensive role through its oxidative toxicity [42]. Regardless of the source or role, the free radical $\bullet\text{NO}$ has a very short half life ($t_{1/2} = 4$ seconds), reacting with several different molecules normally present to form either nitrate (NO_3^-) or nitrite (NO_2^-)

A commonly used method for the indirect determination of $\bullet\text{NO}$ is the determination of its composition products nitrate and nitrite colorimetrically. This reaction requires that nitrate (NO_3^-) first be reduced to nitrite (NO_2^-), typically by the action of nitrate reductase (Figure 11).

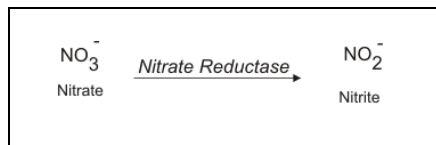


Figure 11. Conversion of Nitrate to nitrite by the action of Nitrate Reductase.

Subsequent determination of nitrite by a two step process (Figure 12) provides information on the “total” of nitrate and nitrite. In the presence of hydrogen ions nitrite forms nitrous acid, which reacts with sulfanilamide to produce a diazonium ion. This then coupled to N-(1-naphthyl) ethylenediamine to form the chromophore which absorbs at 543 nm.[43].

Nitrite only determinations can then be made in a parallel assay where the samples were not reduced prior to the colorimetric assay. Actual nitrate levels are then calculated by the subtraction of nitrite levels from the total. This assay is relatively inexpensive and easy to perform. The reagents are easily obtained and there are numerous commercial kits available for this assay.

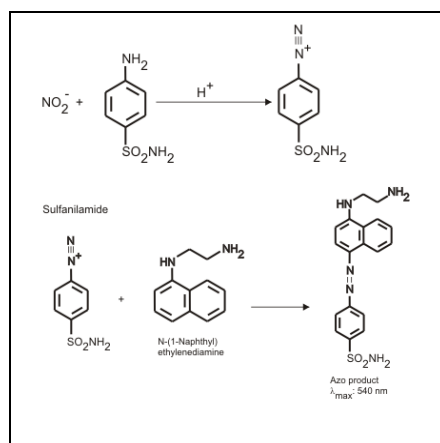


Figure 12. Griess reaction for the determination of nitrate.

In order to improve upon the sensitivity of the Griess reagent assay for $\bullet\text{NO}$ a number of fluorometric assays have been developed. Like the Griess reaction they are dependent on dinitrogen trioxide or nitrous acid (N_2O_3), which is formed spontaneously by the acidification of nitrite (NO_2^-). The most commonly used method employs 2, 3-diaminonaphthalene (DAN), which is relatively nonfluorescent, to react with nitrous acid to form 2, 3 naphthotriazole (NAT), which is highly fluorescent with an excitation wavelength of 375 nm and an emission wavelength of 415 nm (Figure 13).

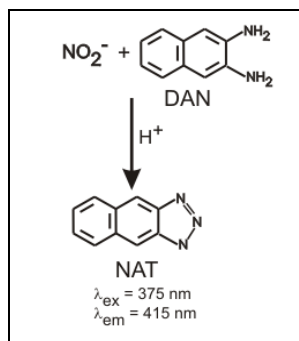


Figure 13. Fluorometric detection of nitrite using 2, 3-diaminonaphthalene (DAN).

Discussion

The interest in reactive oxygen species originally revolved around the pathology associated with the deleterious effects of aerobic respiration: the necessary evil caused by the leakage from the electron transport chain in mitochondria. In this context, research involved the role that these agents played in aging, chronic diseases and cancer.

A new frontier was born with the discovery that the “oxidative burst” by phagocytic cells was actually the result of the intentional production of reactive oxygen species. This was thought to be a very specific application where specific cells produced what can only be described as toxic agents in order to kill invading microorganisms. Further recent work has shown that ROS are produced in all cell types and serve as important cellular messengers for both intra- and inter-cellular communications. It is now apparent that a very complex intra-cellular regulatory system involving ROS exists within cells. Cells respond to ROS moieties in different ways depending on the intensity, duration and context of the signaling. In regards to intracellular signaling it appears that hydrogen peroxide (H_2O_2) is the most interesting candidate, while nitric oxide ($\bullet\text{NO}$) is involved primarily with intercellular signaling.

The chemistry used initially for the detection of ROS was primarily absorbance measurement based. Research generally involved the measurement of glutathione levels to assess oxidative stress at the tissue or whole body level. With millimolar levels of analyte absorbance based measurements where more than adequate to be informative and quantitative. With the discovery that ROS are used as intracellular messengers and regulators, new chemistries were developed with the micromolar detection requirements in mind. These agents are primarily fluorescence based, but recently luminescent based detections have been introduced.

The biggest difficulty reported with much of the cellular ROS research has been with the lack of reporter agents specific for discrete molecules. ROS moieties by their nature are reactive with a number of different molecules; as such designing reporter agents has been difficult. With more specific chemistries, particularly for hydrogen peroxide, the specific mechanisms for regulation will be elucidated.

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