Overdoses of the analgesic and antipyretic acetaminophen represent one of the most common pharmaceutical product poisonings in the United States today (Litovitz et al., 2002). Although considered safe at therapeutic doses, in overdose, acetaminophen produces a centrilobular hepatic necrosis that can be fatal (Prescott, 1980). Whereas the initial biochemical and metabolic events that occur in the early stages of toxicity have been well described, the precise mechanisms of hepatocyte death are poorly understood. Necrosis is recognized as the mode of cell death and apoptosis has been ruled out (Lawson et al., 1999; Gujral et al., 2002).

Several recent excellent reviews on acetaminophen toxicity have been recently published (Bessem and Vermeulen, 2001; Nelson et al., 2002). The following manuscript will review the role of covalent binding in toxicity as well as other factors recently identified that contribute to the toxicity. These factors include oxidative stress, nitrotyrosine formation, inflammatory cytokines, and the possible importance of mitochondrial permeability transition.

**Metabolic Activation of Acetaminophen**

Work from Dr. Gillette’s laboratory firmly established the importance of metabolism in acetaminophen toxicity. It was shown that acetaminophen is metabolically activated by cytochrome P450 to form a reactive metabolite that covalently binds to protein (Mitchell et al., 1973). The reactive metabolite was found to be N-acetyl-p-benzoquinone imine (NAPQI1), which is formed by a direct two-electron oxidation (Dahlin et al., 1984). More recently, the cytochromes 2E1, 1A2, 3A4, and 2A6 (Patten et al., 1993; Thummel et al., 1993; Chen et al., 1998) have been reported to oxidize acetaminophen to the reactive metabolite. Also, Dr. Gillette’s laboratory showed that NAPQI is detoxified by glutathione (GSH) to form an acetaminophen-GSH conjugate. After a toxic dose of acetaminophen, total hepatic GSH is depleted by as much as 90%, and as a result, the metabolite...
covalently binds to cysteine groups on protein, forming acetaminophen-protein adducts (Mitchell et al., 1973). This mechanism is shown in Fig. 1.

To better understand the role of specific adducts in acetaminophen toxicity, our laboratory and Cohen’s laboratory (Bartolone et al., 1988, 1989; Cohen and Khairallah, 1997) developed immunochemical assays that were very specific for acetaminophen covalently bound to cysteine groups on protein (Roberts et al., 1991). Using this antiserum, we reported the relationship between acetaminophen covalent binding and toxicity in mice in a competitive ELISA to quantify the adducts (Pumford et al., 1989, 1990a,b). Western blot assays were used to determine the molecular nature of the acetaminophen-protein adducts (Bartolone et al., 1988; Pumford et al., 1990a,b) and immunohistochemical analyses were used to determine the specific cells that contained the adducts (Bartolone et al., 1989; Roberts et al., 1991). These studies have been reviewed (Hinson et al., 1995; Pumford et al., 1997; Cohen and Khairallah, 1997).

Western blot assays for acetaminophen protein adducts have also been used to study toxicity in human overdose patients. In these studies, adducts have been detected in the blood of human overdose patients with severe toxicity (hepatic transaminases above 5000 IU/l) (James et al., 2001). Using high performance liquid chromatography with electrochemical detection, we recently reported the presence of adducts in the blood samples of overdose patients with mild to moderate toxicity, suggesting that the newer method may be a more sensitive analytical tool than Western blot for the detection of adducts in human sera (Mulford et al., 2002). This assay may assist in the diagnosis of patients with acute liver failure of indeterminate etiology for which acetaminophen is suspect.

**Biochemical Mechanisms of Toxicity**

Events that produce hepatocellular death following the formation of acetaminophen protein adducts are poorly understood. One possible mechanism of cell death is that covalent binding to critical cellular proteins results in subsequent loss of activity or function and eventual cell death and lysis. Primary cellular targets have been postulated to be mitochondrial proteins, with resulting loss of energy production, as well as proteins involved in cellular ion control (Nelson, 1990). Tirmenstein and Nelson (1989) and Tsokos-Kuhn et al. (1988) reported alterations of plasma membrane ATPase activity following toxic doses of acetaminophen.

A number of proteins bound to acetaminophen have been isolated and identified. A review of the individual proteins that were isolated and identified by individual analysis has been published (Cohen and Khairallah, 1997; Pumford et al., 1997). Subsequently, Qui et al. (1998) used matrix-assisted laser desorption ionization mass spectrometry to identify 20 additional proteins containing covalently bound acetaminophen. Table 1 shows the proteins that have been identified to form adducts with acetaminophen. The proteins identified by our laboratory (Pumford et al., 1997) included a 100-kDa cytosolic protein determined by sequence analysis to be the enzyme, N-10-formyltetrahydrofolate dehydrogenase. This enzyme is involved in 1-carbon metabolism and oxidizes formaldehyde to carbon dioxide. Studies in mice reported that the activity of this enzyme was decreased by 20% at 2 h after toxic doses of acetaminophen (Pumford et al., 1997). A second protein, a 50-kDa mitochondrial protein, was isolated and determined to be glutamate dehydrogenase (Halmes et al., 1996). This enzyme is involved in 1-carbon metabolism and oxidizes formaldehyde to carbon dioxide. Studies in mice reported that the activity of this enzyme was decreased by 20% at 2 h after toxic doses of acetaminophen. A second protein, a 50-kDa mitochondrial protein, was isolated and determined to be glutamate dehydrogenase (Halmes et al., 1996). This enzyme reversibly metabolizes glutamate to α-keto-glutarate and ammonia. The activity of this enzyme was also decreased approximately 25% at 2 h. Based on the enzyme inhibition data for these two enzymes, it appeared that covalent binding with acetaminophen resulted in only partial inhibition of enzyme activities under toxic conditions in mice. Although it is plausible that partial inhibition of a large number of enzymes may contribute to cell death, the data generated questions relative to the validity of the hypothesis that covalent binding to critical proteins is the only mechanism of acetaminophen toxicity.

Loss of mitochondrial or nuclear ion balance has also been suggested to be a toxic mechanism involved in acetaminophen-mediated cell death since either of these losses can lead to increases in cytosolic...
Ca\(^{2+}\) concentrations, mitochondrial Ca\(^{2+}\) cycling, activation of proteases and endonucleases, and DNA strand breaks (Nelson, 1990; Ray et al., 1993; Salas and Corcoran, 1997). The effect of the addition of NAPQI on isolated mitochondria has been reported (Weis et al., 1992) and inhibition of mitochondrial respiration has been investigated as an important mechanism in acetaminophen toxicity (Donnelly et al., 1994).

### Early Research on Oxidative Stress

Oxidative stress is another mechanism that has been postulated to be important in the development of acetaminophen toxicity. Thus, increased formation of superoxide would lead to hydrogen peroxide and peroxidation reactions by Fenton-type mechanisms. It has been shown that NAPQI reacts very rapidly with GSH (\(k_1 = 3.2 \times 10^4\) M\(^{-1}\) s\(^{-1}\) at pH 7.0) (Coles et al., 1988), and there are a number of potential mechanisms that have been suggested to play a role. Under conditions of NAPQI formation following toxic acetaminophen doses, GSH concentrations may be very low in the centrilobular cells, and the major peroxide detoxification enzyme, GSH peroxidase, which functions very inefficiently under conditions of GSH depletion (Nakamura et al., 1974), is expected to be inhibited. In addition, during formation of NAPQI by cytochrome P450, the superoxide anion is formed, with dismutation leading to hydrogen peroxide formation (Dai and Cederbaum, 1995). Also, others have suggested that peroxidation of acetaminophen to the semiquinone free radical would lead to redox cycling between the acetaminophen and the semiquinone. This mechanism may lead to increased superoxide and toxicity (de Vries, 1981). However, we found that the semiquinone reacted rapidly to form polymers and no evidence for reaction of oxygen was observed (Potter et al., 1989).

A significant amount of evidence has pointed to the potential involvement of oxidative stress in acetaminophen toxicity. Nakae et al. (1990) reported that administration of encapsulated superoxide dismutase decreased the toxicity of acetaminophen in the rat. Moreover, the iron chelator, deferoxamine, has been shown to decrease toxicity in rats (Sakaida et al., 1995). Our laboratory showed that deferoxamine caused a delay in the rate of development of acetaminophen toxicity in mice, but after 24 h, the relative amount of toxicity was not affected (Schnellmann et al., 1999). These data suggest that an iron-catalyzed Haber-Weiss reaction may also play a role in the development of oxidant stress and injury.

### Role of Kupffer Cells

Several laboratories have studied the role of macrophage activation (Laskin et al., 1995) in acetaminophen toxicity. Kupffer cells are the phagocytic macrophages of the liver. When activated, Kupffer cells release numerous signaling molecules, including hydrolytic enzymes, eicosanoids, nitric oxide, and superoxide. Kupffer cells may also release a number of inflammatory cytokines, including IL-1, IL-6, and TNF-α (Laskin et al., 1995), and multiple cytokines are released in acetaminophen toxicity (Blazka et al., 1995; Hogaboam et al., 1999a, 2000; Bourdi et al., 2002a,b). Laskin et al. (1995) examined the role of Kupffer cells in acetaminophen hepatotoxicity by pretreating rats with compounds that suppress Kupffer cell function (gadolinium...
chloride and dextran sulfate). These investigators reported that rats pretreated with these compounds were less sensitive to the toxic effects of acetaminophen. Similar effects were reported in the mouse (Blazka et al., 1995). Goldin et al. (1996) showed that treatment of mice with liposomes containing dichloromethylene disphosphonate to knock out the Kupffer cells also decreased acetaminophen toxicity. Similarly, we reported that pretreatment of mice with gadolinium chloride or dextran sulfate decreased the toxic effects of acetaminophen (Michael et al., 1999). These studies suggested a critical role for Kupffer cells in the development of acetaminophen hepatotoxicity; however, recent work by Ju et al. (2002) came to a different conclusion. They pretreated mice with gadolinium chloride and found that the number of Kupffer cells in the liver was only partially decreased. Consistent with previous reports, they showed decreased acetaminophen toxicity in the pretreated mice. However, treatment of mice with dichloromethylene diphosphonate completely depleted the liver of Kupffer cells, but toxicity was increased. These data raise questions relative to the importance of Kupffer cells in acetaminophen toxicity.

Nitrotyrosine and Acetaminophen Toxicity

We recently showed that nitrotyrosine occurs in the centrlobular cells of the liver of acetaminophen-treated mice (Hinson et al., 1998). Immunohistochemical analysis of liver of acetaminophen-treated mice indicated that nitrification occurred in the same cells that contained acetaminophen adducts and developed necrosis (Fig. 2) (Hinson et al., 1998). We postulated that nitrotyrosine was formed by a reaction of peroxynitrite with tyrosine. Nitration of tyrosine has been shown to be an excellent biomarker of peroxynitrite formation (Kaur and Halliwell, 1994). It is formed by a rapid reaction between nitric oxide and superoxide, and we found that NO synthesis (serum levels of nitrate plus nitrite) was increased in acetaminophen toxicity (Hinson et al., 1998). Also, others reported the induction of hepatic iNOS in the acetaminophen-treated rat (Gardner et al., 1998). NO and superoxide react to produce peroxynitrite (ONOO⁻) at a rate near the diffusion-controlled limit (7 × 10⁹ M⁻¹ s⁻¹). Peroxynitrite is a species that not only leads to the nitration of tyrosine but is also a potent oxidant that can attack a wide range of biological targets (Pryor and Squadrito, 1995), and under conditions of reduced cellular oxidant scavenging capability, peroxynitrite is highly toxic (Beckman and Koppenol, 1996). The anion is relatively stable, but the acid rearranges to nitrate with a half-life of 1.9 s at pH 7.4; the pK is 7.5 (Beckman and Koppenol, 1996). Oxidation reactions can involve one or two-electron processes. Oxidation of lipids (Rubbo, 1998), proteins, or DNA bases (Pryor and Squadrito, 1995) has been reported. Thus, peroxynitrite is an excellent candidate for a toxic species. Moreover, it is normally detoxified by GSH/GSH peroxidase, and GSH is depleted in acetaminophen toxicity (Radi et al., 1991). GSH peroxidase is a key enzyme in this defense mechanism (Sies et al., 1997). Thus, a normal detoxification mechanism for peroxynitrite is impaired. Also, even though acetaminophen itself will detoxify peroxynitrite (Whiteman et
Nitrite may be oxidized by heme or free metals, leading to the NO$_2^-$ radical (Lawson et al., 2000). Also, nitrite may be oxidized by heme or free metals, leading to the NO$_2^-$ radical (Thomas et al., 2002). Studies in IL-10 knockout mice suggest that the major murine enzyme important in tyrosine nitration was iNOS. Interestingly, these experiments showed that acetaminophen caused a 3-fold increase in lipid peroxidation (oxidative stress) in the iNOS knockout mice but no increase in the wild-type mice. Thus, in the wild-type mice, toxicity was accompanied by tyrosine nitration, whereas in the iNOS knockout mice, toxicity was accompanied by oxidative stress. In a subsequent study (Hinson et al., 2002), we determined the effect of NOS inhibitors on acetaminophen toxicity in mice. The iNOS inhibitor aminoguanidine did not significantly alter acetaminophen toxicity, but it greatly decreased tyrosine nitration and increased lipid peroxidation. Thus, the iNOS inhibitor gave information similar to that obtained in the iNOS knockout mice. These data were interpreted to indicate that excess levels of superoxide were formed in acetaminophen toxicity. When NO is present, as in the wild-type mice, the superoxide preferentially reacts to form peroxynitrite, which nitrates proteins. In the absence of NO, superoxide leads to lipid peroxidation (Fig. 3). These data indicate the importance of NO in the disposition of superoxide, leading to oxidative stress.

Cytokines and Other Inflammatory Mediators in Acetaminophen Toxicity

Several laboratories have reported that inflammatory cytokines are increased in acetaminophen toxicity. Blazka reported the up-regulation of TNF-$\alpha$ and IL-1$\beta$ in the acetaminophen-treated mouse (Blazka et al., 1995, 1996). In addition, he showed that selective immunoneutralization of either TNF-$\alpha$ or IL-1$\beta$ partially decreased toxicity for a period of time. In vitro studies by Kuo showed that IL-1$\beta$ caused a dose-dependent up-regulation of NO in rat hepatocytes exposed to acetaminophen (Kuo et al., 1997). Consistent with these data, we recently found that IL-1$\beta$ and NO up-regulation in the acetaminophen-treated mouse are temporally related (James et al., 2003b). Although others have confirmed the up-regulation of TNF-$\alpha$ in acetaminophen toxicity (Simpson et al., 2000), its role in the mediation of toxicity is somewhat controversial. TNF-$\alpha$ knockout mice were not protected from toxicity (Boess et al., 1998), and a recent report showed that immunoneutralization of TNF-$\alpha$ had no effect on toxicity (Simpson et al., 2000). Studies in IL-10 knockout mice suggest that IL-10 is protective in APAP toxicity by controlling NO and iNOS formation (Bourdi et al., 2002a). In addition, the increased susceptibility of IL-10 knockout mice to acetaminophen was associated with increased levels of TNF-$\alpha$ and IFN-$\gamma$. Thus, it may be that proinflammatory cytokines contribute to the toxicity, and that they are regulated by anti-inflammatory cytokines, such as IL-10 and others.

Macrophage migration inhibitory factor (MIF) is a recently described protein that has characteristics of a cytokine, a hormone, and an enzyme. It may promote the up-regulation of other pro-inflammatory cytokines, adhesion molecules, matrix metalloproteinase-2 expression, NO release, and cyclooxygenase-2 and has counter-regulatory effects on endogenous glucocorticoids (Baugh and Bucala, 2002). Pohl and colleagues reported that MIF was up-regulated in acetaminophen toxicity (Bourdi et al., 2002b). Moreover, MIF knockout mice were less susceptible to acetaminophen and had decreased IFN-$\gamma$ production and increased heat shock protein expression (Bourdi et al., 2002a). Heat shock proteins are considered to be protective mechanism against various physiologic and environmental stressors (Bourdi et al., 2002b). In addition, cyclooxygenase-2 has been reported to be hepatoprotective in acetaminophen, possibly due to up-regulation of heat shock proteins (Reilly et al., 2001).

Various chemokines have also been reported to be up-regulated in acetaminophen toxicity. Chemokines were initially recognized for their role in leukocyte recruitment. However, Lawson et al. (2000) showed that neutrophils followed the development of toxicity and that administration of antibodies to $\beta_2$ integrins had no effect on toxicity. Chemokine up-regulation in acetaminophen toxicity appears to be hepatoprotective. Hogaboam showed that macrophage inhibitory protein-2 (MIP-2) and other related chemokines promoted hepatocyte regeneration in acetaminophen-treated mice (Hogaboam et al., 1999a). In additional studies, viral vector delivery of MIP-2 to acetaminophen-treated mice was protective against acetaminophen toxicity (Hogaboam et al., 1999b). Studies in mice deficient in CCR2, the primary receptor for the chemokine MCP-1 (monocyte chemoattractant protein-1), showed these mice to have increased toxicity to acetaminophen and increased formation of TNF-$\alpha$ and IFN-$\gamma$ (Hogaboam et al., 2000). Cumulatively, these studies suggest that cytokines play complex roles in the toxicity and that alterations in the equilbrium of pro- and anti-inflammatory cytokine formation contribute to oxidative stress.
Superoxide Formation and Mitochondrial Dysfunction in Acetaminophen Toxicity

Superoxide may be formed via a number of mechanisms including formation from cytochrome P450 (Puntarulo and Cederbaum, 1996) and other enzymes. We evaluated the importance of activation of Kupffer cells, macrophages, or neutrophils (the so-called respiratory burst) in acetaminophen toxicity. This sudden excess utilization of oxygen by activated phagocytes is a result of increased activity of the enzyme, NADPH-oxidase. The result is release of superoxide anion at the outer surface of the plasma membrane (Baggiolini and Wymann, 1990). We utilized mice genetically deficient in Gp91 phox, a critical subunit of NADPH oxidase (James et al., 2003a), and found that these mice and wild-type mice had comparable toxicity to acetaminophen. Also, both knockout mice and wild-type mice had the same degree of tyrosine nitration in the liver. An analysis of mitochondrial glutathione disulfide was found to be comparable in the two groups (James et al., 2003a). These data suggest that the increased superoxide in acetaminophen toxicity is not from activated macrophages.

Available data suggest that mitochondrial dysfunction may be an important mechanism in acetaminophen-induced hepatotoxicity. It is known that mitochondrial permeability transition (MPT) occurs with formation of superoxide, and this may be the source of superoxide leading to peroxynitrite and tyrosine nitration. MPT represents an abrupt increase in the permeability of the inner mitochondrial membrane to small molecular weight solutes. Oxidants such as peroxides and peroxynitrite, Ca$^{2+}$, and P$_i$ promote the onset of MPT, whereas Mg$^{2+}$, ADP, low pH, and high membrane potential oppose onset. Associated with the permeability change is membrane depolarization, uncoupling of oxidative phosphorylation, release of intramitochondrial ions and metabolic intermediates, and mitochondrial swelling. MPT mechanisms have been reviewed by Lemasters et al. (1998). In the late 1980s it was shown that cyclosporin A specifically blocked the onset of MPT in a saturable manner, implying a protein channel or pore. It has been subsequently recognized that this pore transports both anionic and cationic solutes of mass less than 1500 Da and is the previously identified multiple conductance channel. Of particular note is the fact that oxidation of vicinal thiols in the pore promote an open state of MPT and release of calcium. NAPQI is known to reduce the vicinal thiols at the MPT pore and prevent the further progression of toxicity (Palmeira and Wallace, 1997). These data are consistent with a mechanism whereby acetaminophen toxicity is by NAPQI-mediated oxidation of thiol groups in mitochondria leading to MPT. The toxicity is mediated by mitochondrial dysfunction resulting in production of reactive oxygen/nitrogen species (Fig. 4).

Summary

Dr. Gillette and researchers in his laboratory made fundamental contributions to our understanding of the pathogenesis of drug and chemical toxicity. With the analgesic acetaminophen it was shown that the hepatic necrosis was not a result of the parent compound. Metabolism by cytochrome P450 enzymes to a reactive metabolite was necessary for the production of toxicity. After therapeutic doses of acetaminophen, the reactive metabolite was efficiently detoxified by conjugation with GSH. However, after toxic doses, GSH was depleted by the conjugation reaction and the metabolite covalently bound to protein. Covalent binding correlated with development of toxicity. Treatment with cysteine to increase GSH detoxification was shown to be an effective antidote against toxicity. The latter finding led to the development of N-acetyl cysteine as the current clinical antidote. Since these initial findings, many investigators have added additional details relative to the concept of how acetaminophen is toxic, and some of these are discussed in this review. Despite these recent studies, the concept of metabolic activation as the critical initiating event in the development of toxicity has remained. Moreover, metabolic activation has proven to be a general mechanism relevant for the development of toxicity for many drugs and chemicals. Dr. Gillette reviewed his major contributions to science in the Annual Review of Pharmacology and Toxicology (Gillette, 2000) and in Drug Metabolism Reviews (Gillette, 1995).

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