Reduction of Hepatotoxicity Induced by Acetaminophen Overdoses in a Mouse Model of Inflammation Induced by Freund’s Adjuvants

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Abstract

Acetaminophen (APAP) is often used as an analgesic and antipyretic during the inflammatory process. Its toxicity in overdoses depends on the integrity of the hepatic cytochrome P450 (CYP). The oxidative drug metabolism mediated by CYP can be inhibited during inflammatory diseases or after use of immuno-stimulants and vaccines. The objective of this work was to evaluate if inflammation is able to modulate the toxicity of APAP. Five female Balb/c mice were injected subcutaneously with Freund Complete Adjuvant (FCA), and boosted with Freund’s Incomplete Adjuvant (FIA) at 14th day. Then, they were treated with 360 mg/kg of acetaminophen orally during the 14th, 15th and 16th days. Conventional control groups were included with APAP administration without immuno-stimulation. Serum levels of IL-1β, TNFα, IFNγ, α-1-acid glycoprotein (α-1-AGP), alanine transaminase (ALT), aspartic acid aminotransferase (AST), lactate dehydrogenase (LDH) and hepatic CYP2E1 expression were measured. Inoculation site of adjuvants and liver histopathological responses were also evaluated. FCA/FIA injection produced acute inflammatory response in the inoculation site and increased serum levels of the pro-inflammatory cytokines, α-1-AGP and LDH with reduction of hepatic CYP2E1 expression. A reduction of liver damage induced by APAP overdoses was also observed, suggesting that inflammatory processes can be protective against APAP hepatotoxicity.

Keywords: Inflammation; Immunotoxicity; Freund’s adjuvants; Acetaminophen; Hepatotoxicity

Introduction

It has been documented that when host defense mechanisms are stimulated, there is a concomitant decrease in different hepatic cytochrome P450 enzymes (CYP), with impact in the drug biotransformation and elimination. This has resulted in a number of clinically important unwanted drug responses in patients with infections or inflammatory responses [1]. Moreover, several reports has shown that the administration of immuno-stimulating drugs, such as influenza and Bacillus Calmette Guerin (BCG) vaccinations, endotoxins or interferons, can affect the metabolism of several drugs [2-4]. Analgesics and antipyretics are often co-administered with immuno-stimulatory drugs, after vaccine application or during disease states with an inflammatory component; consequently, the study of these interactions is very important for the prediction of toxicity manifestation in treated patients.

Acetaminophen (N-acetyl-p-aminophenol) (APAP), also referred to as paracetamol, is one of the common analgesics and antipyretic drugs. It is generally considered harmless at therapeutic doses, but in overdose causes severe and sometimes fatal hepatic damage in humans and experimental animals [5,6]. The main metabolic pathways of acetaminophen in humans are hepatic glucuronidation and sulphation. Furthermore, several CYP isoenzymes metabolize a small proportion of APAP at therapeutic doses being oxidized to N-acetyl-p-benzoquineminine (NAPQI), a highly reactive intermediate metabolite that yields hepatotoxicity. In overdoses the production of NAPQI increases producing severe hepatic damage [6] (Figure 1).

Pharmacokinetics studies in human volunteers and animal models have evidenced that CYP2E1 is the main CYP isoform involved in the hepatotoxicity of APAP, although other isoforms such as: CYP1A2, CYP3A4 and CYP2A6 may also participate [7-9]. The importance of CYP2E1 in acetaminophen toxicity was demonstrated by the finding that CYP2E1 null mice were much less sensitive to acetaminophen hepatotoxicity than the wild-type mice or CYP1A2 null mice. The double null mice (CYP2E1−/−; CYP1A2−/−) were only mildly sensitive to the toxic effects of acetaminophen. Moreover, in CYP2E1 null mice in which the human CYP2E1 gene was introduced as an artificial chromosome genomic clone of bacterial origin, the hepatotoxic effects of acetaminophen were restored to a significant extent [10,11].

Oxidative stress is also considered to be involved in the induction of hepatotoxicity by APAP overdose, causing decreasing in antioxidant enzyme activities such as catalase and glutathione peroxidase, increasing the effect of reactive oxygen species (ROS) like hydrogen peroxide, superoxide and peroxynitrite [12-15].

Various authors reported a rapid decrease in total CYP contents in FCA-induced inflammation in rat liver and the selective down-regulation of specific CYP isoforms, as illustrated by decreased mRNA

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levels (CYP2B, CYP2C11, CYP3A1, and CYP2E1), protein contents (CYP2B, CYP2C11, and CYP2E1) or catalytic activities (CYP2C6, CYP2C11, and CYP2E1) [16]. In animal models, using endotoxins as an immuno-stimulation model, also diminished the catalytic activity of CYP2E1 [17,18], including decreased expression of CYP1A, 2B1/2, and 3A subfamily associated with reversible changes in the pharmacokinetic parameters of theophylline [18]. In 1994, Raiford and Thigpen reported that Kupffer cells stimulated with Corynebacterium parvum reduced parameters of theophylline [18]. In 1994, Raiford and Thigpen reported that Kupffer cells stimulated with Corynebacterium parvum reduced parameters of theophylline [18].

**Materials and Methods**

**Adjuvants**

Freund Complete Adjuvant (263810) (FCA); is a suspension of Mycobacterium butyricum in a mixture of paraffin oil and an emulsifying agent, mannide monooleate. Formulation per 10 mL ampule: Mannide Monooleate (1.5 mL), Paraffin oil (8.5 mL) and Mycobacterium butyricum (5 mg). Freund Incomplete Adjuvant (263910) (FIA): is essentially FCA without Mycobacteria. Formulation per 10 mL ampule: Mannide Monooleate (1.5 mL) and Paraffin oil (8.5 mL). DIFCO Laboratories, Detroit, MI. They were prepared immediately before inoculation according to a well-established method. Briefly adjuvant and a solution of NaCl 0.9% (QUIMEFA, Cuba) were mixed in proportion v/v using two glass syringes with Luer Lock connector during 10 minutes.

**Acetaminophen**

APAP purchased from QUIMEFA, Cuba, was prepared as oral suspension at a final concentration of 50 mg/mL in sterile distilled water.

**Animals and treatment**

Female Balb/c mice (20-25 g) were obtained from the National Center for the Laboratory Animals Production (CENPALAB, Havana, Cuba). The present study was conducted according to the Guiding Principles for the Care and Use of Laboratory Animals. The protocol was approved by the Committee on the Ethics of Animal Experiments of Toxicology and Biomedicine Center. All efforts were made to minimize suffering. The animals were maintained under controlled conditions.
stored in a -70°C freezer until use. Microsomal preparations were isolated in 100 mM Tris-acetate buffer (pH 7.4) containing 1 mM sodium ethylenediamine tetraacetate (EDTA). Microsomal preparations were centrifuged, washed in pyrophosphate buffer (pH 7.4) and stored frozen at –20°C.

Isolation of hepatic microsomal fractions

Hepatic microsomal fractions of mice were prepared by differential centrifugation, washed in pyrophosphate buffer (pH 7.4) and stored in 100 mM Tris-acetate buffer (pH 7.4) containing 1 mM sodium ethylenediamine tetraacetate (EDTA). Microsomal preparations were stored in a -70°C freezer until use.

Measurement of cytokines in serum

Cytokine concentrations were determined 8 h after the second application of Freund’s Adjuvant (FA) (14th day) to all groups of mice, using commercially available ELISA kits (eBioscience, San Diego, CA, USA). Briefly, each well of a 96-well plate was coated with 100 µL of capture antibody, and incubated overnight at 4°C. After washing and blocking with assay dilution, serum or standard were added to individual wells; then the plates were maintained for 2 h at room temperature. The plates were washed while biotin-conjugated detecting mouse antibody was added to each well and incubated at room temperature for 1 h. The plates were washed again and further incubated with avidin-HRP for 30 min before detection with TMB solution. Finally, reactions were stopped by adding 1 M H3PO4, and the absorbance at 450 nm was measured with an ELISA reader (Molecular Devices, Sunnyvale, CA, USA). The amount of cytokine was calculated from the linear portion of the generated standard curve.

Biochemical analysis of serum

The mice were anaesthetized with Pentobarbital 50 mg/kg IP diluted in a solution of NaCl 0.9% (Quimefa, Cuba) and blood (1.5 ml) was drawn from the vein of the tail 24 h after the last application of APAP (the 17th day). The serum were obtained by coagulation and centrifugation within 15 min were allowed to clot at room temperature and stored frozen at -20°C until analysis. The aspartic acid aminotransferase (AST), alanine aminotransferase (ALT), and lactate dehydrogenase (LDH) were quantified using a standard clinical automatic analyzer (Hitachi, 902) and specifics kit (Roche). The severity of the inflammatory reaction was assessed by measuring the levels of pro-inflammatory cytokines IL-1β, TNFα and IFNγ were observed to increase in the serum of all the groups of mice treated with Freund’s Adjuvants (FA), the concentration of pro-inflammatory cytokine IL-1β, TNFα and IFNγ were observed to increase in the serum of all the groups of mice.

Immunoblot analysis

Hepatic microsomes were analyzed for CYP2E1 immunochemically. Microsomal proteins were separated by SDS-polyacrylamide gel electrophoresis (10% acrylamide) at 160 V for 1 h and electrophotoretherically transferred to nitrocellulose paper. The nitrocellulose paper was incubated with anti-mouse cytochrome P-450 CYP2E1 antibodies, with goat antibody to mouse CYP2E1, and then with rabbit anti-goat IgG conjugated with alkaline phosphatase (Bio-Rad). The color was developed with 5-bromo-4-chloro-3-indole phosphate and p-nitroblue tetrazolium chloride (Bio-Rad) according to the manufacturer’s instructions. The resulting blots were quantitated by densitometry, using Adobe Photoshop with a HP Precision Scanner and oneDScan software (Scanalytics) [23].

Necropsy and histopathology

After the blood collection, anaesthetized animals were sacrificed by cervical dislocation. Necropsy was made and all organs were macroscopically examined. Them, histological processing was performed according to standardized methods. Briefly, the sites of inoculation (dorsal subcutaneous tissue for subcutaneous or anterior quadriceps muscle groups of the left hindpaw for intramuscular) and the livers obtained from all treated mice, were fixed in 10% formalin, embedded in paraffin, sectioned at 4 µm thickness and stained with hematoxylin and eosin.

Statistical analysis

All data are reported as means ± S.D. The comparison of the results from the various experimental groups and their corresponding controls was carried out using a one-way analysis of variance followed by Turkey’s post hoc test. The effects were considered significant when p ≤ 0.05. The statistical analyses were performed using Statgraphics plus 5.1 software (StatSoft).

Results

Measurement of cytokines and biochemical analysis in serum

After 8 hours of applying the second dose of Freund’s Adjuvants (FA), the concentration of pro-inflammatory cytokine IL-1β, TNFα and IFNγ were observed to increase in the serum of all the groups of mice that received Freund’s Adjuvants (FA) (Figure 2).

Analyzing the enzymatic level in the treated groups, it was noted that a significant increment of ALT and AST in the APAP-treated group as evidence of hepatotoxicity induced by the overdose. However, it is interesting that in the group with co-administration of FA the levels of both enzymes were lower than positive control treated with APAP alone, indicating a hepatoprotective effect provoked by the inflammation (Figure 3).

Regarding to α-1-AGP levels, it was significantly increased in all mice treated with FA without affection for the APAP treatment (Figure 4). LDH were significantly increased in the serum of mice treated with APAP, FA and combined treatment in comparison with control groups. However, there were differences within these treated groups. Mice treated with APAP and previous s.c application of FA exhibited higher level of LDH than the other groups, being significant difference in comparison with APAP and APAP/FA i.m groups (Figure 5).

Expression of CYP2E1 in the liver

CYP2E1 was identified as a single band that appeared at approximately 56 kDa. In the groups treated with FA, the expression...
of CYP2E1 was significantly decreased to approximately 40-50% in comparison with the control groups. Apparently the groups that received FA via s.c route had lower expression in comparison with the control groups. (a) signifies significant difference when compared with their correspondent control group and APAP treated group, (p<0.05) (ANOVA followed by Tukey’s post hoc test).

Pathological findings in the injection site and the liver

The main pathological finding at the injection sites and the liver in all the mice groups are detailed in Table 2. Mice previously immunostimulated with FA (i.m and s.c), showed inflammatory reactions in the injection site. The group under APAP treatment exhibited signs of mild hepatic necrosis, and other changes in the hepatic morphology according to the pattern produced by moderate overdoses of APAP, while mice with both treatment APAP and FA developed slight changes indicating a hepatoprotection, and not relevant modification on the tissue architecture in the other groups (Figure 7).

Discussion

APAP is frequently prescribed in the medical practice as analgesic of CYP2E1 is significantly decreased to approximately 40-50% in comparison with the control groups. Apparently the groups that received FA via s.c route had lower expression in comparison with the control groups. Only are marked the more important differences (p<0.05). (ANOVA followed by ELISA.

Figure 2: Effect of administration of Freund’s Adjuvants (FA) via either i.m or s.c routes in the serum levels of IL-1β, TNFα and IFNγ in serum of mice Balb/c. The serum levels of IL-1β, TNFα and IFNγ were measured in all treated groups and controls. Mice (n=5) were bled at 14h, 8 h after application of FA and before administration of APAP. Serum was pooled from each group and measured cytokine profile in triplicates by ELISA.

Figure 3: Effect of administration of Freund’s Adjuvants (FA) via either i.m or s.c routes in the levels of ALT and AST in serum in a mice model of APAP hepatotoxicity. All values are expressed as the arithmetic mean ± SE of 5 mice. a: significant difference in comparison with control groups, b: significant difference in comparison with APAP group (p<0.05). Only are marked the more important differences (p<0.05). (ANOVA followed by Tukey’s post hoc test).

Figure 4: Effect of administration of Freund’s Adjuvants (FA) via either i.m or s.c routes in the levels of α-1-acid glycoprotein (α-1-AGP) in serum in a mice model of Acetaminophen (APAP) hepatotoxicity. All values are expressed as the arithmetic mean ± SE of 5 mice. In FA-treated mice, α-1-AGP levels were significantly increased (a) when compared with their correspondent control group and APAP treated group, (p<0.05) (ANOVA followed by Tukey’s post hoc test).

Figure 5: Effect of administration of Freund’s Adjuvants (FA) via either i.m or s.c routes in the levels of lactate dehydrogenase (LDH) in serum in a mice model of Acetaminophen (APAP) hepatotoxicity. All values are expressed as the arithmetic mean ± SE of 5 mice. In FA-treated mice, LDH levels were significantly increased (a) when compared with their correspondent control group and APAP treated group, (p<0.05) (ANOVA followed by Tukey’s post hoc test).

Figure 6: Hepatic cytochrome P-450 (CYP2E1) expression in negative control subcutaneous (s.c) and intramuscular (i.m), positive control of Acetaminophen (APAP) hepatotoxicity, Freund’s adjuvants (FA) administrated s.c or i.m and combination of APAP/FA s.c or APAP/FA i.m mice groups, quantitated by immuno-blotting and densitometry. The averages of the values derived from the control mice were expressed as 100%. The data are presented as the means ± S.D. and were obtained from five mice per group. (a) represents significative difference when compared with their correspondent control group and APAP treated group, (p<0.05) (ANOVA followed by Tukey’s post hoc test).
and antipyretic during inflammatory process. On the other hand, overdose of APAP is the most frequent cause of drug induced hepatic failure in several countries [24]. Several studies have revealed that inflammation and immuno-stimulation can modulate the expression of different CYP enzymes, affecting the metabolism of some drugs [1-4]. In this way, Prandota has reviewed a lot of cytokines, growth factors and other substances released during inflammatory response with down-regulating effects on the metabolism of endogenous and exogenous substances [25].

This study has highlighted the role of inflammation induced by FA on the modulation of hepatotoxicity after APAP overdose, incriminating the role of proinflammatory cytokines on the inhibition of the CYP activity, reducing the APAP-induced hepatotoxicity. The dose used was 360 mg/kg via oral route, which induced an increment of biomarkers of hepatic damages and provoked a moderated hepatotoxicity that is able to detect an effect of the inflammation induced by FA in the mice model. The releasing of cytokines, such as IL-1, IL-2, IL-6, TNFα, TGF-β and IFNs during immuno-stimulation are involved in the reduction of the expression of CYP2E1 [26] and the modulation of drug metabolism, as was evidenced by Masubuchi et al., who demonstrated the role of IL-6 in hepatic heat shock protein expression and protection against acetaminophen-induced liver disease, using IL-6-knockout mice [27]. In this study was measured the concentration of the pro-inflammatory cytokines: IL-1β, TNFα and IFNγ in sera in mice 8 h after the second application of FA, and before application of APAP, and it was observed their elevation as expression of the inflammatory reaction occurring in the inoculation site of the adjuvants.

AGP is other biomarker of acute inflammation elevated in the groups that received FA. AGP is an acute phase protein, which binds basic drugs, and has been proposed to have a role in immunomodulation and to be a nonspecific antimicrobial agent [28,29]. In rats treated with a single dose of FCA, the inflammatory response observed 14 days post-injection (FCA-induced arthritis) is characterized by pathophysiological changes that can alter drug disposition, namely elevated serum levels of AGP [30]. Considering that AGP is able to bind to drugs, further studies of its influence in pharmacokinetic and pharmacodynamic properties of APAP in this model needs to be studied in the future.

The hepatic enzymes ALT and AST are the best enzymatic marker of hepatic necrosis, in particular ALT is the clinical chemistry gold standard of hepatotoxicity. Damaged hepatocytes release their contents including ALT and AST into the extracellular space. The released enzymes ultimately enter into circulation and thereby increase the serum levels of ALT and AST compared to control subjects [31]. In this study, the group treated with APAP showed significant increment of these enzymes in sera due to the hepatic damaged induced by this drug, but in the groups injected with FA and APAP there was not observed such increment, as evidence of protection against APAP-induced hepatotoxicity in animal receiving FA. Regarding to LDH, despite being less specific, it has been used as a marker to evaluate the damage to hepatic tissue membranes by APAP [32]. In all the groups that received APAP and FA plus APAP, the LDH were elevated in contrast with the control groups. Taking into count that LDH is a unspecific biomarker of cellular necrosis, is possible that this result is produced by the sum of the effects of the cellular necrosis at the inoculation site induced by FA in addition to that occurred in the liver by the APAP-induced hepatotoxicity.

<table>
<thead>
<tr>
<th>Groups</th>
<th>Macroscopic findings</th>
<th>Microscopic findings</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Inoculation site</td>
<td>Liver</td>
</tr>
<tr>
<td>Control s.c</td>
<td>Absence of visible tissue alterations</td>
<td>Absence of inflammatory infiltrate or others microscopic alterations</td>
</tr>
<tr>
<td>Control i.m</td>
<td>Absence of visible tissue alterations</td>
<td>Absence of alterations in the hepatic tissue</td>
</tr>
<tr>
<td>Acetam</td>
<td>-</td>
<td>Moderate irregular liver’s yellowish coloration</td>
</tr>
<tr>
<td>FA s.c</td>
<td>Nodule &gt;5 mm, large amount of white tissue and haemorrhagic zones</td>
<td>Severe diffuse inflammation, necrotising granuloma</td>
</tr>
<tr>
<td>FA i.m</td>
<td>Localized nodular Inflammatory zone</td>
<td>Inflammation with necrotising granuloma</td>
</tr>
<tr>
<td>Acetam/ FA s.c</td>
<td>Nodule &gt; 5 mm, large amount of white tissue and haemorrhagic zones</td>
<td>Light liver's yellowish coloration</td>
</tr>
<tr>
<td>Acetam/ FA s.c</td>
<td>Localized nodular Inflammatory zone</td>
<td>Inflammation with necrotising granuloma</td>
</tr>
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Table 2: Main pathological finding at injection sites and liver of treated mice groups (n=5).

Figure 7: Selected histological images of the livers after oral administration of Acetaminophen (APAP) in normal or treated mice with Freund’s Adjuvants (FA). Representative images of macroscopic (upper panels) and microscopic (lower panel) pathological findings. (A) Vehicle control group (×100), (B) APAP treated group, (arrow indicates a focus of hepatic necrosis) (×400), (C) APAP plus FA treatment group (×400). Livers from mice treated with APAP without APAP did not show any damage (not shown).
Many investigators reported that CYP2E1 is the main CYP isoform involved in APAP hepatotoxicity [8-11]. In this study was observed a decreased expression in mice previously treated with FA. This effect may have contributed to reduce the APAP hepatotoxicity. Similar result was reached by other authors using a model of immuno-stimulation with C. parvum [19]. The protective effect induced by the inflammatory response was directly evidenced in the pathological studies of the livers of the group treated with APAP plus FA with a reduction of the hepatic necrosis.

Although our study reveals one aspect of the inflammatory response and its influence in reducing hepatotoxicity by paracetamol, this phenomenon is very complex and other factors not evaluated in our study can also be involved. For example, Kupffer cells can be activated directly or indirectly by various toxicants, including paracetamol, or by the hepatocyte damage initiated by the formation of the reactive metabolite, N-acetyl-p-benzoquinonimine, resulting in the release of reactive oxygen and nitrogen species, all of which may contribute to liver damage with implications in the toxicity [12-15,33]. Thus was reported that the antioxidant effect of beta-D-glucan can prevent the APAP-induced toxicity [34].

Other important issue which reveals the complexity of this effect is that, hepatocyte death results in a sterile inflammatory response and activation of molecular pathways for innate immune activation, such as TLR 9 and the Nalp3 inflammasome, producing pro-inflammatory cytokines that amplifies the initial insult and increases overall tissue injury, as was demonstrated in mice deficient in Tlr9 and the inflammasome components Nalp3 (NACHT, LRR, and pyrin domain–containing protein 3) [35], and, using neutralizing antibodies to TNFα or IL-1 partially prevented liver damage in mice initiated by hepatotoxic doses of APAP [36]. For this reason we measured the level of pro-inflammatory cytokines before the administration of APAP. Besides, some immuno-stimulators such as lipopolysaccharide (LPS) from Gram-negative bacteria can itself induce liver damage, and act in synergy with APAP for the production of pro-inflammatory cytokines [37]. In contrast, in the model of carbon tetrachloride (CCL4) exposure in mice, TNFα was involved in liver repair through its ability to support hepatocyte proliferation following chemical injury [38]. In spite of the diversity of factors that participate in the APAP hepatotoxicity, our results confirm the role of the previous immuno-stimulation, reducing the hepatotoxic effect of this drug.

In conclusion, this result suggest that the use of APAP for the treatment of pain or fever as part of the flu-like syndrome induced by vaccines or immuno-modulators [39-41], and during inflammatory process, does not increase the risk of toxicity in overdose, quite the contrary, this risk probably is reduced. Further studies are required measuring glutathione (GSH), other cytokines involved in the inflammatory process and other members of the CYP in this and other models of inflammation.

References


