Cytochrome P450-mediated metabolism of N-(2-methoxyphenyl)-hydroxylamine, a human metabolite of the environmental pollutants and carcinogens o-anisidine and o-nitroanisole

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ABSTRACT

N-(2-methoxyphenyl)hydroxylamine is a human metabolite of the industrial and environmental pollutants and bladder carcinogens 2-methoxyaniline (o-anisidine) and 2-methoxynitrobenzene (o-nitroanisole). Here, we investigated the ability of hepatic microsomes from rat and rabbit to metabolize this reactive compound. We found that N-(2-methoxyphenyl)hydroxylamine is metabolized by microsomes of both species mainly to o-aminophenol and a parent carcinogen, o-anisidine, whereas 2-methoxy nitrosobenzene (o-nitrosoanisole) is formed as a minor metabolite. Another N-(2-methoxyphenyl)hydroxylamine metabolite, the exact structure of which has not been identified as yet, was generated by hepatic microsomes of rabbits, but its formation by those of rats was negligible. To evaluate the role of rat hepatic microsomal cytochromes P450 (CYP) in N-(2-methoxyphenyl)hydroxylamine metabolism, we investigated the modulation of its metabolism by specific inducers of these enzymes. The results of this study show that rat hepatic CYPs of a 1A subfamily and, to a lesser extent those of a 2B subfamily, catalyze N-(2-methoxyphenyl)hydroxylamine conversion to both its reductive metabolite, o-anisidine, and o-aminophenol. CYP2E1 is the most efficient enzyme catalyzing conversion of N-(2-methoxyphenyl)hydroxylamine to o-aminophenol.

KEY WORDS: o-anisidine; N-(2-methoxyphenyl)hydroxylamine; metabolism; oxidation; cytochrome P450

Introduction

2-Methoxyaniline (o-anisidine) is a potent carcinogen, causing tumors of the urinary bladder in both genders of F344 rats and B6C3F1 mice (NTP, 1978; IARC, 1982). The International Agency for Research on Cancer (IARC) has classified o-anisidine as a group 2B carcinogen (IARC, 1982), which is possibly carcinogenic to humans. Besides its carcinogenicity it exhibits other toxic effects, including hematological changes, anemia and nephrotoxicity (NTP, 1978; IARC, 1982). o-Anisidine is used as an intermediate in the manufacturing of a number of azo and napthol pigments and dyes, which are used for printing (90%) and for paper (3%) and textile (7%) dyeing (NTP, 1978; Garner et al., 1984). Such a wide use of this aromatic amine could result in occupational exposure. Furthermore, it may be released from textiles and leather goods colored with these azo dyes and a large part of the population may be exposed. This carcinogen is also a constituent of cigarette smoke (IARC, 1982; Stabbert et al., 2003). This strongly suggests that o-anisidine ranks not only among occupational pollutants produced in the manufacturing of chemicals, but also among environmental pollutants; it can be assumed that human exposure is widespread. Indeed, o-anisidine was found in human urine samples in the general population, in concentrations of 0.22 µg/l (median) (Weiss and Angerer, 2003). In addition, hemoglobin adducts of o-anisidine were detected in blood samples of persons living in urban or rural environments.
areas of Germany (Faltrer et al., 1994; Branner et al., 1998; Richter et al., 2001). The adducts as well as o-anisidine in urine might originate not only from the sources mentioned above, but also from a possible o-anisidine precursor, 2-methoxynitrobenzene (o-nitroanisole). This chemical was released into the environment in the course of an accident in a German chemical plant, causing subsequently local and regional contamination (Faltrer et al., 1994; Hauthal, 1993; Traupe et al., 1997). o-Nitroanisole exhibits strong carcinogenic activity, causing neoplastic transformation in the urinary bladder, and to a lesser extent, in the spleen, liver and kidneys in rodents (NTP 1993). It is also a toxic compound, causing anaemia. The anaemia is characterized by increased levels of methemoglobin and accelerated destruction of erythrocytes (NTP 1993).

Recently, we have found that o-anisidine is oxidatively activated by peroxidase and cytochrome P450 (CYP) to species binding to DNA in vitro (Stiborová et al., 2001; 2002; 2005; Rýdlová et al., 2005; Naiman et al., 2008). We also demonstrated that o-anisidine forms DNA adducts in vivo. The same adducts as found in DNA incubated with o-anisidine and human microsomes in vitro were detected in urinary bladder, the target organ, and to a lesser extent, in liver, kidney and spleen of rats treated with o-anisidine (Stiborová et al., 2005). The o-anisidine-derived DNA adducts were identified as deoxyguanosine adducts formed from a metabolite of o-anisidine, N-(2-methoxyphenyl)hydroxylamine, which is generated by oxidation of o-anisidine with human, rabbit and rat hepatic microsomes (Stiborová et al., 2005; Rýdlová et al., 2005; Naiman et al., 2008). The same deoxyguanosine adducts were also detected in DNA of the urinary bladder, kidney, liver and spleen of rats treated with o-nitroanisole (Stiborová et al., 2004), an oxidized counterpart of o-anisidine, and in DNA incubated with o-nitroanisole in vitro with human and rat hepatic cytosolic enzymes and xanthine oxidase (Stiborová et al., 1998; 2004). These enzymatic systems were found to produce N-(2-methoxyphenyl)hydroxylamine after o-nitroanisole reduction (Mikšanová et al., 2004). The data indicate that formation of N-(2-methoxyphenyl) hydroxylamine, the reactive metabolite of both carcinogens, is critical for generation of DNA lesions in target organs. Therefore, it is clear that N-(2-methoxyphenyl)hydroxylamine formation and its further conversion, as well as the enzymes participating in such processes, play a key role in carcinogenic effects of both carcinogens.

Recently, we have found that o-anisidine is oxidized by human, rat and rabbit hepatic microsomes not only to N-(2-methoxyphenyl)hydroxylamine, but that this compound is a subject of complex redox cycling reactions, forming also o-aminophenol, o-nitrosoanisole and one additional metabolite, the exact structure of which has not been identified as yet (Stiborová et al., 2005; Naiman et al., 2008). N-(2-methoxyphenyl)hydroxylamine might also be a subject of complex reactions, and its fate is dependent on the environment, in which it occurs. It can be further metabolized to o-aminophenol, o-nitrosoanisole and parent o-anisidine (Naiman et al., 2008), or when nucleophiles such as DNA or proteins are present in the cell, form the adducts (Stiborová et al., 2005) (Figure 1).

The results of our former studies (Stiborová et al., 2005; Naiman et al., 2008) show a similarity among hepatic microsomal CYP systems metabolizing o-anisidine in humans and two animal models, rats and rabbits, which are the species, in which this agent is carcinogenic or toxic (NTP, 1978; IARC, 1982). These findings indicate that both experimental animal species might serve as suitable models to mimic the fate of this carcinogen in human. However, whereas formation of DNA adducts by N-(2-methoxyphenyl)hydroxylamine, generated in reactions catalyzed with human and rat hepatic microsomes, has been clearly proven (Stiborová et al., 2005), conversion of this metabolite to further products has been investigated using only rabbit hepatic microsomes (Naiman et al., 2008). Therefore, the aim of the present study was to evaluate the efficiency of N-(2-methoxyphenyl)hydroxylamine metabolism by hepatic microsomes from rats.

Materials and methods

Chemicals

Chemicals were obtained from the following sources: β-naphthoflavone (β-NF), NADP+, NADPH, glucose 6-phosphate and bicinchoninic acid (2,2’-bicinchonilne-4,4’-dicarboxylic acid) from Sigma Chemical Co. (St. Louis, MO, USA); o-anisidine, o-aminophenol (>99% based on HPLC) from Fluka Chemie AG (Buchs, Switzerland) and glucose 6-phosphate dehydrogenase from Serva (Heidelberg, Germany). All these and other chemicals were of analytical purity or better. 2-Methoxynitrosobenzene was synthesized in analogy to the synthesis described earlier (Seidenfaden, 1971) by oxidation of N-(2-methoxyphenyl)hydroxylamine with potassium dichromate in water and identified by 1H NMR recorded on a 400 MHz instrument in CDCl3 (referenced to TMS): 7.68 (1H, m), 7.36 (1H, m), 6.86 (1H, m), 6.30 (1H, m) and 4.28 (3H, s). N-(2-methoxyphenyl)hydroxylamine was synthesized by the procedure similar to that described earlier (Balaban et al., 1998). N-(2-Methoxyphenyl)hydroxylamine authenticity was confirmed by electrospray mass and CID spectra and high field proton NMR spectroscopy. The positive-ion electrospray mass-spectrum exhibited the protonated molecule at m/z 140.1, while the CID of its ion fragments at m/z 125.2, 108.1 and 109.1. The 1H-NMR spectra were recorded at 400 MHz in dimethyl sulfoxide-d6. The central line of dimethyl sulfoxide at 2.500 ppm was used as reference line. The spectra showed the presence of the following protons: 8.28 (1H, d, J = 2.3 Hz, exchanged with CD3OD), 7.64 (1H, d, J = 1.5 Hz, exchanged with CD3OD), 7.01 (1H, m, Σ J = 9.6 Hz), 6.84 (2H, m, Σ J = 15.0 Hz), 6.75 (1H, m), 3.75 (3H, s). The NMR spectra were recorded on a Bruker Avance II-500 instrument (499.8 MHz for 1H and 125.7 MHz for 13C) in dimethyl sulfoxide-d6 and referenced to the solvent signal (δ 2.50 and 39.70, respectively). 1H NMR spectrum showed the presence of the following signals: 8.96 (1H, bs), 6.65 (1H, m), 6.59 (1H, m), 6.54 (1H, m), 6.40 (1H, m)/
Incubation mixtures used for study of the o-anisidine metabolism contained the following concentrations in a final volume of 100 µl: 100 mM sodium phosphate buffer (pH 7.4), 1 mM NADP⁺, 10 mM D-glucose 6-phosphate, 1 U/ml D-glucose 6-phosphate dehydrogenase (NADPH-generating system), a rat or rabbit hepatic microsomal fraction containing 0.04–1.0 nmol CYP, and 0.1–2.0 mM o-anisidine dissolved in 1.0 µl methanol. The reaction was initiated by adding the substrate. To study metabolism of N-(2-methoxyphenyl)hydroxylamine, incubation mixtures contained the following concentrations in a final volume of 100 µl: 100 mM sodium phosphate buffer (pH 7.4), 1 mM NADP⁺, 10 mM D-glucose 6-phosphate, 1 U/ml D-glucose 6-phosphate dehydrogenase (NADPH-generating system), a rat and rabbit hepatic microsomal fraction containing 0.04–1.0 nmol CYP, and 0.1–1.0 mM N-(2-methoxyphenyl)hydroxylamine dissolved in 1.0 µl distilled water. The reaction was initiated by adding the substrate. After incubation in open glass tubes (37°C, 30 min), the reactions were terminated by adding 100 µl of methanol and centrifuged at 5,000 g for 5 min. Metabolism of o-anisidine and N-(2-methoxyphenyl)hydroxylamine with rat and rabbit CYP enzymatic systems was linear until 40 min. The supernatants were collected and 20 µl aliquots applied onto a high-performance liquid chromatography (HPLC) column, where metabolites of o-anisidine were separated. The HPLC was performed on a C-18 reversed-phase column (250 × 4.6 mm, 5 µm, Nucleosil 100-5, Macherey-Nagel, Duren, Germany). Metabolites were eluted with 18% methanol, 82% 7.18 µM aqueous ammonia, pH 8.0, (v/v) at a flow rate of 0.6 ml/min and monitored at 254 nm. o-Anisidine and N-(2-methoxyphenyl)hydroxylamine metabolites were analyzed by mass spectrometry and by comparing their chromatographic properties on HPLC with those of synthetic standards. 2-Methoxynitrosobenzene, o-aminophenol, N-(2-methoxyphenyl)hydroxylamine and 2-methoxynitrosobenzene standards, were eluted at retention times (r.t.) of 8.8, 11.3, 19.7 and 57.5 min, respectively (Stiborová et al., 2005; Naiman et al., 2008).
Results

Metabolism of \(N\)-(2-methoxyphenyl)hydroxylamine by rat and rabbit hepatic microsomes

When a parental compound from which \(N\)-(2-methoxyphenyl)hydroxylamine is generated, \(o\)-anisidine, was incubated with rat and rabbit hepatic microsomes in the presence of NADPH, two metabolites, \(o\)-aminophenol (t. of 11.3 min) and \(N\)-(2-methoxyphenyl)hydroxylamine (t. of 19.7 min), as well as an additional product peak of metabolite 1 (M1, t. of 7.0 min), which structure has not been identified as yet, were separated by HPLC (see peaks in Figure 2A for the profile obtained with rabbit microsomes) (Naiman et al., 2008).

The results of experiments with \(N\)-(2-methoxyphenyl)hydroxylamine and microsomes demonstrated that metabolites M1 and \(o\)-aminophenol are also formed from this \(o\)-anisidine metabolite by rabbit hepatic microsomes (Figure 2B), while formation of the metabolite M1 from this compound by hepatic microsomes of rats was negligible (Figure 2C). When \(N\)-(2-methoxyphenyl)hydroxylamine was incubated without hepatic microsomal enzymes or without NADPH, metabolite M1 and \(o\)-aminophenol peaks were also detectable by HPLC, but only under acidic conditions (pH 4.5 for 60 min). At pH 7.4, used for microsomal incubations, their spontaneous formation was negligible. This finding indicates that conversion of \(N\)-(2-methoxyphenyl)hydroxylamine in microsomes is mediated by enzymatic reactions. During metabolism of \(N\)-(2-methoxyphenyl)hydroxylamine by hepatic microsomes of both species, a shoulder at 8.8 min was also detectable (Figure 2B,C), suggesting formation of \(o\)-nitrosoanisole (2-methoxynitrosobenzene) (t. of 8.8 min, Figure 2F). Moreover, during the incubations of \(N\)-(2-methoxyphenyl)hydroxylamine with rat and rabbit microsomes and NADPH, an additional product peak was detected by HPLC, being identified to be the parental compound, \(o\)-anisidine (t. of 28.6 min) (Figure 2B,C).

Involvement of CYP enzymes in \(N\)-(2-methoxyphenyl)hydroxylamine metabolism in rat hepatic microsomes

In order to evaluate the participation of individual rat hepatic microsomal CYPs in \(N\)-(2-methoxyphenyl)hydroxylamine metabolism, the induction of individual CYP enzymes was performed with this animal model. Microsomes isolated from livers of uninduced rats and rats pre-treated with \(\beta\)-NF (enriched with CYP1A1/2), PB (enriched with CYP2B1/2) and ethanol (enriched with CYP2E1) were used (Table 1).

Except of the enzymes present in microsomes of livers of rats pre-treated with ethanol, the enzymes of all other microsomes tested in this study formed from \(N\)-(2-methoxyphenyl)hydroxylamine predominantly its reductive metabolite, \(o\)-anisidine. More than 2-fold higher levels of \(o\)-anisidine than \(o\)-aminophenol were determined when \(N\)-(2-methoxyphenyl)hydroxylamine was incubated with these microsomes and NADPH (Table 1). Levels of the \(N\)-(2-methoxyphenyl)hydroxylamine reductive metabolite, \(o\)-anisidine, did not correspond to activities of NADPH:CYP reductase in individual microsomes. Namely, activities of this enzyme in hepatic microsomes of control (uninduced) rats and those induced with \(\beta\)-NF, PB and ethanol used in the experiments are similar, being 0.210, 0.199, 0.325 and 0.201 \(\mu\)mol/min/mg protein, respectively. While incubations of \(N\)-(2-methoxyphenyl)hydroxylamine with hepatic microsomes of rats pre-treated with \(\beta\)-NF led to a 2.4- and 1.9-fold increase \((P < 0.05)\) in \(o\)-aminophenol and \(o\)-anisidine formation, respectively (Table 1), another inducer of CYP enzymes, PB, had much less effect. Even though a 1.4- and 1.2-fold increase in \(o\)-aminophenol and \(o\)-anisidine formation, respectively, was mediated by treating rats with this CYP inducer (Table 1), this increase was statistically insignificant. Ethanol, an inducer of CYP2E1, stimulated production of \(o\)-aminophenol from \(N\)-(2-methoxyphenyl)hydroxylamine, by 3-fold \((P < 0.05)\), whereas decreased levels of the \(N\)-(2-methoxyphenyl)hydroxylamine reduction metabolite, \(o\)-anisidine. These results indicate that rat hepatic CYP2E1, CYPs of a 1A subfamily and, to a lesser extent, those of a 2B subfamily, are capable of metabolizing \(N\)-(2-methoxyphenyl)hydroxylamine in rat livers.

It should be noted that the results of experiments with inducers should be carefully interpreted, because these inducers are not absolutely specific for individual CYPs. Therefore, to confirm the role of these CYPs in \(N\)-(2-methoxyphenyl)hydroxylamine metabolism, additional experimental approaches such as selective inhibition of CYPs and utilization of the purified CYP reconstituted with NADPH: CYP reductase are planned to be employed in further studies.

Discussion

The results of this study show that rat and rabbit hepatic microsomes can metabolize \(N\)-(2-methoxyphenyl)hydroxylamine, a reactive metabolite of carcinogenic \(o\)-anisidine and \(o\)-nitroanisole. This compound is responsible for genotoxic effects of both carcinogens, because it is easily decomposed to the nitrenium/carbenium ion forming DNA adducts (Figure 1) (Stiborová et al., 2004; 2005; Naiman et al., 2008). The results demonstrate that \(N\)-(2-methoxyphenyl)hydroxylamine is also further metabolized to \(o\)-aminophenol, \(o\)-nitrosoanisole and the parent compound, \(o\)-anisidine. The

| Table 1. Metabolism of \(N\)-(2-methoxyphenyl)hydroxylamine in rat hepatic microsomes induced with different agents |
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| | \(N\)-(2-methoxyphenyl)hydroxylamine metabolites | |
| Hepatic microsomes | \(o\)-aminophenol | \(o\)-anisidine |
| from rats pre-treated with \(\beta\)-NF | 2.0 ± 1.0 | 5.8 ± 0.7 |
| None - control microsomes | 4.8 ± 1.7 | 11.1 ± 3.3 |
| \(\beta\)-naphthoflavone (CYP1A1/2) | 2.8 ± 2.5 | 7.0 ± 2.0 |
| Phenobarbital (CYP2B1/2) | 6.1 ± 3.1 | 3.5 ± 0.7 |

\(^{a}\) The numbers are the peak area/min/nmol CYP for each metabolite, averages ± S.E.M of three determinations in separate experiments.

\(^{b}\) Isoforms of CYP induced are shown in brackets.
Figure 2. HPLC elution profiles of metabolites of 1 mM \( o \)-anisidine incubated with rabbit microsomes (A), of 1.0 mM \( N -(2\text{-methoxyphenyl})\) hydroxylamine incubated with rabbit (B) and rat (C) hepatic microsomes. (D) synthetic \( N -(2\text{-methoxyphenyl})\)hydroxylamine and \( o \)-anisidine. (E) \( o \)-aminophenol. (F) \( o \)-nitrosoanisole. For incubation conditions see Materials and methods. Peaks eluting between 2.0 and 5.5 min, solvent front, NADPH and protein components of microsomes and NADPH-generation system.
formed o-anisidine may be O-demethylated again to o-ami-
nophenol (Figure 1). The question whether o-aminophenol
is also formed from N-(2-methoxyphenyl)hydroxylamine by
its O-demethylation to N-(2-hydroxyphenyl)hydroxylamine,
which is subsequently reduced to o-aminophenol (Figure 1),
remains to be answered. No metabolites formed by this
reaction were observed.

Recently, redox cycling reactions similar to those we
found with N-(2-methoxyphenyl)hydroxylamine were
observed by Kim et al. (2004), who studied metabo-
lism of several aromatic and heterocyclic amines by a
CYP1A2/NADPH:CYP reductase enzymatic system. They
reported that the CYP system catalyzes oxidation of the
N-hydroxylated intermediate formed from the carcinogenic
heterocyclic amine 2-amino-3-methylimidazo[4,5-
N]quino-
line (IQ), to a nitrosodervative. They demonstrated that
NADPH:CYP reductase can catalyze the reduction of the
IQ oxidation products, N-nitroso-IQ and N-hydroxyl-IQ, to
N-hydroxy-IQ and the parent amine, IQ (Kim et al., 2004).
N-hydroxylation products of two other aromatic amines
investigated by Kim et al. (2004), 2-aminofluorene and
4-aminobiphenyl, are, however, reduced non-enzymatically,
by NADPH. We have not determined whether reduction
of N-(2-methoxyphenyl)hydroxylamine to o-anisidine
requires catalysis by NADPH:CYP reductase or occurs
non-enzymatically, or is mediated by other enzymes.
However, preliminary experiments performed in our
laboratory suggest that although NADPH:CYP reductase
might partially participate in N-(2-methoxyphenyl)
hydroxylamine reduction to o-anisidine, CYP enzymes
present in hepatic microsomes are more effective in this
process. (Naiman et al., unpublished results). Indeed, the
results of the present study demonstrate that rat hepatic
microsomes reduce N-(2-methoxyphenyl)hydroxylamine
to o-anisidine independently on activities of NADPH:CYP
reductase. The present study shed also some light on the
role of specific microsomal CYP enzymes in metabolism of
N-(2-methoxyphenyl)hydroxylamine. The CYP1A enzymes
seem to be most efficient in N-(2-methoxyphenyl)hydrox-
ylamine reduction. Nevertheless, the question whether
CYP2E1 is also effective in reducing N-(2-methoxyphenyl)
hydroxylamine, remains to be answered. Among hepatic
microsomes tested in this study, those of rats treated with
ethanol (enriched with CYP2E1) produced the lowest levels
of o-anisidine from N-(2-methoxyphenyl)hydroxylamine.
In contrast, o-aminophenol was the major metabolite
in microsomes enriched with CYP2E1, generated at the
highest levels among the microsomes employed in the
experiments. These findings suggest that CYP2E1 is not
effective in N-(2-methoxyphenyl)hydroxylamine reduc-
tion. Nevertheless, because CYP2E1 is the most effective CYP
enzyme oxidizing o-anisidine to o-aminophenol (Stiborová
et al., 2005; Naiman et al., 2008), one can speculate that
this enzyme efficiently utilizes o-anisidine, which could
be generated in this microsomal system, oxidizing it to
o-aminophenol. Therefore, the participation of CYP2E1
in N-(2-methoxyphenyl)hydroxylamine reduction to
o-anisidine cannot be excluded and awaits further investi-
gation. The study utilizing purified CYP2E1 reconstituted
with NADPH:CYP reductase is planned to be performed to
explain this question.

While the formation of N-(2-methoxyphenyl)hydroxyl-
amine was clearly identified to be the activation pathway
of o-anisidine and o-nitroanisole metabolism (Stiborová
et al., 2004; 2005), biological significance of formation of
o-aminophenol for detoxication/activation metabolism
awaits further investigation. o-Aminophenol might be con-
sidered to be mutagenic, because it induces sister chromatid
exchanges in a dose-dependent manner in cultured human
lymphocytes in vitro and in Chinese hamster bone marrow
cells in vivo (Kirchner and Bayer, 1992). In addition, Brennan
and Schiestl (1997) reported that o-aminophenol is positive
in the deletion recombination assay in Saccharomyces cere-
visiae. Even though o-aminophenol has not been found to
form covalent DNA adducts, it was demonstrated in in-vitro experiments to cause DNA damage, forming 8-oxy-
7,8-dihydro-2′-deoxyguanosine in the presence of metal
ions such as Cu(II) (Okhuma and Kawanishi, 2001). Hence,
due to such processes, o-aminophenol may contribute to
initiation of the o-anisidine- and/or o-nitroanisole-
mediated carcinogenesis in the urinary bladder, and in a
tumor development induced by other bladder carcinogenic
aromatic amines, which produce this compound as one of the
metabolites (Brennan and Schiestl, 1997). Furthermore,
O-demethylation reactions produce formaldehyde (Figure
1), which is known to modify DNA, generating several
products including hydroxymethyl adducts and cross-links
(Beland et al., 1984; Huang and Hopkins, 1993; Cheng et al.,
2003). Formaldehyde is mutagenic in a variety of different
test systems and carcinogenic in laboratory animals (IARC,
2006) and has been described as “carcinogenic to human”
by the IARC and “reasonably anticipated to be a human
carcinogen” by the U.S. Department of Health and Human
Services (2004). Therefore, on the one hand, it is plausible
that formaldehyde-DNA adducts could also play a role in
carcinogenesis by o-anisidine. On the other hand, however,
formaldehyde produced in the cell is also detoxified by
conjugation to glutathione and oxidized (Dhарeshwar and
Stella, 2008); therefore, it is not likely a strong contributor
to carcinogenicity caused by o-anisidine.

It should be noted that tumor development in a specific
organ is influenced by promotional pressures on initiated
cells in target organs and not only by the levels of DNA
adducts formed by the compounds like o-anisidine and
o-nitroanisole. It is known that radicals formed from sev-
eral carcinogens producing oxidative DNA damage, such
as 8-hydroxy-2′-deoxyguanosine, are important not only in
initiation, but also in promotion phases of carcinogenesis
(Imaoka et al., 2004). Therefore, their formation from o-ami-
nophenol may be one of the factors contributing to tumor
promotion in o-anisidine- and/or o-nitroanisole-mediated
carcinogenesis. In addition, o-anisidine is oxidized by sev-
eral peroxidases, which are expressed in target organs (e.g.
COX), to form radicals besides DNA adducts (Brennan and
Schiestl, 1999; Sasaki et al., 1998). Hence, the production of
such free radicals in or near the target cells may be another
factor important in the promotional process in o-anisidine-
mediated tumor development. However, the exact functions
of such and/or other promoting pressures caused both by \(\alpha\)-anisidine and \(\alpha\)-aminophenol in an \(\alpha\)-anisidine-mediated tumorigenesis remain to be resolved.

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**REFERENCES**

Balaban AT, Garfield HE, Lesko MJ, Setz WA. (1998) Synthesis and spectral data of some new \(N\)-nitroso-\(N\)-phenylhydroxylamine (cupferon) derivatives. Org Prep Proced Int 30: 439–446.

Beland FA, Fullerton NF, Heilich RH. (1984) Rapid isolation, hydrolysis and chromatography of formaldehyde-modified DNA. J Chromatogr 308: 121–131.

Brauner B, Kutzer C, Zwickenplug W, Scherer G, Heller W-D, Richter E. (1998) Heme globin adducts from aromatic amines and tobacco-specific nitrosamines in pregnant smoking and non-smoking women. Biomarkers 3: 35–47.

Brennan RJ, Schiestl RH. (1997). Aniline and its metabolite generate free radicals in yeast. Mutagenesis 12: 215–220.

Brennan RJ, Schiestl RH. (1999) The aromatic amine carcinogens \(\alpha\)-toluidine and \(\alpha\)-anisidine induce free radicals and intrachromosomal recombination in Saccharomyces cerevisiae. Mutat Res 430: 37–45.

Cheng G, Shi Y, Sturla S, Jalas J, Mckeele EI, Villalta PW, Wang M, Hecht SS. (2003) Reactions of formaldehyde plus acetaldehyde with deoxyguanosine and DNA. Formation of cyclic deoxyguanosine adducts and formaldehyde cross-links. Chem Res Toxicol 16: 145–152.

Dhaheshwar SS, Stella VJ. (2008) Your prodrug releases formaldehyde: Should you be concerned? Nat J Pharm Sci: 418–4193.

Faifer B, Kutzer C, Richter E. (1994) Bimonitoring of hemoglobin adducts: aromatic amines and tobacco-specific nitrosamines. Clin Investig 72: 364–371.

Garnier RC, Martin CN, Clayson DB. (1984) (2nd ed. Searle C, Ed.) Carcinogenic amines and tobacco-specific nitrosamines. CRC Press. 18: 1109–1118.

Huang H, Hopkins PB. (1998) DNA internist cross-linking by formaldehyde: nucleotide sequence preference and covariant structure of the predominant cross-link formed in synthetic oligonucleotides. J Am Chem Soc 115: 9402–9408.

Imada S, Osada M, Minamiyama Y, Yukiura T, Toyokuni S, Takekura S, Hiroi T, Funae Y. (2004) Role of phenobarbital-inducible cytochrome P450s as a source of active oxygen species in DNA-damage. Cancer Lett 203: 117–125.

IARC. (1982) Ortho- and para-anisidine and their hydrochlorides. IARC, Monographs on the Evaluation of the Carcinogenic Risk of Chemicals to Humans, No. 27, IARC, Lyon.

IARC. (2006) Formaldehyde, 2-butoxyethanol and 1-terc-butoxypropan-2-ol. IARC Monographs on the Evaluation of Carcinogenic Risk to Humans, Vol. 88, pp. 39–325, IARC, Lyon.

Kim D, Kadialar FF, Teitel CH, Guengerich FP. (2000) Formation and reduction of aryl and heterocyclic nitro compounds and significance in the flux of hydroxylamines. Chem Res Toxicol 13: 529–538.

Kicher G, Bayer U. (1992) Genotoxic activity of the aminophenols as evidenced by the induction of sister chromatid exchanges. Hum Toxicol 1: 387–392.

Miklanová M, Novák P, Frei E, Stiborová M. (2004) Metabolism of carcinogenic 2-nitroaniline by rat, rabbit, porcine and human hepatic cytosol. Collect Czech Chem Commun 69: 589–602.

Naiman K, Dračínská H, Martínková M, Šulc M, Dračínský M, Kejlová L, Hodek P, Hudeček J, Libenda J, Schmeiser HH, Frei E, Stiborová M. (2008) Redox cycling in the metabolism of the environmental pollutant and suspected human carcinogen \(\alpha\)-anisidine by rat and rabbit hepatic microsomes. Chem Res Toxicol 21: 1610–1621.

NTP. (1978) Bioassay of \(\alpha\)-anisidine hydrochloride for possible carcinogenicity. NTP Technical Report 89, National Institute of Health, US Department of Health and Human Services, Bethesda, MD.

NTP. (1993) Toxicology and Carcinogenesis. Studies of 2-nitroanisole. NTP Technical Report 416, National Institute of Health, US Department of Health and Human Services, Bethesda, MD.

Okumura Y, Kawanshi S. (2001) Osvitadena DNA damage induced by a metabolite of carcinogenic \(\alpha\)-anisidine: enhancement of DNA damage and alteration in its sequence specificity by superoxide dismutase. Arch Biochem Biophys 389: 49–56.

Omura T, Sato R. (1964) The carbon monoxide-binding pigment of liver microsomes. I. Evidence for its hematoprotein nature. J Biol Chem 239: 2370–2378.

Richter E, Rosler S, Scherer G, Gostomzyk KG, Gruhl A, Kamer U, Behrendt H. (2001) Haemoglobin adducts from aromatic amines in children in relation to area of residence and exposure to environmental tobacco smoke. Int Arch Occup Environ Health 74: 421–428.

Rýdlová H, Miklanová M, Rýdlová H, Stiborová M. (2005) Carcinogenic pollutants, \(\alpha\)-nitroanisole and \(\alpha\)-anisidine are substrates and inducers of cytochromes P450. Biomed Papren 49: 441–447.

Sakai YF, Nishidate E, Su YQ, Matsuda N, Tsuda S, Suza N, Furukawa Y, Ueno S. (1998) Organ-specific genotoxicity of the potent rodent bladder carcinogen \(\alpha\)-anisidine and p-cresidine. Mutat Res 412: 155–160.

Seidenfaden W. (1971) Methoden der Organischen Chemie (Houben-Weyl), Band X/1, Georg Thieme Verlag, Stuttgart, p. 1058.

Sottocasa GL, Kuylenstierna I, Ernst I, Bergstrand A. (1967) An electron transport inhibitor formed in synthetic oligonucleotides. Biochemistry 6: 9402–9408.