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Research article

Polymorphisms in GSTT1, GSTM1, NAT1 and NAT2 genes and bladder cancer risk in men and women

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Abstract

**Background:** Cigarette smoking is an established risk factor for bladder cancer. Epidemiological and biological data suggest that genetic polymorphisms in activating and detoxifying enzymes may play a role in determining an individual’s susceptibility to bladder cancer in particular when in combination with specific environmental exposures such as cigarette smoking. N-acetyltransferase (NAT) enzymes, NAT1 and NAT2, are involved in the activation and detoxification of tobacco smoke constituents. Polymorphisms in these genes alter the ability of these enzymes to metabolize carcinogens, as certain allelic combinations result in a slow or rapid acetylation phenotype. Glutathione S-transferases (GSTs) also detoxify tobacco smoke constituents, and polymorphisms within the GSTM1 and GSTT1 genes can result in a complete lack of enzyme activity.

**Methods:** We assessed the association between common polymorphisms identified in the GSTM1, GSTT1, NAT1, and NAT2 genes and the risk of bladder cancer in two nested case-control studies within the Nurses’ Health Study (n = 78 female cases, 234 female controls) and the Health Professionals’ Follow-up Study (n = 139 male cases, 293 male controls). We also evaluated whether cigarette smoking modified the associations of the genotypes and bladder cancer risk in men and women.

**Results:** Overall, we observed no statistically significant associations between the polymorphisms and bladder cancer risk among men and women, although given our sample size, we had limited power to detect small to moderate effects. There was however the suggestion of an increased risk among female ever smokers with the NAT2 slow genotype and an increased risk in male never smokers with the GSTM1 null genotype.

**Conclusion:** In summary, these prospective results are consistent with previous literature supporting associations between bladder cancer and the NAT2 slow acetylation and the GSTM1 null genotypes.

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Background
Cigarette smoking is the predominant risk factor for bladder cancer in males and females [1-5]. Carcinogens such as aminophenyls (ABPs) found in tobacco have been implicated in bladder cancer etiology in smokers [6]. N-acetyltransferase (NAT) enzymes, NAT1 and NAT2, are involved in the metabolism of these carcinogens via O- and N-acetylation [7]. NAT2 and NAT1 are involved in the detoxification and bioactivation of carcinogens [8,9]. Four major NAT1 alleles, NAT1*3, NAT1*4, NAT1*10, NAT1*11 [10], and three common NAT2 alleles, NAT2*5, NAT2*6, NAT2*7, have been identified in Caucasian populations [7]. Individuals homozygous for NAT2 rapid acetylator alleles are classified as rapid-acetylator phenotype; individuals homozygous for NAT2 slow acetylator alleles are classified as slow-acetylator phenotype, and heterozygous individuals (one rapid and one slow acetylator allele) are classified as the intermediate phenotype [11]. The slow NAT2 acetylation genotype compromises its detoxification ability, and studies have consistently observed an association between the slow NAT2 genotype and increased bladder cancer risk [11-13]. The presence of one copy of the NAT1*10 allele has been associated with a rapid phenotype [8,10] however a more recent study does not support these earlier findings [14]. Several studies have investigated the association between the NAT1 variant alleles and bladder cancer risk with inconsistent results [14-20]. Fewer studies however have formally evaluated whether the relationship of cigarette smoking and bladder cancer risk differed by acetylation status [11,16,18-20].

Glutathione S-transferases (GSTs) are involved in the metabolism of environmental carcinogens, reactive oxygen species, and chemotherapeutic agents by catalyzing reactions between glutathione and electrophilic compounds [21,22]. Glutathione S-transferase M1 (GSTM1) is involved in the detoxification of polycyclic aromatic hydrocarbons (PAHs) and benzo(a)pyrene found in tobacco smoke [23,24]. Glutathione S-transferase T1 (GSTT1) is involved in activation and detoxification reactions and catalyzes the conjugation of industrial chemicals, e.g. ethylene oxides, with glutathione [25]. Homozygous deletions of the GSTM1 and GSTT1 genes are common and result in a complete loss of enzyme activity [22,26,27]. Because the metabolism of tobacco-related carcinogens may be influenced by the activity of GSTs, polymorphisms in GSTM1 and GSTT1 may modify the risk of bladder cancer associated with these carcinogens. The GSTM1 null polymorphism has been consistently associated with an increased risk of bladder cancer in pooled and meta-analyses [11,23,28]. Studies investigating the importance of GSTT1 in bladder carcinogenesis are more limited and inconsistent [19,24,29-35]. Since exposure to tobacco smoke carcinogens is a risk factor for bladder cancer, genetic modulation of carcinogen metabolism may explain some inter-individual bladder cancer susceptibility. Given their biological role, polymorphisms within the GSTT1, GSTM1, NAT1, and NAT2 genes may be important in determining an individual’s susceptibility to bladder cancer. Recent studies have also suggested that although the risk associated with each variant may be small, in combination with other genetic and/or environmental factors, the effects of the polymorphisms may be increased. We examined the associations between polymorphisms within these key genes and bladder cancer risk in a nested case-control study of women participating in the Nurses’ Health Study (NHS) and a nested case-control study of men participating in the Health Professionals’ Follow-Up Study (HPFS). Furthermore, we assessed the potential for effect modification by cigarette smoking for the associations between the genotypes and bladder cancer risk.

Methods
Nurses’ Health Study
The NHS began in 1976 when 121,700 female United States registered nurses aged 30–55 years completed a self-administered questionnaire. Detailed information on individual characteristics and behaviors was obtained from the questionnaires at baseline and biennially thereafter. Between 1989 and 1990, blood samples were collected from 32,826 women; follow-up for this subcohort exceeds 96%. The methods used for blood collection have been previously detailed [36].

Case-control study
In our study, we included both incident and prevalent bladder cancer cases from the NHS blood cohort. Trained physicians who were blinded to exposure information reviewed hospital records and pathology reports. We were able to confirm approximately 95% of self-reported bladder cancer cases. Eligible incident cases consisted of women with confirmed bladder cancer that had been diagnosed anytime after blood collection (1989–90) and up to June 1, 2000, with no previously diagnosed cancer except for nonmelanoma skin cancer. Prevalent cases were defined as having confirmed bladder cancer diagnosed after questionnaire return in 1976 and before the date of blood collection, with no previously diagnosed cancer except for nonmelanoma skin cancer. Controls were randomly selected participants who had given a blood sample and were free of diagnosed cancer (except nonmelanoma skin cancer) up to and including the interval in which the case was diagnosed. Controls were matched to cases 3:1 according to year of birth, smoking status at blood draw (never versus ever), month of blood collection, and fasting status at blood draw (for possible plasma hormone analyses). This case-control study con-
sists of 78 bladder cancer cases (47 incident cases and 31 prevalent cases), and 234 matched controls. In addition, 2646 women who were controls in either a nested case-control study of breast cancer (n = 1686) [37,38], colon cancer (n = 461) [39], and colon polyps (n = 499), were free of cancer other than nonmelanoma skin cancer, and were genotyped for the three NAT2 polymorphisms. All cases were confirmed through histopathologic reports reviewed by a study investigator. Eligible cases in this analysis were confirmed through histopathologic reports reviewed by a study investigator.

**Case-control study**

In our study, we included both incident and prevalent bladder cancer cases from the HPFS blood cohort. All cases in this analysis were confirmed through histopathologic reports reviewed by a study investigator. Eligible incident cases consisted of men with confirmed bladder cancer that had been diagnosed anytime after blood collection (1993–95) and up to June 1, 2000, with no previously diagnosed cancer except for nonmelanoma skin cancer. Prevalent cases were defined as having confirmed bladder cancer diagnosed after questionnaire return in 1986 and before the date of blood collection, with no previously diagnosed cancer except for nonmelanoma skin cancer.

Controls were matched to cases 3:1 according to year of sample collection. For cases accrued between 1993 and 1995 from 18,025 participants. Approximately 95% of the samples arrived within 24 hours of blood draw.

**Health professionals’ follow-up study**

The HPFS is an ongoing prospective study of the causes of chronic diseases in men. The cohort began in 1986 when 51,529 U.S. male health professionals aged 40 to 75 years responded to a mailed questionnaire [41]. These men provided detailed information on medical histories and health-related exposures at baseline and biennial questionnaires thereafter. The follow-up for these participants is approximately 93%. Blood samples were collected between 1993 and 1995 from 18,025 participants. Approximately 95% of the samples arrived within 24 hours of blood draw.

**Sample collection**

Venous blood samples were separated into plasma, buffy coat, and red blood cells and stored in liquid nitrogen. Genomic DNA was extracted from 50 μL buffy coat diluted with 150 μL of PBS using the QIAGEN QIAmp Blood protocol according to the manufacturer’s instructions. Genomic DNA concentrations were calculated in 96-well format using PicoGreen technology (Molecular Probes, Eugene, OR).

**Genotyping methods**

Genotyping was performed at the DFCI/Harvard Cancer Center High Throughput Genotyping Core. The NAT2 II14T (NAT2*5A), R197Q (NAT2*6A), and G286E (NAT2*7A) polymorphisms were genotyped by the 5' nuclelease assay (Taqman) on the ABI PRISM 7900HT Sequence Detection System (Applied Biosystems, Foster City, CA). A description of and methods for each NAT2 assay can be found at the National Cancer Institute SNP500Cancer website [42]. We did not genotype polymorphisms that are rare (defined as < 5% frequency) in Caucasian populations [7], such as the NAT2*14 allele (G191A) [43]. For consistency with previous studies, participants were classified as slow NAT2 acetylators if they were homozygous for any combination of the three slow acetylators (NAT2*5A, NAT2*6A, NAT2*7A) [11]. Rapid acetylators for NAT2 were defined as being either homozygous or homozygous for the wildtype NAT2*4 allele.

We genotyped four common NAT1 alleles, NAT1*3 (C1095A), NAT1*4 (wildtype), NAT1*10 (C1095A and T1088A), NAT1*14 (G560A, T1088A and C1095A), and NAT1*11 (deletion of nine nucleotides from 1080 to 1088) [15,44]. The NAT1*4 allele is the most common allele in all populations studied, and the homozygous NAT1*4 genotype has been associated with normal NAT1 acetylation activity [7]. The NAT1*10 allele is considered the putative rapid allele in comparison with NAT1*3, NAT1*4, NAT1*11, and NAT1*14 [10]. All individuals with the NAT1*10 genotype were classified as either homozygous or heterozygous rapid acetylators.
Genotypes for the GSTT1 and GSTM1 deletions were determined by polymerase chain reaction (PCR) using a previously published protocol [40]. In both assays, the absence of the PCR product was indicative of the null genotype; these assays do not distinguish between heterozygous or homozygous wildtype genotypes.

All genotyping was performed by laboratory personnel blinded to case-control status, and blinded quality control samples were inserted to validate genotyping identification procedures; concordance for blinded samples was 100%.

**Statistical analysis**

We used a χ2 test to assess whether the genotypes were in Hardy-Weinberg equilibrium and to determine P values for differences in genotype frequencies between cases and controls. The associations between the genotypes and bladder cancer risk were examined by using conditional and unconditional logistic regression to calculate odds ratios (ORs) and 95% confidence intervals (CIs). Unconditional logistic regression models assessing the main effect of the genotype on bladder cancer risk included the additional control groups to maximize the sample size, stabilize CIs, and to increase the power to detect meaningful associations. In addition to the matching factors, analyses were also adjusted for packyears of smoking (i.e. average reported number of cigarette packs smoked per day multiplied by the number of years of smoking). Inclusion of additional factors, e.g. geographic region, alcohol intake, cruciferous vegetable intake, did not substantially change the point estimates, and therefore these factors were not included in the final models. To test statistical interactions between the genotypes and cigarette smoking in unconditional models, we first used a likelihood-ratio test (LRT) to compare nested models that included terms for all combinations of the genotypes and cigarette smoking status to the models with indicator variables for the main effects only (nominal LRT). To test the statistical interaction between the various genotypes, a similar approach was employed. All p-values are two-sided. We used the SAS Version 8.2 software (SAS Institute, Cary, NC). Because the allele frequencies of NAT1, NAT2, GSTM1, and GSTT1 differ by ethnicity [7,23,24,45,46], all analyses were restricted to Caucasians. Numbers may vary for the different analyses due to missing genotype data. We had 80% power to detect the following ORs for the men: OR = 1.8 for the GSTM1 null genotype assuming a genotype prevalence of 50%; OR = 2.0 for the GSTT1 null genotype assuming a genotype prevalence of 15%; OR = 2.3 for the NAT2 slow acetylation genotype assuming a genotype prevalence of 62%; OR = 2.1 for the NAT1*10 carrier assuming a genotype prevalence of 35%.

**Results**

**Population characteristics**

Our study population included 78 bladder cancer cases and 234 matched controls from the NHS and 139 bladder cancer cases and 293 matched controls from the HPFS for a total of 217 bladder cancer cases and 526 matched controls. The risk factor profile for female bladder cancer cases and controls were similar with no statistically significant differences between cases and controls (Table 1). Similarly, no significant differences in risk factor distributions were observed in cases and controls in the HPFS (Table 1). Risk factor distributions between incident and prevalent cases in the NHS and incident and prevalent cases in the HPFS were also similar. A comparison of the population characteristics of the second control group with the first control group revealed no material differences in risk factor profiles in the NHS and HPFS.

We compared the distributions of the GSTM1, GSTT1, NAT1, and NAT2 genotypes between incident and prevalent bladder cancer cases in men and women separately to determine whether the variant alleles were associated with survival. All of the genotype frequencies were similar among incident and prevalent cases in the NHS and in the HPFS (p > 0.2). Therefore, all incident and prevalent cases in each cohort were combined to form one case group for all statistical analyses. The genotype frequencies were in Hardy-Weinberg equilibrium for cases and controls. The allele frequencies among the controls for the GSTM1 null allele, GSTT1 null allele, NAT2 rapid genotype, and the NAT1 rapid genotype were similar to previously published reports in Caucasians [10,18,23,26,38,46,47]. Results from the conditional logistic regression analyses using only the matched dataset were similar to the results obtained from the unconditional analyses that included the additional controls.

**Nurses’ Health Study**

In the NHS, the prevalence of GSTM1 null genotype was similar among cases and controls (48.4% versus 52.5%, respectively, p = 0.54), in contrast to the GSTT1 null genotype, which was more prevalent in cases than controls (21.9% vs. 15.2%, respectively, p = 0.16). After adjusting for the matching factors and packyears of smoking, we observed no association between the GSTM1 and GSTT1 polymorphisms and bladder cancer risk in women (Table 2). We did not observe any statistically significant effect modification by cigarette smoking status for the GSTM1 and the GSTT1 null genotypes and bladder cancer risk (p
for interaction $> 0.30$). Our results also do not support a gene-gene interaction between the GSTT1 and GSTM1 polymorphisms ($p$ for interaction $= 0.88$).

The frequency of the NAT2 slow acetylation genotype was similar among cases and controls (68.3% versus 62.1%, respectively, $p = 0.32$) (Table 3). The adjusted OR for the slow acetylation genotype compared to the rapid acetylation genotype was 1.33 (95% CI, 0.77–2.31). After stratification by cigarette smoking status, the association between NAT2 slow acetylation genotype and bladder cancer risk was stronger but not statistically significant among ever smokers (OR = 1.76; 95% CI, 0.88–3.52) ($p$ for interaction = 0.15). We observed no significant association between bladder cancer risk and individuals carrying the NAT1*10 allele (Table 3), and no effect modification by cigarette smoking status for the NAT2 or NAT1 genotypes and bladder cancer risk ($p$ for interaction $> 0.4$).

**Health professionals’ follow-up study**

There were no significant differences in GSTM1 and GSTT1 genotype frequencies among cases and controls ($p = 0.09$ and 0.63, respectively), and no statistically significant associations between the GSTM1 and GSTT1 polymorphisms and bladder cancer risk in males (Table 2). We did observe a statistically significant interaction between the GSTM1 null genotype, cigarette smoking, and bladder cancer risk in males ($p$ for interaction $= 0.02$). Among never smokers, the GSTM1 null genotype was associated with a statistically significant increased risk (OR $= 3.23$ (95% CI, 1.38, 7.58)), and among ever smokers, the OR was 0.96 (95% CI, 0.55–1.66). The association between GSTT1 polymorphism and bladder cancer risk remained similar after stratification by smoking status ($p$ for interaction $= 0.69$), and no significant gene-gene interactions with GSTM1 and GSTT1 were detected ($p$ for interaction $= 0.22$).

The frequency of the NAT2 slow acetylation genotype was similar among cases and controls (57.3% versus 61.8%, $p = 0.32$) (Table 3). The adjusted OR for the slow acetylation genotype compared to the rapid acetylation genotype was 0.78 (95% CI, 0.53–1.15). We observed no significant association between bladder cancer risk and carrying the NAT1*10 allele (Table 3). Furthermore, we did not observe any statistically significant effect modification by cigarette smoking status for the NAT2 or NAT1 genotypes and bladder cancer risk ($p$ for interaction $> 0.4$).

**Discussion**

Evidence suggests that polymorphisms in activating and detoxifying enzymes may interact to effect the level of DNA damage sustained by a specific tissue and ultimately influence disease risk [47]. Therefore, imbalances between activation and detoxification processes may result in an increase in bladder cancer risk due to the accumulation of carcinogen metabolites, e.g. from cigarette smoking. Overall, in our population-based case-control study, we observed no statistically significant associations between the GSTT1, GSTM1, NAT1, and NAT2 polymorphisms and bladder cancer risk.

Aromatic amines within tobacco smoke are the most important class of bladder carcinogens [48]. These compounds may be partially responsible for the increased...
bladder cancer risk observed among slow NAT2 acetylators who have a decreased capacity to detoxify aromatic amines. Our data suggest an association between the NAT2 slow acetylation genotype and increased bladder cancer risk in female smokers. Our findings are biological plausible and are consistent with a recent study in Spain [11], which found that NAT2 slow acetylators have an increased risk of bladder cancer that was stronger for cigarette smokers compared to never smokers.

NAT1 polymorphisms may also affect individual bladder cancer risk by interacting with cigarette smoking. Our findings do not support an association between the NAT1 polymorphisms, cigarette smoking, and bladder cancer; however we had little power to detect such an association. Additional studies that have assessed the relationship between NAT1*10 allele and bladder cancer risk have been inconsistent with some studies observing an increased risk [17,20], a decreased risk [15], or no association [11,16,18,19]. Larger epidemiological studies are required to clarify the relationship between bladder cancer risk and the NAT1*10 allele.

We observed no significant associations with the GSTM1 polymorphism and bladder cancer risk, which is in contrast with previous findings [11,23]. The potential role of the GSTT1 polymorphism on bladder cancer susceptibility is less certain. Studies that have addressed the role of GSTT1 polymorphism and bladder cancer have been inconsistent. Of the published studies, some suggest an increased risk [19,31,34,35] with the GSTT1 null genotype, others no association [11,29,30], and only one suggests a decreased risk [24]. We observed no significant association with the GSTT1 polymorphism and bladder cancer risk.

The strengths of our study include the prospective design and the detailed collection of exposure information (i.e. cigarette smoking) prior to bladder cancer diagnosis. We were also able to formally assess and test gene-environment interactions. However, our study has a small sample size resulting in low power to detect minor to modest genotype-disease associations and gene-environment interactions, therefore such associations cannot be ruled out.

Conclusion
In summary, our data support the prior evidence that the GSTM1 null genotype and the NAT2 slow acetylation genotype may affect an individual's bladder cancer risk.

Abbreviations
HPFS, Health Professionals' Follow-Up Study; NHS, Nurses' Health Study; N-acetyltransferase, NAT; GSTT1, Glutathione S-transferase T1; GSTM1, Glutathione S-transferase M1; PAH, polycyclic aromatic hydrocarbons; OR, odds ratio; CI, confidence interval; LRT, likelihood ratio test

Competing interests
The author(s) declare that they have no competing interests.

Authors' contributions
MM carried out the data analysis and wrote the manuscript. DM and ID conceived of the study, participated in
Table 3: Association between NAT1 and NAT2 and bladder cancer risk among women and men

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<tr>
<th>Genotype</th>
<th>NHS Case, n (%)</th>
<th>Control, n (%)</th>
<th>OR (95% CI)</th>
<th>OR (95% CI)</th>
<th>HPFS Case, n (%)</th>
<th>Control, n (%)</th>
<th>OR (95% CI)</th>
<th>OR (95% CI)</th>
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<td><strong>NAT2 genotype</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Rapid and intermediate acetylators</td>
<td>20 (31.8)</td>
<td>1007 (37.9)</td>
<td>1.00 ref</td>
<td>1.00 ref</td>
<td>53 (42.7)</td>
<td>463 (38.2)</td>
<td>1.00 ref</td>
<td>1.00 ref</td>
</tr>
<tr>
<td>Slow acetylator</td>
<td>43 (68.3)</td>
<td>1645 (62.0)</td>
<td>1.31 (0.77, 2.26)</td>
<td>1.33 (0.77, 2.31)</td>
<td>71 (57.2)</td>
<td>750 (61.8)</td>
<td>0.81 (0.55, 1.19)</td>
<td>0.78 (0.53, 1.15)</td>
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<tr>
<td><strong>NAT1 genotype</strong></td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Any allele</td>
<td>48 (72.9)</td>
<td>139 (67.2)</td>
<td>1.00 ref</td>
<td>1.00 ref</td>
<td>84 (65.6)</td>
<td>179 (65.8)</td>
<td>1.00 ref</td>
<td>1.00 ref</td>
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<tr>
<td>*10/*10 carrier</td>
<td>17 (26.2)</td>
<td>68 (32.9)</td>
<td>0.76 (0.40, 1.42)</td>
<td>0.77 (0.41, 1.44)</td>
<td>44 (34.4)</td>
<td>93 (33.9)</td>
<td>1.06 (0.68, 1.66)</td>
<td>1.07 (0.68, 1.70)</td>
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<tr>
<td>*10/*10 + *10/*10</td>
<td>39 (70.9)</td>
<td>116 (65.2)</td>
<td>1.00 ref</td>
<td>1.00 ref</td>
<td>71 (65.7)</td>
<td>149 (64.2)</td>
<td>1.00 ref</td>
<td>1.00 ref</td>
</tr>
<tr>
<td><strong>10/10</strong></td>
<td>16 (29.1)</td>
<td>62 (34.8)</td>
<td>0.79 (0.41, 1.54)</td>
<td>0.81 (0.42, 1.57)</td>
<td>37 (34.3)</td>
<td>83 (35.5)</td>
<td>0.98 (0.60, 1.59)</td>
<td>1.00 (0.61, 1.65)</td>
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1 unconditional logistic regression adjusted for age and smoking status
2 unconditional logistic regression adjusted for age, smoking status, and packyears of smoking

its design and coordination and helped to draft the manuscript. All authors read and approved the final manuscript.

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