Reduction of Gstm1 Expression in the Stroke-Prone Spontaneously Hypertension Rat Contributes to Increased Oxidative Stress


Abstract—Human essential hypertension is a classic example of a complex, multifactorial, polygenic disease with a substantial genetic influence in which the underlying genetic components remain unknown. The stroke-prone spontaneously hypertensive rat (SHRSP) is a well-characterized experimental model for essential hypertension and endothelial dysfunction. Previous work, identified glutathione S-transferase \( \mu \) type 1, a protein involved in detoxification of reactive oxygen species, as a positional and functional candidate gene. Quantitative real-time polymerase chain reaction showed a highly significant, 4-fold reduction of glutathione S-transferase \( \mu \) type 1 mRNA expression in 5- and 16-week-old SHRSP compared with the congenic and normotensive Wistar Kyoto rats. This suggests that differential expression is not attributable to long-term changes in blood pressure. DNA sequencing identified one coding single nucleotide polymorphism (R202H) and multiple single nucleotide polymorphisms in the promoter region. mRNA expression changes were reflected at the protein level, with significant reductions in the SHRSP glutathione S-transferase \( \mu \) type 1. Protein was colocalized with aquaporin 2 to the principle cells of the renal collecting ducts. Coupled to significant increases in nitrotyrosine levels in the kidney, this suggests a pathophysiological role of this protein in hypertension and oxidative stress. Similar processes may underlie oxidative stress in the vasculature.

Key Words: rats, stroke-prone SHR ■ hypertension, genetic ■ gene expression ■ oxidative stress

Human essential hypertension is a classic example of a complex, multifactorial, polygenic disease with a substantial genetic influence in which the underlying genetic components remain unknown.\(^1\)\(^-\)\(^4\) The methodological difficulties in studying the genetic determinants of hypertension have given a major impetus for development of similar but inherently simpler paradigms in rodent models of genetic hypertension that remain under complex control.\(^5\)\(^-\)\(^7\) Genetic heterogeneity can be reduced by the use of inbred strains with complete control over environmental influences. Moreover, the ability to produce genetic crosses and analyze large numbers of progeny facilitate genetic analysis, including genetic dissection of complex phenotypes, gene–gene and gene–environment interactions.\(^8\)\(^-\)\(^10\)

The stroke-prone spontaneously hypertensive rat (SHRSP) is a well-characterized experimental model for essential hypertension and endothelial dysfunction.\(^11\)\(^-\)\(^13\) Genome-wide scans performed on several rat crosses have identified quantitative trait loci (QTLs), which are involved in blood pressure regulation.\(^5\) However, these represent large chromosomal regions and contain too many putative candidate genes to pursue classic positional cloning strategies. More recently, generation of congenic strains in which blood pressure QTLs from a normotensive strain have been introgressed into a hypertensive background has allowed genetic dissection of QTLs in hypertensive strains.\(^13\)\(^-\)\(^16\) Recent studies using a combination of the SP.WKY\(\text{Gla}\) congenic strain, derived from SHRSP\(\text{Gla}\) and WKY\(\text{Gla}\), and genome-wide microarray expression profiling, have shown significantly reduced expression of glutathione S-transferase \( \mu \) type 1 (\(Gstm1\)) in kidneys of SHRSP\(\text{Glu}\) compared with SP.WKY\(\text{Glu}\)\(,2\)\(^c\) congenic and WKY\(\text{Glu}\) controls.\(^17\) \(Gst\) forms a superfamily, the dimeric proteins of which catalyze a number of distinct glutathione-dependent reactions but can also function as peroxidases and isomerases.\(^18\)\(^-\)\(^20\) The primary role of \(Gst\) is the metabolism of a broad range of reactive oxygen species (ROS) and xenobiotics, and they have been implicated in a number of diseases, including childhood asthma\(^21\) and lung cancer,\(^22\) although little work has been undertaken in cardiovascular disease and hypertension.

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The current study was designed to investigate renal expression and cellular localization of GSTM1 together with parallel measurements of oxidative stress in renal and vascular tissues.

### Methods

#### Rat Strains

Inbred colonies of SHRSP<sub>ca</sub> and WKY<sub>ca</sub> have been developed at the University of Glasgow since 1991, as described previously. The congenic strain used in the current study contains a 22-cM segment transferred from WKY<sub>ca</sub> to the genetic background of SHRSP<sub>ca</sub> using a marker-assisted “speed” congenic strategy as described previously. The full name of this strain is SP.WKY<sub>ca</sub>2c* (D2Wox9-D2 Mgh12), abbreviated to SP WKY<sub>ca</sub>2c* for simplicity. Brown Norway (BN) and the spontaneously hypertensive rat (SHR) strains were purchased from Harlan. These studies were approved by the home office according to regulations regarding experiments with animals in the United Kingdom, which are equivalent to US regulations.

#### Quantitative Real-Time Polymerase Chain Reaction

Renal total RNA was extracted from 5- and 16-week-old rats using RNeasy kits (Qiagen), treated with DNase Free (Ambion), and accurately quantified using Ribogreen (Molecular Probes). Normalization was confirmed by performing real-time polymerase chain reaction (PCR) on either Lightcycler (Roche) or TaqMan (Applied Biosystems) of β-actin (Promega) with comparable threshold cycle values.

Lightcycler RT-PCR was performed in a single run with 0.5 μmol/L each primer for Gstm<sub>1</sub> F5’-TTT GAG CCC AAG TGC CTG GA-3’ R 5’-GCA GGA TCC AAT GTG GAC AG-3’. A standard curve was generated from various dilutions of cloned, linearized Gstm<sub>1</sub> plasmid. TaqMan probes for Gstm<sub>1</sub> (Rn00755117m1-labeled FAM) and β-actin (4352340E-labeled VIC) were multiplexed. Expression of Gstm<sub>1</sub> relative to β-actin in each sample was derived using the comparative (∆∆CT) method.

#### Sequencing

Two strategies were used to sequence the Gstm1 gene from SHR-SP<sub>ca</sub>, SP.WKY<sub>ca</sub>2c*, WKY<sub>ca</sub>, and the SHR and BN. Renal RNA was used as a template for RT-PCR amplifying Gstm1 from each of the 5 strains. PCR primers were also designed to exon 1 and genomic DNA regions upstream of the Gstm1 using BN genome sequence as a template (supplemental Table I, available online at http://www.hypertensionaha.org). Gstm1 upstream sequences from rat Gstm1, mouse gstm1 and gstm3, and all human GSTM family were obtained from ENSEMBL and compared using rVISTA 2.0, and putative promoter regions were inferred from the transcriptional database.

#### Western Analysis of GSTM1 and Nitrotyrosine in Rat Kidney

Kidneys were removed rapidly from terminally anesthetized 16-week-old SHRSP<sub>ca</sub>, SP.WKY<sub>ca</sub>2c*, WKY<sub>ca</sub>, and the SHR and BN. Renal RNA was used as a template for RT-PCR amplifying Gstm1 from each of the 5 strains. PCR primers were also designed to exon 1 and genomic DNA regions upstream of the Gstm1 using BN genome sequence as a template (supplemental Table I, available online at http://www.hypertensionaha.org). Gstm1 upstream sequences from rat Gstm1, mouse gstm1 and gstm3, and all human GSTM family were obtained from ENSEMBL and compared using rVISTA 2.0, and putative promoter regions were inferred from the transcriptional database.

#### Immunohistochemistry on Rat Kidneys

Wax sections (5 μm) were obtained from kidneys of 16-week-old SHRSP<sub>ca</sub> and WKY<sub>ca</sub> male rats. After treatment with antigen retrieval solution (DAKO), sections were blocked with 20% serum in PBS for 1 hour. Antibodies were incubated overnight at 4°C with an antibody against GSTM1 and then aquaporin 2 (AQP2). Washing with PBS was followed by incubation with a mixture of secondary antibodies, anti-rabbit IgG—fluorescein isothiocyanate and donkey anti-goat IgG conjugated with Alexa Fluor 350 (Molecular Probes), at room temperature for 1 hour. Fluorescence was detected on the Olympus BX40 fluorescent microscope using the U-MWIB and U-MWU cubes.

#### Superoxide Levels in Kidney and Vascular Tissues

Superoxide was measured using 20 μmol/L lucigenin chemiluminescence in thoracic aorta as described previously. Similar methods were used for kidney tissue dissected into renal medulla and cortex. The tissue was homogenized in 0.05 mol/L phosphate buffer, pH 7.8, and detected with 1.5 μmol/L lucigenin. Frozen sections of thoracic aorta were prepared (30 μm). Samples were incubated with hydroethidine (2 μmol/L for 20 minutes) and florescence detected using a Bio-Rad laser scanning confocal microscope. SHRSP<sub>ca</sub>, WKY<sub>ca</sub>, and SP.WKY<sub>ca</sub>2c* samples were analyzed in parallel. Dedicated software was used to measure average florescence of each vessel.

#### Results

#### Lightcycler Quantitative Real-Time PCR

Renal Gstm1 mRNA levels were assessed by quantitative real-time PCR (qRT-PCR) in male rats at 5 weeks of age, before the onset of significant hypertension in the SHRSP<sub>ca</sub> and at 16 weeks of age, when hypertension is fully established (Figure 1). There were significant reductions in Gstm1 mRNA in the SHRSP<sub>ca</sub> compared with SP.WKY<sub>ca</sub>2c* and WKY<sub>ca</sub> in 5- and 16-week age groups with similar levels in SP.WKY<sub>ca</sub>2c* and Wistar Kyoto rats (WKY).

#### Sequencing of Rat Gstm1

Sequencing of SHRSP<sub>ca</sub>, SHR, SP.WKY<sub>ca</sub>2c*, and WKY<sub>ca</sub> Gstm1 exons identified a nonsynonymous single nucleotide polymorphism (SNP), changing arginine 202 (Arg 202) to
histidine (R202H) in the SP.WKY_gla2c* congeneric and WKY-gla strains. The same amino acid was identified in the BN rat but not in other Gstm isoforms from rat, mouse, and human (Figure 2A; Table). In addition, the crystal structure of rat GSTM1 was referred to to model the potential effects of the substitution of R202H, in which Arg 202 was found to be surface located and distal from the active site (data not shown). Using genomic DNA as template, sequencing was extended to include the upstream, regulatory regions and identified 11 SNPs, an insertion, and a deletion (Figure 2A). In all cases, sequence differences between the SHRSP_gla and SHRSP_gla and BN (Figure 2A). Moreover, these sequence differences were predictive for renal Gstm1 expression levels in each of the strains (Figure 2B). rVISTA 2.0 plots identified conserved sequences in the putative promoter between rat Gstm1, mouse gstm1, mouse gstm3, and human GSTM1 and GSTM5. Of the 11 SNPs identified, 3 were localized to conserved transcription factor binding sites: acute myloid leukemia (AML1) and hepatic nuclear factor 4 sites (HNF4).

Western Analysis
To determine whether the significant reduction in Gstm1 mRNA levels resulted in a significant reduction in GSTM1 immunoreactive protein, Western analysis was performed in male, 16-week-old SHRSP_gla, SP.WKY_gla2c*, and WKY_gla strains (Figure 3A). A single immunoreactive protein band of ~26 kDa was detectable in each of the strains using GSMT1 antibody. Densitometry of these immunoblots was performed and confirmed significant reductions of GSTM1 protein levels in the SHRSP_gla (n=3; SHRSP_gla 2.3±0.5 versus SP.WKY_gla2c* 4.4±0.6; 95% confidence interval [CI], 0.7, 3.5; SHRSP_gla 2.3±0.5 versus WKY_gla 4.8±0.1; 95% CI, −1.0, −4.1; F=18.2; P=0.005). Nitrotyrosine immunoreactivity was used as a measure of oxidative stress in the kidneys of SHRSP_gla (Figure 3B). Western analysis clearly identified immunoreactive bands corresponding to nitrotyrosine at several sizes extracted from rat kidney. These bands were consistently more intense in kidneys from SHRSP_gla than SP.WKY_gla2c* and WKY_gla when normalized to Gapdh (Figure 3B).
**Discussion**

We investigated renal expression and cellular localization of the protein encoded by *Gstm1* together with parallel measurements of oxidative stress in renal and vascular tissues. We identified previously *Gstm1* as a positional candidate gene for hypertension in the SHRSP strain using a combination of congenic strain construction and microarray expression profiling. Using qRT-PCR, we observe a significant reduction in renal *Gstm1* mRNA levels in 5-week-old SHRSP compared with SP.WKY 2c* congenic and WKY parental rats at a time point before the onset of significant hypertension in the SHRSP strain. This suggests that altered gene expression of *Gstm1* may contribute directly to the pathogenesis of hypertension and is not an adaptive response caused by long-term differences in blood pressure.

Recent developments from the rat genome consortium have allowed the first assessment of the frequency of SNPs within rat strains, and many have focused on SNPs in protein coding regions because these polymorphisms are most likely to contribute to phenotypic differences. The identification of Arg 202 in the SHRSP strain and His 202 in the WKY strain is intriguing; however, it is clear that amino acid 202 is principally conserved as arginine in many of the GSTM enzymes. Furthermore, the modeling of the R202H amino acid change showed no perturbations other than the breaking of a local salt-bridge, and therefore, the substitution would be unlikely to affect enzyme activity. However, it is clear that SNPs in noncoding regions may also have functional effects, as suggested by evolutionary conservation and the mapping of human disease susceptibility to noncoding regions. The frequency and organization of SNPs identified in the *Gstm1* regulatory sequences are consistent with the observation that SNPs are not randomly distributed across loci, reflecting regional variation with only a small proportion potentially disrupting transcription factor binding sites. Using *in silico* strategy, 3 of the 13 SNPs identified were mapped to conserved promoter regions across rat, mouse, and human *Gstm* genes, including 2 AML1 and HFN4 transcription factors and may account for differences of expression between SHRSP and WKY strains. The expression of several other glutathione S-transferases and cytochrome P450s has been shown to be regulated by HNF transcription factors. These results are further supported by our new findings that the *Gstm1* gene sequence and its mRNA expression are very similar between the SHRSP strain and the SHR (Harlan).

The significant reduction in *Gstm1* protein levels and immunohistochemical localization present an intriguing hypothesis. The distal part of the nephron, composed of the distal convoluted tubule and collecting duct, has the primary role in determining net NaCl and K balance. One of the principal functions of the collecting tubule is the reabsorption of NaCl. This activity is regulated at least partially by NO. A reduced bioavailability of NO has been postulated to...
contribute to the development of hypertension, but the underlying mechanism has not been resolved, particularly in light of the fact that a number of groups have shown either no change or enhanced expression of NO synthase in the kidneys of hypertensive rats. Welch et al demonstrated that the SHR kidney has increased immunoreactive expression of nitrotyrosine. Because antioxidants such as membrane-permeant superoxide dismutase blunt exaggerated tubular glomerular filtration responses, it has been proposed that the SHR kidney has an increased production of superoxide, which decreases the bioavailability of locally formed NO. We now suggest that the SHR kidney has an increased production of superoxide, which decreases the bioavailability of locally formed NO. We now suggest that the SHR kidney has an increased production of superoxide, which decreases the bioavailability of locally formed NO. We now suggest that the SHR kidney has an increased production of superoxide, which decreases the bioavailability of locally formed NO. We now suggest that the SHR kidney has an increased production of superoxide, which decreases the bioavailability of locally formed NO.

Figure 4. Immunohistochemical localization of GSTM1 and AQP2 in rat kidney sections. GSTM1 expression in SHRSPGlu (A and C) and WKYGlu (B and D) kidneys. E, AQP2 expression in WKYGlu. F, Overlay of GSTM1 and AQP2 sections in WKYGlu. Nonimmune IgG control sections for GSTM1 (G) and AQP2 (H). Sections were counterstained with propidium iodide to visualize nuclei (red). All experiments were performed ≥3× with representative pictures being shown here.

Perspectives
We propose that GSTM1 may represent a novel candidate gene for hypertension and oxidative stress. The oxidative stress pathway has been implicated not only in the pathogenesis of endothelial dysfunction and hypertension but also all other modifiable cardiovascular risk factors, including diabetes, obesity, and hyperlipidemia. Therefore, imbalance between generation of ROS and endogenous antioxidant defenses might be central to several cardiovascular phenotypes.
existence of 4 human orthologues will make it possible to translate these data directly to human studies.

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