Nitric oxide generation in children with malaria and the NOS2G-954C promoter polymorphism

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Planche T, Macallan DC, Sobande T, Borrmann S, Kun JF, Krishna S, Kremsner PG. Nitric oxide generation in children with malaria and the NOS2G-954C promoter polymorphism. Am J Physiol Regul Integr Comp Physiol 299: R1248–R1253, 2010. First published September 1, 2010; doi:10.1152/ajpregu.00390.2010.—Previous epidemiological studies have demonstrated a protective association between the NOS2G-954C (NOS2Lambaréné) polymorphism in inducible nitric oxide synthase and severe malaria. The polymorphism is common in children with uncomplicated compared with severe malaria. We now show that the likely mechanism for such protection is increased flux of nitrogen from arginine into nitric oxide (NO) during episodes of malaria. Forty-seven boys with uncomplicated malaria received an infusion of 15N-arginine to measure directly whole body NO production. The NOS2G-954C genotype previously associated with reduced risk of severe malaria in Gabon was also assessed. Evaluable data were obtained from 40 boys, of whom 6 were NOS2G-954C heterozygotes. Heterozygotes had higher urinary 15N nitrate enrichments, 2.3 ± 0.6 vs. 1.4 ± 0.5 atoms percent excess (P = 0.001) and higher ratios of 15N between urine nitrate and plasma arginine (87 ± 11 vs. 57 ± 18%, P = 0.001) consistent with accelerated NO production. We also derived total NO production rates, combining data with total urine production rate and nitrate concentration; these showed no difference by genotype (0.62 ± 0.36, n = 6 vs. 0.83 ± 0.50 μmol/kg·h, n = 16; P = 0.36), but data were confounded by very high variability in measurements of urine output and nitrate concentrations. This study supports the idea that NOS2 genotype protects against severe malaria by increasing NO production during episodes of uncomplicated malaria.

malaria; nitric oxide; nitric oxide synthase; polymorphism

The nitric oxide radical (NO) modulates key physiological processes and antimicrobial defenses. NO is synthesized from L-arginine by the enzyme nitric oxide synthase (NOS). The inducible form of the enzyme, iNOS, and NOS2 (NOS1 and NOS3 being constitutive enzymes) is found in many cells and tissues that are important in orchestrating immunoregulatory processes. Examples include macrophages, where NO has a role in parasite killing and endothelial cells, where vascular tone and adhesion-receptor expression play a critical role in immune responses. NOS2 can elicit high levels of NO production, and its expression is largely controlled by proinflammatory cytokines through transcriptional mechanisms (10).

Several years ago, we noted that a polymorphism in the NOS2 gene, NOS2G-954C (NOS2Lambaréné), was distributed nonrandomly in children with severe and uncomplicated malaria in Gabon, being more frequent in children with uncomplicated disease (18). The NOS2G-954C polymorphism was also associated with significant delay in time to reinfection with malaria, when compared with children who did not carry it (17). Extending these studies to other regions confirmed that this polymorphism is found in other malaria-endemic regions, such as Tanzania (19), is present in Americans of African origin (19), but it is very rare in southeast Asia (3, 9), and absent in white Americans (19) and Germans (18). Heterozygosity for the NOS2 promoter G954C polymorphism, but not C1173T, was associated with a significantly lower incidence of malaria compared with carrying the wild-type allele in children in Uganda (incident rate ratio = 0.69, P = 0.05) (23). However, not all studies have found a protective association from this genotype. In Tanzanian children, no consistent associations were found between several NOS2 promoter haplotypes and malaria severity and anemia, NOS2 expression or plasma/urine [nitrate + nitrite] (NOx) concentrations (19, 20), although in one subgroup, the G954C haplotype was associated with protection from clinical malaria (20).

What is the mechanism for such putative protection? Malaria induces NOS expression in peripheral blood mononuclear cells (PBMC) of children with malaria, an effect promoted by parasite-generated hemozoin (15). G954C heterozygosity is associated with higher plasma nitrate levels in young children with malaria (<24 mo) (7) and with elevated unstimulated NOS enzyme activity in PBMC (17). Similarly, the C1173T polymorphism also appears to protect by increased NO synthesis as reflected by increased fasting urine and plasma NO metabolite concentrations in Tanzanian children (13). Taken together, these data suggest that specific genotypes promote enhanced NO responses, which protect against severe malaria (7, 13, 15, 29), but the direct in vivo physiological link has not yet been conclusively demonstrated.

One of the difficulties establishing the effect of a specific genotype on NO metabolism is that surrogate measures of NO production, such as plasma and urine NOx concentrations, are highly variable, being profoundly influenced by dietary nitrate intake, urinary output, and changes in renal function. Even after controlling for dietary influences and correcting with creatinine concentrations, NOx levels do not provide wholly reliable estimates of NO production. These methodological limitations can be avoided by using isotopically labeled arginine, which distinguishes between nitrate derived from NO production and that arising from other sources (22).

We took this latter approach, using 15N-labeled arginine to measure in vivo rates of NO production in children with...
uncomplicated malaria. We then applied the principle of Mendelian deconfounding to test the original hypothesis that increased nitric oxide production protects against severe malaria (27), by relating results of in vivo NO production in patients with uncomplicated malaria to the presence of the NOS2G-954C gene polymorphism for NOS2. Tests of this hypothesis are particularly relevant as interventional studies designed to increase NO production in malaria are being implemented (31).

METHODS

Subjects and Clinical Assessment

Male children with uncomplicated malaria aged between 3 and 10 yr attending the Albert Schweitzer Hospital, Lambaréné, Gabon, were recruited to the study. Only male subjects were included to facilitate collection of urine samples. Uncomplicated malaria was defined by fever (rectal temperature >38°C) and parasitemia (the presence of 20,000–200,000 parasites/μl of asexual stages of Plasmodium falciparum in thick or thin blood films), in the absence of clinical or biochemical evidence of severe malaria [such as repeated vomiting, convulsions, coma, severe anemia (packed cell volume <20%), hyperlactatemia (≥5 mmol/l) or hypoglycemia (≤2.2mmol/l)]. Alternative diagnoses were excluded clinically. Children were admitted and managed for malaria according to standard protocols, as described elsewhere (24), receiving a single oral dose of sulfadoxine/pyrimethamine as therapy. All study procedures were approved by the Ethics Committees of the International Foundation of the Albert Schweitzer Hospital and the Gabonese Ministry of Health, and informed consent was obtained from all parents.

Clinical Protocol

To investigate NO metabolism during an episode of malaria, we used in vivo labeling with guanadino-[15N2]-arginine, as previously described (22). Because the guanadino nitrogens of arginine are the substrate for NO production, the rate of NO production can be derived from the rate of appearance of [15N]-nitrate in urine. Subjects received L-[guanadino-15N2]arginine (Cambridge Isotopes Laboratory, Cambridge, MA) as an intravenous infusion at a rate of 2 μmol/kg·h−1 over 12 h after a priming dose (2 μmol/kg) to achieve rapidly steady-state levels of enrichment in plasma arginine. Plasma samples (0.4 ml) were taken for measurement of arginine enrichment at baseline and at approximately hourly time-points from 6 h to the end of the study. At the start of the infusion 14 μg/kg of [15N]-sodium nitrate was given as an oral solution to prime the urinary nitrate pool with [15N]; this avoids long equilibration times before plateau measurements of urinary [15N] can be made (22). A urine sample was collected at the beginning of the study, when subjects were encouraged to void urine. Subjects were encouraged to void again at 6 h, 8 h, and the end of the infusion, and all urine volumes were measured and aliquots (≥5 ml) retained for [15N]-nitrate analysis. If boys did not void after 12 h, the infusion was continued until voiding. No dietary restrictions were used in vivo labeling with guanadino-15N2-arginine, as previously described (22).Subjects received L-[guanadino-15N2]arginine (Cambridge Isotopes Laboratory, Cambridge, MA) as an intravenous infusion at a rate of 2 μmol/kg·h−1 over 12 h after a priming dose (2 μmol/kg) to achieve rapidly steady-state levels of enrichment in plasma arginine. Plasma samples (0.4 ml) were taken for measurement of arginine enrichment at baseline and at approximately hourly time-points from 6 h to the end of the study. At the start of the infusion 14 μg/kg of [15N]-sodium nitrate was given as an oral solution to prime the urinary nitrate pool with [15N]; this avoids long equilibration times before plateau measurements of urinary [15N] can be made (22). A urine sample was collected at the beginning of the study, when subjects were encouraged to void urine. Subjects were encouraged to void again at 6 h, 8 h, and the end of the infusion, and all urine volumes were measured and aliquots (≥5 ml) retained for [15N]-nitrate analysis. If boys did not void after 12 h, the infusion was continued until voiding. No dietary restrictions were used in vivo labeling with guanadino-15N2-arginine, as previously described (22).
were NOS2G-954C heterozygotes, and one was homozygous for this polymorphism. Clinical characteristics and level of parasitemia were similar for wild-type homozygotes and heterozygotes.

When $^{15}$N enrichments were assessed, plasma arginine enrichment reached a plateau in most subjects at about 2 or 3 atoms percent excess (APE) (mean 2.39 APE) after about 6 h; a typical plot is shown in Fig. 1. This enrichment equates to an average arginine flux through the plasma pool of $\sim$84 μmol/h·kg total body weight, in a similar range, but about 50% higher than values obtained previously in healthy adults, 56 μmol/h·kg [recalculated from (22) for total weight]. Urinary nitrate enrichment reached a plateau in most subjects at $\sim$1.5 APE. In two (wild-type) subjects isotopic plateau estimation was not possible and in a further four (all wild-type), only usable nitrate or arginine enrichment data were available, but not both.

When isotopic enrichments were compared, we found that urinary nitrate $^{15}$N enrichments were significantly higher in heterozygotes for NOS2G-954C than in wild-type subjects, 2.27 ± 0.63 vs. 1.37 ± 0.51 APE, respectively ($P = 0.001$ by Student’s $t$-test; Table 2, Fig. 2). Furthermore, the ratio of urinary nitrate enrichment to plasma arginine enrichment, which gives an index of the proportion of urinary nitrate arising from NO production, was also significantly higher in heterozygotes than in control subjects: 87 ± 11% vs. 57 ± 18% ($P = 0.001$ by Student’s $t$-test; Table 2, Fig. 2). The value from the single homozygote (for NOS2C-954) is given in the table, but no comparisons were made with other groups, in view of the fact that this was a sole individual. Thus, heterozygosity for NOS2G-954C appears to be characterized by higher rates of conversion of arginine to nitrate in children with uncomplicated malaria.

We also attempted to derive data on total nitrate excretion (reflecting constitutive, as well as inducible NO production), but data were confounded by the difficulty collecting complete and accurate timed urine collections in sick young boys in field clinical settings (we wished to avoid clinically unnecessary catheterization); refusal or inability to pass urine and partial voiding and incomplete urine collections were common. As a consequence, we found very wide interindividual variation in calculated total nitrate production rates, ranging by a factor of almost 10 (minimum 0.3, maximum 2.5 μmol/h·kg, Table 2, Fig. 2), whether normalized for body weight or body surface area. Combining nitrate production rate data with enrichment data yielded total NO production rates with similarly wide variance, resulting in data that overlapped between groups: 9.9 ± 4.9 μmol/h in heterozygotes vs. 16.0 ± 11.9 μmol/h in wild-type subjects ($P = 0.22$, Mann Whitney $U$-test) and coefficients of variation of $>$50% [compare values of $<30$% from previous studies (22) used for power calculations]. Total NO production rates, normalized for body weight, were 0.83 ± 0.50 μmol/h·kg in wild-type and 0.62 ± 0.36 μmol/h·kg in heterozygotes. Normative data are not available for children, but these values are three- or four-fold higher than those seen in healthy adults 0.23 ± 0.04 μmol/h·kg [recalculated for total body weight from (22); $n = 8$; $P < 0.001$ and $P < 0.05$ respectively]. Normalizing for body surface area rather than weight yielded similar conclusions (data not shown).

**DISCUSSION**

Some studies have suggested a protective role against malaria for the NOS2G-954C polymorphism (NOS2LaMbaréné) in African children (17). We now provide evidence that the mechanism for this protection is enhanced synthesis of nitric

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**Table 1. Demographic characteristics**

<table>
<thead>
<tr>
<th></th>
<th>$n$</th>
<th>Age, mo (range)</th>
<th>Weight, kg (SD)</th>
<th>Height, cm (range)</th>
<th>Parasitemia, $\times 10^9$/l (median)</th>
</tr>
</thead>
<tbody>
<tr>
<td>All subjects</td>
<td>40</td>
<td>66.9 ± 23.8</td>
<td>18.8 ± 4.6</td>
<td>110 ± 11</td>
<td>45,216</td>
</tr>
<tr>
<td>Wild-type</td>
<td>33</td>
<td>(34–128)</td>
<td>(12.8–30.4)</td>
<td>(91–134)</td>
<td>(11,304–461,560)</td>
</tr>
<tr>
<td>Heterozygotes</td>
<td>6</td>
<td>68.3 ± 21.9</td>
<td>19.0 ± 4.4</td>
<td>111 ± 10</td>
<td>43,960</td>
</tr>
<tr>
<td>Homozygote</td>
<td>1</td>
<td>58.7 ± 35.4</td>
<td>17.5 ± 6.2</td>
<td>105 ± 15</td>
<td>82,834</td>
</tr>
</tbody>
</table>

Values are expressed as means ± SD for age, weight, and height characteristics and as the median for parasitemia. No significant differences were found in any of the parameters shown between wild type and heterozygotes by Student’s $t$-test (2-tailed) or Mann Whitney $U$ test for nonparametric comparisons.
Oxide from arginine. Using in vivo labeling studies, we find that during an episode of uncomplicated malaria, heterozygotes for the NOS2G-954C polymorphism have higher rates of conversion of arginine to NO (by a mean of \(66\%\)) when compared with those without the polymorphism. (We excluded severe cases to avoid a potential selection bias, as we hypothesized that progression from uncomplicated to severe disease would itself be associated with alterations in NO production.) This study provides a mechanistic pathway explaining how the innate NO defense pathway may limit the impact of *P. falciparum* infection, consistent with previous work from Gabon and Uganda, showing reduced episodes of clinical malaria in those carrying the NOS2G-954C polymorphism (17, 23).

There are several mechanisms by which NO may exert its protective effects in malaria. First, NO is directly parasiticidal in vitro (2, 25). Previous work has shown inconsistent relationships between parasitemia in vivo and indirect measures of NO production, such as plasma nitrogen oxides (7), although elevations in NO are sometimes inversely correlated with peripheral parasitemia (1, 16). In this study, there was no relationship between admission parasitemia and measures of NO synthesis. Second, increased NO may modulate many aspects of endothelial cell function in ways that protect against development of severe disease (30, 31). For example, NO counteracts the upregulatory effects of proinflammatory stimuli on the expression of endothelial cell adhesion molecules, such as

![Fig. 2. Effect of NOS2G-954C promoter polymorphism on products of nitric oxide (NO) synthesis.](http://ajpregu.physiology.org/)

**Table 2. Indices of NO metabolism in malaria**

<table>
<thead>
<tr>
<th>Genotype</th>
<th>Plasma Arginine, %</th>
<th>Urine Nitrate, %</th>
<th>Nitrate/Arginine Ratio, %</th>
<th>Urine Total Nitrate Production Rate</th>
<th>Total, (\mu)mol/h</th>
<th>Per Unit Weight, (\mu)mol/h/kg</th>
<th>(^{15})N Nitrate Excretion Rate</th>
<th>NO Production Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wild-type</td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>n</td>
<td>27</td>
<td>27</td>
<td>23†</td>
<td>26</td>
<td>26</td>
<td>20</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>Average</td>
<td>2.39</td>
<td>1.37</td>
<td>57.3</td>
<td>23.9</td>
<td>1.3</td>
<td>0.35</td>
<td>16.0</td>
<td>0.83</td>
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<tr>
<td>SD</td>
<td>0.52</td>
<td>0.51</td>
<td>18.3</td>
<td>14.2</td>
<td>0.7</td>
<td>0.22</td>
<td>11.9</td>
<td>0.50</td>
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<tr>
<td>NO polymorphism</td>
<td></td>
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<tr>
<td>n</td>
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<td>6</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>6</td>
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<tr>
<td>Average</td>
<td>2.67</td>
<td>2.27*</td>
<td>86.9*</td>
<td>11.2</td>
<td>0.7</td>
<td>0.26</td>
<td>9.9</td>
<td>0.62</td>
</tr>
<tr>
<td>SD</td>
<td>0.90</td>
<td>0.63</td>
<td>10.8</td>
<td>5.3</td>
<td>0.4</td>
<td>0.16</td>
<td>4.9</td>
<td>0.36</td>
</tr>
<tr>
<td>NO polymorphism</td>
<td></td>
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<tr>
<td>Homozygotes</td>
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<td></td>
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<td></td>
</tr>
<tr>
<td>n = 1</td>
<td>2.16</td>
<td>1.15</td>
<td>53.2</td>
<td>21.8</td>
<td>1.2</td>
<td>0.25</td>
<td>11.6</td>
<td>0.66</td>
</tr>
</tbody>
</table>

\*P < 0.01 by Student’s t-test, two tailed. †In 4 subjects, only arginine or only nitrate data were available.
as intracellular adhesion molecule-1 and vascular cell adhesion molecule-1 (8, 26). This would be predicted to decrease the risk of complications resulting from microvascular obstruction in severe syndromes of malaria by reducing cytoadhesion of parasitized erythrocytes. Consistent with this suggestion, low NO bioavailability is associated with poorer outcome in an animal model of cerebral malaria (12). A possible mechanistic role for NO in the coma of human cerebral malaria has been reviewed recently (6).

In this study, we also attempted to evaluate differences in whole body NO production rates between heterozygotes and wild-type subjects but found no significant difference. We believe this is because whole body NO production estimates were confounded by uncertainty in the true values for urine production rate and nitrate concentration. Furthermore, it appears that not all nitrate produced systemically will appear in the urine (28). Comparing serial samples (data not shown), we found very high intraindividual variability in urine production rates and in urinary nitrate measurements (urine dilution sometimes changing dramatically with rehydration after admission). Such observations highlight the difficulties inherent in the use of NO, data alone to derive NO production, particularly in clinical or field settings and explains some of the variability seen in other published studies. The use of $^{15}$N-arginine as a specific tracer for NO synthesis allowed us to circumvent such difficulties by making direct comparisons between $^{15}$N enrichment in plasma arginine and urinary nitrate. An alternative model mathematically consistent with our findings is that children with the wild-type promoter had a difference in $^{15}$N nitrate enrichment but not total NO production because they excreted larger amounts of unlabeled nitrate. It is hard to conceive a physiological mechanism by which this might occur unless dietary nitrate intake were very biased between the two groups; although we did not control dietary intake there is no reason to suppose this was the case. This study was limited by a number of subjects whose data could not be used. Longer infusion times may have improved the proportion achieving plateau values but would have been logistically more difficult. When compared with historical control healthy adults, our data are consistent with accelerated NO production in children with malaria, although the relative contributions of age and disease cannot be separated.

Why is the geographical distribution of the NOS2G-954C polymorphism restricted to areas that have malaria? This observation would be consistent with deleterious consequences of the heterozygous state in nonmalaria-affected populations, although alternative explanations warrant further investigation. An analogy may be drawn here with the sickle cell trait, although there are no data to support the notion that a homozygous state for the polymorphism (NOS2G-954C) is deleterious to the carrier. This polymorphism is found in populations of African origin, but it is not found in Caucasians or in most Asians (3). The possibility of linkage disequilibrium between NOS2 haplotypes must also be considered (4, 19). Other polymorphisms of NOS2 may also contribute to variation in NO synthesis, including single nucleotide substitutions at positions $-1173$ (C-1173T) (13), and $-1659$ (C-1659T) (4), as well as a microsatellite repeat (CCTTTn) 2.5 kb upstream from the NOS2 transcription start site (5). Although such genotypes have been associated with protection from malaria, they were not included in our primary hypothesis for testing; we chose to focus on NOS2G-954C in this study because of its high local prevalence, but the possibility of linkage disequilibrium between NOS2 haplotypes must also be considered (4, 19).

Despite best-available parasiticidal therapy, mortality from malaria is still significant, especially in children, emphasizing the need for better adjunctive therapies. Of the mortality associated with childhood malaria, a significant proportion is related to cerebral disease. Endothelial adhesion of parasitized erythrocytes is a contributor to pathology and modifying NO metabolism is, therefore, one potential avenue toward increasing survival. Proposals to consider interventions that aim to do this should include consideration of the effects of host genotype on whole body NO production.

One proposed strategy is to administer arginine directly on the basis that arginine availability may become rate-limiting for NO production during an episode of malaria (12, 21). In support of such an approach, some data suggest that arginine flux may be accelerated in infected individuals (32). Consistent with this, our values for arginine flux were 50% higher than in healthy adults studied using the same methodology, although the relative contributions of age and disease cannot be distinguished. This accelerated flux is probably not solely related to increased NO production as only about 5% of plasma arginine flux is directed toward NO synthesis in the healthy state (22). Arginine infusion appears to be safe (32), but efficacy data are pending.

Perspectives and Significance

This study has extended our previous epidemiological observations by providing a mechanistic link between the NOS2G-954C polymorphism and in vivo NO physiology. This study also has methodological implications: the use of $^{15}$N-arginine as a tracer, combined with a novel assay for $^{15}$N in nitrate (14), allowed us to identify changes in NO flux, which probably would not have been apparent from nitrate measurements alone. This study also supports the further exploration of NO manipulation as adjunctive therapy in the treatment of malaria.

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DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the authors.

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