Role Of Endothelin-1 and Nitric Oxide Bioavailability in Transplant-Related Vascular Injury
Comparative Effects of Rapamycin and Cyclosporine

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Background—Cyclosporine (CyA) is associated with many side effects, including endothelial dysfunction and transplant vasculopathy (TxV). We previously demonstrated that CyA results in impairment of nitric oxide bioavailability and enhanced sensitivity to endothelin-1 (ET-1). In this study, we evaluated rapamycin (SRL) for its effects on the endothelium.

Methods and Results—Lewis rats (n = 8) were injected with SRL (1.5 mg/kg), CyA (5 mg/Kg), or saline (Con) intraperitoneally daily for 2 weeks. Thoracic aortic segments were assessed for endothelial-dependent (Edep) and independent (Eind) relaxation after exposure to acetylcholine and sodium nitroprusside by deriving the percent maximum relaxation (Emax). ET-1 plasma levels were also measured. Thoracic aortic expression of endothelial nitric oxide synthase (eNOS), ETα and ETβ receptors (Rc), were determined. Oxidative injury was assessed by changes in 8-isoprostane levels. CyA exposure resulted in lower Edep vasorelaxation compared with control and SRL (Emax: SRL, 58 ± 4%; CyA, 24 ± 7%; Con, 52 ± 8%; P = 0.001). No differences in Eind vasorelaxation were seen. CyA exposure also increased sensitivity to ET-1 (% maximum contraction [Cmax]: Con, 211 ± 8%; SRL, 230 ± 5%; CyA, 259 ± 3%; P = 0.04). Only SRL treatment reduced ET-1 plasma levels. CyA reduced eNOS expression by 30% and increased ETA Rc expression by 34% compared with both Con and SRL (P = 0.02). CyA resulted in higher 8-isoprostane levels (CyA, 50 ± 2%; SRL, 3 ± 3%; Con, 2 ± 5%; P = 0.02).

Conclusions—CyA results in vascular dysfunction characterized by impairment of Edep vasorelaxation and enhanced sensitivity to vasospasm. SRL did not impair Edep vasorelaxation or increase sensitivity to vasospasm while lowering ET-1 levels and preserving eNOS protein expression. We conclude that SRL is less deleterious to the vasculature than CyA and may prevent TxV by these mechanisms. (Circulation. 2006;114[suppl I]:I-214–I-219.)

Key Words: cyclosporine ■ endothelial function ■ nitric oxide ■ rapamycin

Cyclosporine (CyA) was the first anti-rejection drug that impacted the results of clinical organ transplantation by reducing the incidence and severity of rejection and remains an important component of modern therapy. Unfortunately, CyA is associated with many side effects, such as nephrotoxicity, hepatotoxicity, neurotoxicity, and hypertension. CyA has also been implicated in the development of endothelial dysfunction and transplant vasculopathy (TxV). CyA demonstrated that eNOS mRNA expression is increased after CyA treatment, suggesting that impaired NO production is likely due to decreases in eNOS protein synthesis or a shift to free radical production. There is also evidence that CyA may generate free radicals. These free radicals may result in direct endothelial injury and impaired vasomotor function.

Rapamycin (SRL), a relatively new immunosuppressant, is a macrolide antibiotic. SRL belongs to a class of drugs known as inhibitors of target of rapamycin (TOR). Several studies have demonstrated that SRL has both an anti-proliferative effect and a protective effect against the development of TxV in a rodent model. Corbin et al have shown that SRL led to vasomotor relaxation of rat aortic rings in a dose-
dependent fashion. In contrast, Jeanmart et al demonstrated that SRL results in worse endothelial-dependent vasorelaxation than CyA. However, both of these studies exposed the vasculature to rapamycin ex vivo for a short duration, making in vivo correlation unreliable. In addition the vehicle used for rapamycin in Jeanmart’s study also resulted in endothelial dysfunction. Whether SRL results in endothelial dysfunction or impairs NO–ET-1 homeostasis remains unclear. Clinically, SRL has been demonstrated to reduce the incidence, progression, and severity of TxV, yet the mechanisms by which SRL leads to endothelial protection and prevention of TxV remain unknown.

Our investigations assess the role of CyA and SRL on the development of endothelial dysfunction in a rodent model of vascular injury. Specifically, we examine the effects of CyA and SRL exposure on NO homeostasis and ET-1 signaling. We chose a nontransplant model for these initial experiments to evaluate the direct effects of CyA and SRL in the absence of either ischemia-reperfusion or immune-mediated injury.

**Materials and Methods**

All authors have read and agree to the manuscript as written. The authors had full access to the data and take full responsibility for their integrity.

Animal care conformed to the Canadian Council on Animal Care Guide to the Care and Use of Experimental Animals (National Institutes of Health publication 86-23, revised 1996). Male Lewis rats (200 to 300 grams, n = 8 per group) were administered the drug of interest (saline control, CyA [5 mg/kg per day]) or SRL [1.5 mg/kg per day]) via peritoneal injection for a period of 14 days before assessment of endothelial function. On the day of euthanization (day 15), rats were anesthetized using isoflurane. A median sternotomy was performed and the thoracic aorta excised for tissue sampling. Segments of the descending thoracic aorta were procured for assessment of endothelial function. Before tissue excision, 1 mL of blood from the right ventricle was collected for analysis of ET-1 plasma levels. The rats were then exsanguinated under general anesthesia.

**Endothelial Function Assessment**

Endothelial-dependent and independent vascular relaxation was assessed in isolated segments of thoracic aorta after treatment. The aorta was dissected and segments 5 mm in length were used for the assessment of in vitro vascular function using a small vessel myograph for isometric tension recording. After mounting the vessel on a pressure transducer, maximum vasoconstriction was achieved with exposure to phenylephrine (100 nmol/L). After stabilization, endothelial-dependent relaxation was assessed by incremental exposure to acetylcholine (Ach). Endothelial-independent relaxation was assessed using incremental exposure to sodium nitroprusside (SNP).

Complete vasomotor data for all groups are presented in the figures and the percent change from these baseline values was calculated to compare differences between groups.

**Assessment of Oxidative Injury**

8-isoprostane levels were measured as an indicator of free radical injury. 8-isoprostane is the stable end product of arachidonic acid oxidation generated by reactive oxygen species injury. Determination of 8-isoprostane levels from thoracic aortic tissue was performed using a commercially available kit (Cayman Chemical Company; Ann Arbor, Mich). Baseline assessments were made on aortic segments harvested from control animals not subjected to intraperitoneal injections and the percent change from these baseline values was calculated to compare differences between groups.

**Statistical Analysis**

Statistical analysis was performed with the SAS statistical software program version 8.2 (SAS Institute Inc, Cary, NC). Continuous data were analyzed by analysis of variance (ANOVA) and are expressed as the mean±standard deviation. When the F-statistic of the ANOVA was significant (P<0.05), a Duncan multiple range test was performed to specify differences between groups.

**Results**

All animals survived until day of euthanization with no complications. There was minimal variability from aortic segments within each animal and no animals were excluded from the study. Plasma measurements of each immunosuppressant revealed a mean CyA level of 60±11 ng/mL and an SRL level of 7±1 ng/mL.

**Endothelial Function**

Endothelial-dependent vasorelaxation of the thoracic aorta was impaired after CyA treatment (Figure 1a). CyA resulted in an Emax% of 24±7%, lower than that of control 52±8% and SRL 58±4% (P<0.001). No significant differences in endothelial-independent vasorelaxation to SNP were seen between groups (Figure 1b). However, when examining the relaxation curves, a lag in vasodilatory response to SNP is observed after CyA therapy. The concentration of SNP necessary to achieve 50% of maximal vasodilatory response demonstrated significant differences between groups (Figure 2). A doubling of the SNP Ed50 was seen after CyA (Ed50 6.3×10−4±1.2 mol/L) treatment compared with both control (Ed50 3.2×10−8±1.0 mol/L) and SRL (Ed50 2.5×10−8±1.1 mol/L) (P=0.01). Differences between SRL and control were not significant.

**Oxidative Assessment**

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Sensitivity to ET-1–induced vasospasm revealed significant differences between groups, with %Cmax greater in the CyA-treated group compared with control and SRL (CyA 259% ± 3% versus SRL 230% ± 5% versus control 211% ± 8%; P < 0.04) (Figure 1c).

Plasma ET-1 Levels
CyA exposure did not alter plasma ET-1 levels compared with control (CyA 0.9 ± 0.1 fmol/L; control 1.0 ± 0.1 fmol/L) (Figure 3). However, SRL-treated animals demonstrated a significantly lower plasma ET-1 level (0.4 ± 0.1 fmol/L, P < 0.05).

Oxidative Injury
Figure 4 demonstrates that CyA treatment resulted in a greater increase in oxidative injury as measured by 8-isoprostane levels compared with control and SRL (CyA 50% ± 2% versus SRL 33% ± 3% versus control 25% ± 5%; P < 0.05).

Endothelin Receptor Expression
Thoracic aortic ETA Rc protein expression was significantly (P < 0.004) increased after CyA exposure compared with both control and SRL (Figure 5a). However, ETB Rc protein expression was not different between groups (Figure 5b) (P = 0.29).

Nitric Oxide Synthase Expression
Two-week exposure to CyA resulted in a downregulation of eNOS protein expression compared with both control and SRL (P < 0.001) (Figure 5c). However, extremely low inducible NOS expression was observed in all animals, with no difference between groups.

Discussion
Our study confirms that CyA results in endothelial dysfunction. CyA treatment alters normal vascular homeostasis as demonstrated by impaired endothelial dependent vascular
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induced vasospasm. CyA also resulted in a higher ED₅₀ to
pose vessels to vasoconstriction. This was confirmed by our
ET-1 levels seen with CyA treatment may therefore predis-
required to maintain normal homeostasis. The normal plasma
reduction in ET-1 levels (which was not observed) would be
CyA decreased NO levels and therefore a compensatory
compared with control, a relative increase may exist because
Figure 4. The 8-isoprostane levels in the thoracic aorta after 2
weeks of treatment. Cyclosporine (CyA) exposure significantly
increased oxidant injury compared with rapamycin (SRL) and
control.

The novel aspects of our study relate to the
mechanism of CyA-induced endothelial injury and the benefi-
cial effects of SRL treatment, which maintains ET-1-NO
homeostasis. Our investigations revealed the following ob-
servations (summarized in Table 1):

1. SRL exposure reduced plasma ET-1 levels.
2. CyA exposure significantly increased ETₐ Rc expres-
sion whereas SRL had no effect on ETₐ Rc expression.
3. CyA impaired eNOS protein expression.
4. CyA exposure led to greater oxidative injury as mea-
sured by 8-isoprostane levels compared with both SRL
and control.

Normal vessel function is maintained by the balance between
NO and ET-1. Our study demonstrated that CyA alters both
NO and ET-1 regulation. eNOS protein expression was
reduced after treatment with CyA. The reduction in eNOS
may be a consequence of CyA inhibiting cyclophilin cist-
trans peptidyl-prolyl isomerase function, resulting in im-
paired eNOS folding and therefore increased degradation.
Second, although ET-1 levels were not elevated by CyA
treatment, ETₐ Rc protein expression in the thoracic aorta
was significantly increased with no concomitant change in
ETₐ Rc protein expression. ETₐ Rc and ETₐ Rc activation on
smooth muscle cells results in vasoconstriction, whereas ETₐ
Rc on endothelial cells results in vasodilation. Therefore,
an increased ETₐ Rc-to-ETₐ Rc ratio results in greater vasocon-
striction. Although, CyA does not increase ET-1 levels
compared with control, a relative increase may exist because
CyA decreased NO levels and therefore a compensatory
reduction in ET-1 levels (which was not observed) would be
required to maintain normal homeostasis. The normal plasma
ET-1 levels seen with CyA treatment may therefore predis-
pose vessels to vasoconstriction. This was confirmed by our
observation that CyA results in greater sensitivity to ET-1-
induced vasospasm. CyA also resulted in a higher ED₉₀ to
SNP compared with the other treatment groups indicating
impaired cGMP-dependent SMC relaxation. Previous studies
have suggested that CyA treatment increases free radical
production and our study confirmed that oxidative injury
occurred after CyA exposure.²¹,²² We therefore speculate that
CyA treatment results in functional uncoupling of the eNOS
enzyme producing free radicals instead of NO. Krauskopf et
al also showed that CyA can generate superoxide in smooth
muscle, which may lead to impaired function.²³ Therefore,
oxidative injury may account for the smooth muscle dysfunc-
tion observed in our vascular assessments.

SRL therapy did not decrease eNOS protein expression as
seen after CyA treatment. As a result, there was no impair-
ment in endothelial-independent or dependent vasodilation.
SRL treatment did not result in increased sensitivity to ET-1.
In addition, SRL treatment resulted in less oxidative injury
compared with CyA. Therefore, SRL may improve endo-
thelial and smooth muscle function by enhancing NO bioavail-
ability and reducing oxidative injury.

The mechanisms by which SRL preserves endothelial
function may also be the mechanism by which it attenuates
the development of allograft vasculopathy. Simonson et
al have demonstrated that ET-1 inhibition attenuates the
development of TxV.²⁰ Therefore, the ability to lower ET-1 levels
may be a mechanism by which SRL attenuates allograft
vasculopathy in transplant recipients. SRL treatment pre-
served eNOS expression compared with CyA and represents
another mechanism by which SRL protects against vascu-
lopathy. Lee et al have shown that eNOS protects the aortic
allograft from the development of transplant athere-
sclerosis.²¹ Oxidative stress is well-known to result in endothelial
damage and athereosclerosis and, in these studies, SRL ex-
posure resulted in less free radical injury compared with CyA.

Our findings suggest possible treatment strategies for
improving vasomotor function in patients receiving standard
immunosuppression. An effective strategy to treat CyA in-
duced vasomotor dysfunction should include ET-1 antago-
nism in addition to functional coupling of eNOS. This may be
achieved by using Bosentan for ET-1 antagonism and tetra-
hydrobiopterin (BH₄), an essential eNOS cofactor, for stabil-
izing the eNOS complex and reducing free radical produc-
tion. We have previously demonstrated that the use of BH₄
partially attenuated the deleterious effects of CyA.²² Our
findings provide potential mechanisms for the development
of CyA-induced hypertension as well as a direct mechanism
by which CyA may lead to TxV. SRL may prove to be an
alternative therapy to CyA for preserving vasomotor function.
Poston et al using a rodent heterotopic heart transplant model
demonstrated the ability of rapamycin to reverse chronic graft
vascular disease.²³ Their study describes the beneficial effects
of rapamycin on vasculopathy but did not evaluate the
underlying mechanism of benefit. Their study did reveal that
TxV occurs in the absence of myocardial rejection, suggest-
ing that rapamycin’s protective effects are likely not mediated
by its immunosuppressive activity. Our studies suggest that
alterations in NO-ET-1 homeostasis plays a critical role in
the development of TxV. Using the same model, Yamaguchi
et al demonstrated that ET-1 blockade reduces TxV, support-
ing our hypothesis that ET-1 is involved in the pathogenesis
of TxV.²⁴ In this study, ET-1 production was inhibited
preoperatively before transplantation with the use of anti-
sense oligodeoxynucleotides, resulting in a 7- to 10-day suppression of ET-1. Our present study demonstrated that ET-1 levels are not elevated by CyA and that ETA receptor upregulation lasts for at least 2 weeks, indicating that chronic therapy may be required for enhanced protection against CyA induced TxV. Verrier et al demonstrated in a rodent model of orthotopic aortic allograft transplantation that ischemia and reperfusion results in endothelial injury leading to the development of TxV. Therefore, Yamaguchi’s study may in fact demonstrate the protective effect of acute ET-1 blockade in limiting ischemia–reperfusion-induced TxV rather than drug-induced TxV. Both of these studies support our hypothesis that

Figure 5. a, Quantitative Western blot analysis of ETA receptor (Rc) expression in the thoracic aorta. Cyclosporine (CyA) treatment resulted in increased ETA Rc expression compared with rapamycin (SRL) and control (CON). b, Quantitative Western blot analysis of ETA receptor protein expression in the thoracic aorta. No differences were observed between groups. c, eNOS protein expression. Quantitative Western blot analysis of eNOS protein expression in the thoracic aorta. Cyclosporine (CyA) decreased eNOS expression whereas rapamycin (SRL) demonstrated no reduction in eNOS protein expression compared with control (CON).
Summary of Vascular Effects of Cyclosporine (CyA) and Rapamycin (SRL)

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<th>Vasoreactivity to ET-1</th>
<th>CyA</th>
<th>SRL</th>
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<tr>
<td>% Emax</td>
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<td>ET-1 levels</td>
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<tr>
<td>ROS</td>
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<tr>
<td>ET-1Rca</td>
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<td>ET-1Rcb</td>
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<tr>
<th>Vasoreactivity to Ach</th>
<th>CyA</th>
<th>SRL</th>
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<tbody>
<tr>
<td>% Emax</td>
<td>↓↓↓</td>
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<tr>
<td>eNOS</td>
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<td>ROS</td>
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Ach indicates acetylcholine; eNOS, endothelial nitric oxide synthase; ET-1, endothelin-1; ET-1Rc, ET-1 receptor (either A or B); ROS, reactive oxygen species.

by maintaining vascular homeostasis rapamycin may prevent TxV and that ET-1 antagonism may provide additional benefit.

Study Limitations

The present study was designed to investigate the direct effect of CyA and SRL on vascular function in the absence of an immune response or a period of ischemia and reperfusion. Clearly, the effects of the latter 2 variables will need further assessment in a heterotopic transplant model similar to that of Poston and Yamaguchi. In addition, we evaluated changes in aortic tissue as opposed to coronary arteries. Although the responses are likely consistent, it is possible that both CyA and SRL exert differential effects on coronary vasculature than seen in thoracic aorta. However, the macrovascular effects of these agents have important clinical implications for the development of postoperative renal insufficiency and hypertension. Lastly, we did not evaluate the effects of combination therapy with both CyA and SRL, a currently clinical strategy.

In summary, we have made the following conclusions based on the present data: (1) CyA results in alteration of both NO and ET-1 regulation likely leading to impairment of vasodilation, increased sensitivity to vasospasm, and increased oxidative injury; (2) SRL preserves the eNOS complex and lacks the deleterious effects of CyA on the endothelium; and (3) SRL therapy decreases ET-1 levels.

These findings provide important mechanistic data to explain observed effects in future studies using a heterotopic transplant model. Furthermore, these data strongly suggest a potential clinical role for simultaneous endothelin antagonism and NO augmentation.

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Disclosures

None.

References

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