Novel cardioprotective effects of tetrahydrobiopterin after anoxia and reoxygenation: Identifying cellular targets for pharmacologic manipulation

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Objectives: Contemporary cardioprotective strategies to prevent perioperative ischemia-reperfusion injury have focused on the L-arginine nitric oxide pathway. Tetrahydrobiopterin is an absolute cofactor required for the enzyme nitric oxide synthase and is thus a critical determinant of nitric oxide production. We hypothesized that ischemia-reperfusion results in diminished levels of tetrahydrobiopterin, which might represent a key cellular defect underlying endothelial and myocyte dysfunction after ischemia-reperfusion. To this aim, we examined the effects of tetrahydrobiopterin supplementation in (1) an in vivo experimental model of global ischemia-reperfusion and (2) an in vitro human ventricular heart cell model of simulated ischemia-reperfusion. Measures of endothelial function, oxidant production, cell survival, and cardiac function were used to assess outcome.

Methods: In study 1 Wistar rats were divided into one of 2 groups (n = 10 per group). One group received tetrahydrobiopterin (25 mg·kg⁻¹·d⁻¹ for 7 days), and the other group served as the control group. Hearts were subjected to 30 minutes of ischemia followed by 30 minutes of reperfusion, and left ventricular developed pressure, left ventricular systolic pressure, and left ventricular end-diastolic pressure were determined by using the modified Langendorff technique. In study 2 we quantitated myocardial malondialdehyde, a marker of lipid peroxidation, in ventricular tissues from both groups of animals using butanol phase extraction and spectrophotometric analysis. In study 3 coronary vascular responses were determined in vascular segments of the left coronary artery in both groups of animals after ischemia-reperfusion. Endothelium-dependent and endothelium-independent vasodilatation to acetylcholine and sodium nitroprusside, respectively, were compared between groups. In study 4, using a human ventricular heart cell model of simulated ischemia-reperfusion, we studied the effects of tetrahydrobiopterin (20 μmol/L) on cellular injury (as assessed by means of trypan blue uptake).

Results: After ischemia-reperfusion, myocardial dysfunction was evidenced by a decrease in left ventricular developed pressure and an increase in left ventricular end-diastolic pressure (P = .01 compared with baseline). Hearts from tetrahydrobiopterin-treated rats exhibited protection against ischemia-reperfusion injury (left ventricular developed pressure: 74 ± 4 vs control 42 ± 8 mm Hg, P = .01; left ventricular end-diastolic pressure: 12 ± 3 vs 34 ± 7 mm Hg, P = .01). Furthermore, tetrahydrobiopterin treatment attenuated the rise in malondialdehyde levels after ischemia-reperfusion (P = .01). After reperfusion, coronary endothelial function to acetylcholine was attenuated (P = .003 vs sham-treated mice), whereas responses to
sodium nitroprusside remained unchanged. Tetrahydrobiopterin-treated rats exhibited an improvement in acetylcholine-mediated vasorelaxation \((P = .01\) vs ischemia-reperfusion group). Cellular injury, as assessed by means of trypan blue uptake, was higher in human ventricular heart cells subjected to simulated ischemia-reperfusion; this effect was prevented with tetrahydrobiopterin treatment \((P = .001)\).

**Conclusions:** Supplemental tetrahydrobiopterin provides a novel cardioprotective effect on left ventricular function, endothelial-vascular reactivity, oxidative damage, and cardiomyocyte injury after ischemia-reperfusion injury and might represent an important cellular target for future operative myocardial protection strategies.

**Isolated Perfused Heart Study**

All rats were anesthetized with sodium pentobarbital (60 mg/kg administered intraperitoneally), and the hearts were removed and placed in ice-cold Krebs buffer with the following composition: 120 mmol/L NaCl, 4.7 mmol/L KCl, 1.2 mmol/L KH2PO4, 1.2 mmol/L MgSO4, 1.25 mmol/L CaCl2, 25 mmol/L NaHCO3, and 11 mmol/L glucose (pH 7.4). The hearts were then transferred to the isolated perfusion apparatus and perfused in a retrograde fashion through the aorta with oxygenated (95% O2 and 5% CO2) Krebs buffer maintained at 37°C. The hearts were electrically stimulated at a rate of 300 beats/min and perfused at a constant flow rate of 10 mL/min. A water-filled latex balloon was inserted into the left ventricle through the left atrium and connected to a pressure transducer (Gould Satham) for the measurement of left ventricular end-diastolic pressure (LVEDP), left ventricular systolic pressure, and left ventricular developed pressure (LVDP; ie, left ventricular systolic pressure minus LVEDP). LVEDP during the phase of equilibration was set between 5 and 8 mm Hg.

Four hearts from the saline-treated group were continuously perfused with Krebs buffer for 90 minutes and served as the sham control group. Hearts from the other rats were subjected to 30 minutes of global ischemia followed by 30 minutes of reperfusion. The Krebs buffer was supplemented with BH4 (20 μmol/L) during the assessment of the treated group. After completion of the experiment, the hearts were frozen in liquid nitrogen for the assessment of malondialdehyde (MDA), a marker of lipid peroxidation, as described below.

**Determination of MDA Levels in Myocardium**

MDA levels in the myocardium were measured in duplicate by using a modification of the method of Ohkawa and associates, as described by Chen and colleagues. Ventricular tissue was dissected and homogenized. The assay mixture consisted of 0.1 mL of the tissue homogenate, 0.4 mL of 0.9% NaCl, 0.5 mL of 3% sodium dodecylsulfate, and 3 mL of thiobarbituric acid and acetic acid and was heated for 75 minutes at 95°C. Thereafter, 1 mL of cold 0.9% NaCl was added to the mixture, which was cooled and

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**Materials and Methods**

**Animals**

Male Wistar rats (200-250 g) were divided into one of 2 groups \((n = 10\) per group). Experiments were performed in accordance with the Canadian Animal Care Guidelines. The first group of rats was treated with BH4 \((25 \text{ mg} \cdot \text{kg}^{-1} \cdot \text{d}^{-1})\) administered intravenously for 7 days, and the second group of rats received saline injections. Similar doses have been used in an experimental model of porcine lung transplantation. After treatment, hearts were excised for isolated perfusion study by using the modified Langendorff technique.

One of the most common and predictable forms of ischemia-reperfusion (I/R) injury occurs during cardiac operations, when the heart is arrested for surgical intervention and subsequently reperfused by removal of the aortic crossclamp. Devising pharmacologic strategies to counter perioperative I/R injury might serve to restore functional integrity during cardioplegic arrest. Contemporary cardioprotective strategies to prevent I/R injury have focused on the L-arginine-nitric oxide (NO) pathway. Tetrahydrobiopterin (BH4) is an essential cofactor required for nitric oxide synthase (NOS), and hence NO production is critically dependent on the presence of adequate amounts of BH4. Diminished levels of BH4 might lead to an uncoupling of NOS, with the resultant production of reactive oxygen species instead of NO. The beneficial effects of BH4 supplementation have been recently confirmed in a variety of cardiovascular disease states.

In the present study we hypothesized that I/R injury results in diminished bioavailability of BH4, which might lead to endothelial and myocyte dysfunction. To this aim, we examined the effects of BH4 treatment on cardiac dysfunction, impaired endothelium-dependent vasodilatation, and lipid peroxidation in a model of global I/R. To examine whether BH4 exerts direct cardioprotective effects (independent of other cell types), we studied the effects of this cofactor on cellular injury in a human ventricular cardiomyocyte model of simulated I/R. We herein report, for the first time, novel cardioprotective effects of BH4 on the aforementioned pathways, which suggest that BH4 might represent an important cellular target for future operative myocardial protection strategies.
extracted with 5 mL of n-butanol. After centrifugation at 3000 rpm for 15 minutes, the butanol phase was assayed spectrophotometrically at 532 nm. Tetramethoxypropane (in amounts of 0, 0.1, 0.2, 0.4, 0.8, and 1.0 nmol) served as the external standard. MDA levels in myocardium were expressed as micromoles per gram of tissue.  

**Endothelial Function Assessment**

In a separate experiment we examined the effects of BH4 treatment on endothelium-dependent and endothelium-independent vascular relaxation after global I/R injury. Briefly, after I/R, the left coronary artery was dissected under a microscope, and vascular segments (1-2 mm in length) were used for the assessment of in vitro vascular function by using a small-vessel myograph for isometric tension recording. Care was taken during dissection and mounting to avoid damage to the endothelium. Briefly, after stabilization, the vessels were stimulated according to the following protocol: (1) cumulative dose-response curve (DRC) to phenylephrine (10^−9−10^−5 mol/L); (2) DRC to acetylcholine (10^−6−10^−5 mol/L) in rings precontracted with the effective dose causing 75% maximum contraction (ED75) of phenylephrine; and (3) DRC to sodium nitroprusside (SNP; 10^−11−10^−6 mol/L) in rings precontracted with the ED75 of phenylephrine. The percentage of maximum relaxation was compared between groups.

**Human Heart Cell Model of I/R**

Our method of culturing heart cells from human ventricular biopsy specimens has been previously described in detail. In brief, 5- to 20-mg biopsy specimens were obtained from the right ventricular outflow tract of patients undergoing elective operations for tetralogy of Fallot. The average age of the patients ranged from 4 to 14 years. After digestion with trypsin (0.2%) and collagenase (0.1%), the separated cells were seeded onto cell-culture dishes and cultured at 37°C and 5% CO2 in Iscove’s modified Dulbecco’s medium with 10% fetal bovine serum, 100 U/mL penicillin, 100 μg/mL streptomycin, and 0.1 mmol/L β-mercaptoethanol. Puriﬁcation was achieved by using a dilution cloning technique. Enzymatically isolated cells were seeded at a low density to enable morphologic identiﬁcation of individual cardiomyocytes and separation from contaminating cell types. Single cardiomyocyte colonies were then transferred to a separate culture dish. The use of cardiomyocytes facilitates examining the contribution of I/R independent of other cell types, such as endothelial cells or fibroblasts. Our technique of simulated I/R has also been described in detail previously. In brief, after 30 minutes of stabilization in 10 mL of normoxic phosphate-buffered saline (PBS), ischemia was simulated by exposing the cells to a low volume (1.6 mL) of anoxic PBS at 37°C for 90 minutes. During this period, the cells were placed in an airtight Plexiglas chamber, which was continuously flushed with 100% nitrogen to maintain anoxic conditions. Ischemia was followed by a reperfusion period in which the cells were exposed to 10 mL of normoxic PBS at 37°C for 30 minutes. Both low-volume and anoxic conditions were used to mimic ischemia. The volume of anoxic perfusate used (1.6 mL) was the minimum volume required to coat the cellular monolayer for the prevention of cellular dehydration during the ischemic period. To verify the presence of anoxia, we placed 2 mL of anoxic PBS in a center dish within the sealed chamber and tested at the termination of each ischemic period to ensure a PO2 of 0 mm Hg. Anoxic PBS was prepared by bubbling with 5% CO2 and 95% nitrogen that had first been passed through an oxygen trap (1% wt/vol NaHSO3 in deionized water). The solution (monitored with a blood gas analyzer) was degassed until a PO2 of 0 mm Hg and a PCO2 of less than 10 mm Hg were achieved. A pH of 7.4 ± 0.05 and an osmolality of 290 ± 20 mOsm/L were ensured before use. For the assessment of cellular injury, cells were stained with trypan blue at the end of the reperfusion period (after 150 minutes of incubation for the nonischemic groups). Injured cells were unable to exclude the large-molecular-weight dye and stained blue. The above protocol was repeated in the presence of BH4 (20 μmol/L) added before reperfusion. A single blinded observer performed cell counts.

**Statistical Analysis**

Data are presented as means ± SEM. Data were compared by using a 2-way analysis of variance followed by the Newman-Keuls test for post hoc comparisons.
**Results**

**Cardiac Function Assessment**
The baseline values of LVDP and LVEDP did not differ between the groups at baseline \((P > .2)\). The sham group exhibited no changes in cardiac function during the 90-minute perfusion period \((P > .2)\). After 30 minutes of global ischemia and 30 minutes of reperfusion, the hearts in the untreated groups exhibited cardiac dysfunction, as evidenced by a decrease in LVDP and an increase in LVEDP (Figures 1 and 2, \(P = .01\)). Strikingly, treatment of the rats with BH₄ attenuated I/R-induced myocardial dysfunction, as evidenced by preservation in LVDP and a minimal increase in LVEDP (Figures 1 and 2, \(P = .004\)).

**Myocardial MDA levels**
MDA levels were measured in both groups of rats after I/R as an index of lipid peroxidation.⁷,¹⁰,¹¹ After I/R, MDA levels increased in the myocardium (Figure 3); this effect was attenuated with BH₄ treatment \((P = .01)\).

**Coronary Endothelial Function**
Coronary vascular reactivity to endothelium-dependent (acetylcholine) and endothelium-independent (SNP) vasodilatation was assessed in the left anterior descending artery after I/R. Global I/R resulted in endothelial dysfunction, as evidenced by diminished acetylcholine-mediated vasorelaxation \((P = .003)\). Endothelium-independent responses to SNP remained unchanged after I/R (not shown). Importantly, treatment with BH₄ improved acetylcholine responses, indicating a preservation of endothelial function after I/R (Figure 4, \(P = .001)\).

**Cardiomyocyte Cell Injury**
Figure 5 depicts the effects of simulated I/R on cellular injury (as assessed by trypan blue exclusion) in the presence or absence of BH₄ (20 μmol/L) added during reperfusion. I/R resulted in marked cardiomyocyte cell injury when compared with that seen in the nonischemic control group \((P = .001)\). This response was completely prevented with BH₄ treatment \((P = .001)\).

**Discussion**

**Key Observations**
The following observations have been made in this study: (1) supplementation with the essential NOS cofactor BH₄ improves functional recovery after global I/R; (2) I/R-induced increases in myocardial MDA levels, an index of lipid peroxidation, are attenuated by BH₄; (3) BH₄ treatment restores impaired endothelial function in epicardial coronary arteries after global I/R; and (4) acute BH₄ incubation exerts direct cardioprotective effects in human cardiomyocytes subjected to simulated I/R. These data underscore the importance of BH₄ as a mediator of I/R injury and suggest that this cofactor might exert myocardial protection through...
prevention of endothelial dysfunction, lipid peroxidation, and direct cardiomyocyte injury.

BH₄: An Emerging Cardiovascular Target

In the endothelial cell NO is synthesized from l-arginine by NO synthase (endothelial NOS or NOS III). BH₄ is an essential cofactor required for the activation of NOS and the production of NO. Mechanistically, BH₄ functions as a reducing cofactor, transferring electrons to the enzyme-bound l-arginine.¹¹ Furthermore, it promotes stabilization of the dimeric (active) form of NOS and also increases the affinity of NOS for l-arginine. Additionally, in the presence of low levels of BH₄, NOS functions as a reduced nicotinamide dinucleotide phosphate oxidase, resulting in the production of oxygen-derived free radicals instead of NO.¹ Thus decreased levels of BH₄ might lead to diminished NO production, enhanced NO breakdown, or both. Decreased availability of BH₄ has now been implicated as a pathogenic factor causing endothelial dysfunction in a variety of cardiovascular disease states. Likewise, acute and chronic supplementation with BH₄ has been demonstrated to improve endothelium-dependent vasomotion clinically and experimentally.¹⁻³,⁵

Accumulating evidence suggests that modulation of the l-arginine-NO pathway might exert cardioprotective effects after I/R.¹³⁻¹⁵ Previous studies, including work from our group,¹⁵ have demonstrated that l-arginine supplementation exerts cardioprotective effects by means of increasing NO production. Given the importance of BH₄ in the regulation of NOS, we set out to determine whether exogenous supplementation of this cofactor would enhance functional recovery and endothelial function in an experimental model of global I/R. In addition, we tested the hypothesis that BH₄ exerts direct cardioprotective effects (independent of endothelial cells) in human ventricular cardiomyocytes subjected to I/R.

Potential Mechanisms of BH₄ Cardioprotection

I/R injury incites an acute inflammatory response that affects the structure, function, and metabolism of the endothelium and cardiomyocyte. The cellular element of the microvasculature that appears to be most affected by I/R is the endothelium. Ischemia is known to alter the membrane potential, increase intracellular volume, and impair cytoskeletal organization of the endothelial cell.¹⁶ From a functional standpoint, endothelium-dependent vasodilatation is impaired,¹⁷⁻¹⁹ whereas the responses to endothelium-dependent...
derived contracting factors are exaggerated after I/R. Endo-
thelial dysfunction occurs rapidly during reperfusion and sets the stage for leukocyte-endothelial cell interaction, an important factor in the pathophysiology of I/R injury. The generation of oxygen-derived free radicals is also an impor-
tant mechanism of I/R injury. Dysfunctional endothelium and activated neutrophils are important sources of oxidants, such as superoxide anion. Under normal conditions, the flux

Figure 6. *Top,* BH₄ is a critical cofactor for endothelial NOS (eNOS). In the presence of adequate amounts of BH₄, NOS is coupled and produces mainly NO and small amounts of superoxide. *Bottom,* I/R might directly impair BH₄ bioavailability. This results in an uncoupling of NOS, with a resultant increase in superoxide versus NO production. BH₄ supplementation might represent a novel cellular target for future operative myocardial protective strategies.

L-arg, l-arginine; ec, endothelial cell; vsmc, vascular smooth muscle cell.
of NO greatly exceeds the rate of superoxide production. This allows NO to effectively scavenge the low intracellular levels of superoxide, repel neutrophil adhesion, and exert endothelium-dependent vasodilatation. However, within minutes of reperfusion, the balance between NO and superoxide generation is altered in favor of the latter. In addition to enhanced potential for oxygen radical generation, postischemic hearts might exhibit a decrease in the tissue concentration of intracellular oxidant scavengers, which might further predispose to myocardial damage.

The beneficial effects of BH₄ observed in the present studies likely result from the production of NO, a correction of reperfusion-induced changes in superoxide–NO balance, or both (Figure 6). Both decreased NO production and increased superoxide anion release are well-known inhibitors of endothelial function. Therefore the improvements in endothelial function might have resulted from either one of these mechanisms or a collective effect on both pathways.

In an experimental model of global I/R, we present evidence to suggest that BH₄ might augment functional recovery after I/R by preventing coronary endothelial dysfunction and decreasing MDA, a product of lipid peroxidation and index of tissue injury. However, data from our human heart cell model suggest that BH₄ might exert direct cardiomyocyte protection independent of the presence of endothelial cells, neutrophils, platelets, or fibroblasts. The ability of BH₄ to exert direct cardioprotective effects in the absence of endothelial cells might appear atypical at first; however, we have recently observed similar direct cardioprotective effects of L-arginine and NO donors in this model of simulated I/R.¹⁵

In addition, evidence from our research group suggests that NO might attenuate cardiomyocyte injury by opening of Kₐᵥ channels in a cyclic guanosine monophosphate–dependent fashion. Hence it is possible that through improving NO production–balance, BH₄ exerts cardioprotective effects similar to those noted previously with L-arginine. The mechanism of injury in the Langendorff and in vitro cell-culture preparation might be more weighted toward oxidant injury, and hence BH₄ should be tested in an in vivo model in which both mechanisms and their interactions are engaged.

An important question that merits some discussion relates to the potential clinical applicability of L-arginine versus BH₄ as therapeutic strategies for modulating NO-mediated cardioprotection. Although low-dose L-arginine and BH₄ might function in a very similar fashion in terms of their cardioprotective effects, the dose-response relationship for L-arginine is narrow; higher doses of L-arginine might actually exaggerate cardiomyocyte injury through excessive NO production (Weisel RD, unpublished observations). We believe that one of the primary abnormalities after I/R is a decrease in BH₄ levels. Several biochemical studies have demonstrated that activation of NOS in the presence of suboptimal BH₄ concentrations results in uncoupling of oxygen reduction and arginine oxidation, with the resultant formation of superoxide anion and hydrogen peroxide.¹²,²⁰–²² Hence NOS might become a source of oxygen-derived free radicals in the face of low levels of this cofactor, and there is strong evidence to support this conclusion in vitro.¹²,²⁰–²⁴ Treatment with BH₄ might therefore serve to restore the NO-superoxide anion balance without the deleterious effects of excess NO production observed with high-dose L-arginine administration. BH₄ has very low toxicity and can be administered intravenously in high doses.²⁵

Critique of the Human Ventricular Heart Cell Model

A critique of the model of simulated I/R is provided. The heart cells used in these studies have been extensively evaluated in previous reports. These myocytes retain many characteristics of freshly isolated cells but have distinct differences. These cells become quiescent after enzymatic digestion and passaging. Despite an abundant supply of mitochondria and contractile proteins, the sarcomeres become disrupted during division and do not reestablish their characteristic functional format. However, the metabolic response of these cells after ischemia is similar to our intraoperative findings during cardiac operations.²⁶–²⁸ Furthermore, the cellular concentrations of troponin I, troponin T, and creatine kinase MB isoform are similar to those seen in vivo. Although the molecular and biochemical natures of these cells resemble those of in vivo cardiomyocytes, these cells undergo a partial phenotypic change, become quiescent, and regain their ability to divide. Other investigators have shown that senescent rat cardiomyocytes might also regain their ability to divide in culture. Therefore despite their quiescent state, we believe that these cells are phenotypically cardiomyocytes, retain many characteristics of normal human myocardium, and might simulate the human heart during cardioplegic arrest.

Limitations and Future Studies

A few limitations of these studies must be acknowledged to facilitate objective evaluation of these data. First, we do not provide an assessment of NO production or NO-superoxide anion balance in the present study. Although these represent well-known actions of BH₄, such measurements would have strengthened our conclusions. Our data suggest that the addition of this cofactor reduces oxidative stress and improves NO-mediated vasodilatation to acetylcholine. This is indirect evidence that BH₄ restores the balance between NO and reactive oxygen species after I/R. Second, other mechanisms of I/R injury were not assessed, particularly neutrophil activation or reactive oxygen species production. Third,
we did not measure the circulating levels of BH₄. This remains a challenging assay that is only available at a few centers in the world; however, the concentrations of BH₄ used have been previously demonstrated to result in increased plasma levels in rats. Fourth, it would have been nice to have confirmatory measurements of lactate dehydrogenase, creatine kinase, or troponin release from isolated human cardiomyocytes to support the results of the trypsin blue uptake assay. Finally, the animal studies were conducted after 7 days of treatment with BH₄. No data are available on acute treatment with BH₄, except for the in vitro cell-culture experiments.

Clearly, the most convincing evidence for BH₄ as a mediator of I/R would come from experiments conducted in the setting of cofactor deficiency. Recently, a BH₄-deficient mouse has been described.₁²⁻²⁹ The hyperphenylalaninemic mouse mutant (hph-1) displays 90% deficiency in guanine triphosphate cyclohydrolase I, the rate-limiting step in the synthesis of BH₄. We are currently conducting studies to examine whether global I/R injury is exaggerated in hph-1, BH₄-deficient mice.

Conclusions

Supplemental BH₄ exerts a novel cardioprotective effect on left ventricular function, endothelial-vascular reactivity, oxidative damage, and cardiomyocyte injury after I/R and might represent an important cellular target for future operative myocardial-protection strategies. We suggest that a relative deficiency of BH₄ might occur during I/R, which might shift the balance between NOS-catalyzed NO production and superoxide anion generation; this cellular mechanism is restored with cofactor therapy.

References


Discussion

Dr David Follette (Sacramento, Calif). I have had an interest in I/R for more than 25 years. Although cardioprotective...
strategies have been perfected during this period of time, we
only recently have begun to understand the complex molecular
interactions that are involved in I/R injury. Earlier in this
meeting, we heard how cyclosporine and FK-506 provide pro-
tection against I/R by means of calcineurin inhibition. Many of
the contributions that have enhanced our understanding of this
complex topic have been made by Dick Weisel and the Toronto
group. Today’s study, so nicely presented by Dr Verma, con-
tinues this fine tradition.

We now know that the severity of reperfusion injury is related
to the complex interactions between the endothelial cell and the
cardiac myocyte. As has been shown by Dr Verma today, I/R leads
to an imbalance of NO and superoxide generation. This then
results in endothelial cell dysfunction and tissue destruction. It
appears that the cofactor BH₄ was shown to modify this reaction.
I have several questions for Dr Verma. How did you select the
7-day pretreatment period in your animals?

Dr Verma. Thank you, Dr Follette, for your kind comments.
The 7-day treatment was based on a previous study in which
treating rats at 25 mg/kg/day for 7 days results in a 3-fold increase in the plasma BH₄ levels. We used that as an index of
loading. Unfortunately, we did not measure BH₄ in this study.

Dr Follette. That then leads into the next question. Can you
give us your thoughts on the mechanism of how exogenous sup-
plementation works?

Dr Verma. BH₄ may provide protection from ischemia and
reperfusion by interactions with both the endothelial cell and
cardiomyocyte. In the endothelial cell, BH₄ serves as a key reduc-
ing cofactor, facilitating coupling of eNOS into a predominantly
NO (vs superoxide) producing enzyme. This, in turn, results in
improvement in endothelial function, a key component of reper-
fusion injury. Our data also demonstrate that BH₄ exerts direct
cardiomyocyte protection, independent of other cell types. This
may be related to augmented cardiomyocyte NO production,
which we have previously demonstrated to be an important medi-
ator of mitochondrial potassium channel opening in human cardi-
omyocytes. Opening of these channels results in intramitochon-
drial depolarization and augmented cellular respiration, with
resultant decreases in intracellular calcium.

Dr Follette. Do you believe then that ischemia causes the BH₄
to levels to drop acutely?

Dr Verma. Yes, and actually there are other studies in lung
ischemia models that have demonstrated diminished BH₄, al-
though not in a cardiac I/R model.

Dr Follette. Is it possible then that BH₄ does not have much to
do with reperfusion but rather induces ischemic tolerance?

Dr Verma. Clearly I think the evidence so far in the literature
supports the concept that the greatest damage occurs to the endo-
thelium during the reperfusion phase. We do not have data on BH₄,
but if you compare the effects on coronary endothelial function
between ischemia and I/R, clearly the reperfusion component is
much higher than that of the ischemia component in terms of
impairment in acetylcholine responses. I do believe that BH₄ is
helping the reperfusion phase. I think we are raising the levels to
a supranormal level, and that reserve is decreasing superoxide and,
through that mechanism, preventing cardiac dysfunction and en-
dothelial dysfunction. It is a hard question to answer in the absence
of NO and superoxide measurements. I think we will have those
measurements in the next few months.

Dr Follette. Perhaps you have already partially answered it
earlier when you stated that when you gave the BH₄ acutely it did
not have the same effects as the pretreated, and therefore perhaps
it is inducing some form of tolerance rather than necessarily
affecting the reperfusion process.

Dr Verma. This is possible. The other point is that these are
normal rats. Probably the results would be different or more
dramatic in dysfunctional hearts.

Dr Follette. Lastly, the use of the cardiac myocyte model is
intriguing, and I was especially impressed with your critique of
the method in your article. Can you speculate on how BH₄ can
provide direct myocyte protection independent of endothelial
cell function, which we have always assumed was NO’s pri-
mary site of action.

Dr Verma. Recently, we examined the effects of l-arginine
and other agents, NO donors, on cardiomyocytes (independent of
endothelial cells). Agents that increase NO independent of endo-
thelial cells afford protection in the cardiomyocyte model by
opening potassium channels in the mitochondria. That is the mech-
anism that has been proposed. As you know, NO can stimulate
cyclic guanosine monophosphate, which facilitates the opening of
potassium channels.

Dr Michael Mulligan (Seattle, Wash). I have just a couple of
comments. I think that your hypothesis about how this compound is potentially working is very interesting, but we
have to be careful in interpreting that. I think that your results
are not surprising given the fact that we have seen this already
in the pig heart from the group at Texas A&M back in 1996, but
BH₄ is also known to be an oxygen radical scavenger in and of
itself, and therefore it could be having very nonspecific func-
tions as they relate to NO physiology. We have to be careful
whether we think that it is working by stabilizing endothelial
NOS, such that we produce more NO, and that is somehow
protective. Excess NO is toxic to endothelial cells, and in fact,
BH₄ has been shown to be protective against NO-induced
endothelial toxicity. It has also been shown in 2 articles that
relate to lung injury (one of them to ischemic lung injury) that
NO is injurious to the lung, and BH₄ has also been shown to
potentiate neuronal toxicity in ischemic brain injury.

I think there is more to this story. There might be something
specific about the isoenzyme system in the heart, and it might
rely on a balanced stimulation of endothelin A and B receptors
that relates to NO physiology in ways that we do not under-
stand.

I have been working with NO as it relates to acute lung injury
since 1990, and I still cannot stand up and say it is all good or it
is all bad, and I cannot explain to you how modulation of endo-
thelial NOS activity is so discretely going to result in production of
excessive and injurious peroxynitrite or protective NO.

It is a very elegant study, but I just would advise you from
experience that we have to be careful in the way that we interpret
these things.

Dr Verma. Now, in response to your question about the pig
injury model, no functional data were provided in that study. They
did demonstrate that in the pig heart subjected to I/R, BH₄ acutely
improves endothelial function. I do not know of any cardiac functional data available except those from this study.

Your question about NO being toxic in terms of function is an important one, and clearly our group has demonstrated that L-arginine in higher doses may impair contractility. Probably we should just be using a cofactor that does not stimulate NO production already but restores the balance between NO and superoxide. I personally believe that a combination of low doses of L-arginine and BH4 may work out to be ideal; however, this hypothesis remains to be tested. However, your comments are very well taken, and the precarious balance between the actions of NO on the heart must be kept in mind.