DAF-FM (4-Amino-5-methylamino-2'7'-difluorofluorescein) Diacetate Detects Impairment of Agonist-Stimulated Nitric Oxide Synthesis by Elevated Glucose in Human Vascular Endothelial Cells: Reversal by Vitamin C and L-Sepiapterin

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ABSTRACT

Elevated plasma glucose, as commonly seen in types I and II diabetes mellitus, is known to result in endothelial dysfunction, a condition characterized by a loss of nitric oxide (NO)-dependent regulation of vascular tone. In the present study, we have utilized a recently developed NO-sensitive fluorescent dye, DAF-FM (4-amino-5-methylamino-2',7'-difluorofluorescein) diacetate to directly examine the consequences of elevated glucose on agonist-evoked NO synthesis in cultured human vascular endothelial cells. Exposure of cells for 5 to 7 days to high (20 mM) external glucose markedly reduced NO production in response to ATP, histamine, or the calcium ionophore calcimycin A23187 compared with 5 and 10 mM glucose concentrations. However, high glucose did not affect agonist-evoked elevations in cytosolic-free calcium, as monitored by Fluo-3. The addition of vitamin C (150 μM) and L-sepiapterin (20 μM) for 24 h to 20 mM glucose-treated cells improved stimulus-evoked NO synthesis but had no effect on cells exposed to either 5 or 10 mM glucose. Likewise, impaired NO production in high glucose-treated cells was largely reversed by exposure (3 h) to superoxide dismutase. Cellular levels of endothelial nitric-oxide synthase protein were unaltered by elevated glucose treatment, and no further change was observed after the addition of vitamin C and L-sepiapterin. Taken together, the results of our study serve to directly explain at the cellular level how glucose-impaired NO production in human endothelial cells may be reversed by agents that are reported clinically to improve endothelium-dependent vasorelaxation in patients.

The vascular endothelium exerts precise control over mean systemic blood pressure through the synthesis and release of vasoactive factors (e.g., nitric oxide, prostaglandins, endothelin, arachidonic acid metabolites, etc.) that act on the surrounding smooth muscle layer(s) (Mombouli and Vanhoutte, 1999). In diabetes mellitus, an early consequence of elevated plasma glucose is the development of endothelial dysfunction, which is characterized by an impairment of nitric oxide-dependent vasorelaxation that can lead to retinopathy, end stage renal failure, peripheral neuropathy, atherosclerosis, and heart disease (Lüscher et al., 2003). It is now well recognized that a major consequence of the glucose-mediated metabolic alterations in vascular endothelium is the disruption of normal NO signal transduction (Cosentino and Lüscher, 1998; Creager et al., 2003), which may represent the primary cellular event that initiates the pathogenesis of more severe cardiovascular complications. The increased generation of superoxide radicals, as a result of glucose-mediated metabolic disruption, has been identified as a causative event contributing to endothelial cell dysfunction and the loss of NO synthesis/bioavailability (Brownlee, 2001). For example, impaired endothelium-dependent vasorelaxation in diabetic patients and rodent models of diabetes is improved upon administration of either an antioxidant (e.g., vitamin C) (Ting et al., 1996; Timimi et al., 1998; Beckman et al., 2001) or essential enzyme cofactors that support proper eNOS function (e.g., tetrahydrobiopterin) (Pieper, 1997; Shinozaki et al., 1999; Heitzer et al., 2000; Pannirselvam et al., 2003). Elucidation of the cellular events underlying these observations would greatly increase our understanding of endothelial dysfunction.

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ABBREVIATIONS: NO, nitric oxide; DAF-FM, 4-amino-5-methylamino-2',7'-difluorofluorescein; eNOS, endothelial nitric-oxide synthase; BH4, tetrahydrobiopterin; L-NAME, L-nitro-arginine methyl ester; DMEM, Dulbecco’s modified Eagle’s medium; AM, acetomethyl ester.
To examine how elevated glucose affects the kinetics and magnitude of agonist-evoked NO production in real-time, we have utilized the NO-sensitive fluorescent dye DAF-FM diacetate to monitor NO synthesis directly in cultured human endothelial cells exposed to 5, 10, or 20 mM external glucose for 5 to 7 days. Prolonged exposure to elevated glucose depressed agonist-evoked NO production in response to histamine, ATP, or the calcium ionophore, calcimycin A23187; however, short-term addition of vitamin C (ascorbic acid) and L-epi-sepiapterin (i.e., 24 h) or superoxide dismutase (i.e., 3 h) largely reversed this impairment. Elevated glucose did not affect agonist-induced intracellular Ca\(^{2+}\) transients.

The amounts of immunoreactive NO synthase protein (eNOS) detected in all three groups of glucose-treated cells were unchanged and were not noticeably affected after exposure to vitamin C and/or L-epi-sepiapterin, a biosynthetic precursor of tetrahydrobiopterin (BH4). Taken together, the findings of our study are consistent with an impairment of agonist-evoked NO production in human endothelial cells by glucose-induced oxidative stress and that counteracting this stress leads to a direct increase in NO bioavailability.

**Materials and Methods**

**Preparation of EA.hy926 Cells.** The cultured human umbilical cell line, EA.hy926 (Edgell et al., 1983), was kindly provided by Dr. Cora-Jean Edgell (Dept. of Pathology, University of North Carolina, Chapel Hill, NC). Cells were grown at 37°C in 5% CO\(_2\) on 100-mm tissue culture-quality plastic dishes in Dulbecco’s modified Eagle’s medium (DMEM) containing high glucose, 10% (v/v) heat-inactivated fetal bovine serum (FBS) (HyClone, Logan, UT) and a hypoxanthine/thymidine medium supplement (Sigma-Aldrich, St. Louis, MO). After replating onto 35-mm dishes, cells at 50 to 80% confluence were treated for 4 to 6 days in DMEM containing 1% heat-inactivated FBS (to maintain cells in a quiescent state) and 5, 10, or 20 mM D-glucose (mannose was added as required to achieve consistent osmolality). Glucose-treated cells were incubated with either 150 μM vitamin C or 20 μM L-epi-sepiapterin or both and then harvested ~24 h later for Western blot analysis. Alternatively, some glucose-treated cells were seeded onto fibronectin-coated glass coverslips, maintained under the same concentrations of glucose, and then loaded the next day with the membrane-permeable form of the NO-sensitive fluorescent dye DAF-FM diacetate (see below). For some experiments, superoxide dismutase (SOD), isolated from bovine erythrocytes (Sigma-Aldrich) was added to the culture medium of glucose-treated cells for a period of 3 h at 37°C immediately before recordings of DAF-FM fluorescence. The final concentration of SOD in the medium was 200 U/ml.

**Measurement of NO Production in EA.hy926 Cells.** Intracellular NO was monitored with DAF-FM diacetate, a pH-insensitive fluorescent dye that emits increased fluorescence after reaction with NO to NO\(_2\) an active intermediate of NO formed during the spontaneous oxidation of NO to NO\(_2\) (Kojima et al., 1998). EA.hy926 cells seeded on glass coverslips were incubated at 22°C for 30 min in DMEM containing a low concentration (i.e., 0.5 μM) of DAF-FM diacetate to monitor NO synthesis directly in cultured human endothelial cells exposed to 5, 10, or 20 mM external glucose for 5 to 7 days. Prolonged exposure to elevated glucose depressed agonist-evoked NO production in response to histamine, ATP, or the calcium ionophore, calcimycin A23187; however, short-term addition of vitamin C (ascorbic acid) and L-epi-sepiapterin (i.e., 24 h) or superoxide dismutase (i.e., 3 h) largely reversed this impairment. Elevated glucose did not affect agonist-induced intracellular Ca\(^{2+}\) transients.

The amounts of immunoreactive NO synthase protein (eNOS) detected in all three groups of glucose-treated cells were unchanged and were not noticeably affected after exposure to vitamin C and/or L-epi-sepiapterin, a biosynthetic precursor of tetrahydrobiopterin (BH4). Taken together, the findings of our study are consistent with an impairment of agonist-evoked NO production in human endothelial cells by glucose-induced oxidative stress and that counteracting this stress leads to a direct increase in NO bioavailability.

**Measurement of Intracellular Calcium Transients in EA.hy926 Cells.** Relative changes in cytosolic-free calcium were measured using the fluorescent indicator Fluo-3 (Kao et al., 1989). Cells replated on glass coverslips were incubated for 30 min at room temperature in serum-free DMEM containing 2 μM Fluo-3/AM (Invitrogen). After loading, cells were washed three times with DMEM. Fluo-3 fluorescence signals in EA.hy926 cells were monitored as described above for measurements of NO production.

**Western Blotting.** Glucose-treated EA.hy926 cells, growing on tissue culture dishes, were rinsed once with sterile phosphate-buffed saline and then detached by a 1-min incubation with 0.05% trypsin/0.5 mM EDTA in phosphate-buffered saline. Detached cells were collected by centrifugation at ~100g for 5 min, and then stored at ~8°C as intact cell pellets. These pellets were suspended in ~0.5 ml of ice-cold lysis buffer (20 mM Tris HCl, pH 7.4, 140 mM NaCl, 5 mM KCl, 1% (v/v) Triton X-100, 1 mM EDTA, 2 mM dithiothreitol, 1 mM benzamidine, 0.2 mM phenylmethylsulfonyl fluoride, and 5 μg/ml each of leupeptin, aprotinin, and pepstatin A) followed by incubation on ice for 30 min. Protein concentrations of the whole cell lysates were measured by using a modified Lowry procedure, and equal amounts of total protein were mixed with Laemmli sample buffer containing 0.5% (v/v) β-mercaptoethanol. Protein samples were incubated for ~5 min at 95°C and then resolved by denaturing SDS-PAGE using a 9% separating gel. After overnight transfer of resolved proteins to nitrocellulose membrane (18 V, 4°C), Western blotting was performed using an anti-human eNOS monoclonal antibody (1:1000 dilution) (BD Biosciences, Mississauga, Ontario, Canada), as we have earlier described for other proteins (Swayne and Braun, 2001).

Quantification of eNOS immunoreactivity was carried out by image analysis densitometry using Quantity One software (Bio-Rad Laboratories, Hercules, CA). Under each glucose condition, differences between drug-treated and control groups were calculated after normalization to the corresponding Coomassie Blue-stained gel containing the same lysate samples (see below) using the following formula: % Difference = ([eNOS Intensity\(_{drug}\) - eNOS Intensity\(_{control}\)]/eNOS Intensity\(_{control}\)) × 100, where eNOS Intensity\(_{drug}\) is the amount of eNOS immunoreactivity detected in glucose-treated cells exposed to vitamin C and/or L-epi-sepiapterin and eNOS Intensity\(_{control}\) is the level of eNOS immunoreactivity detected in cells treated by same concentration of glucose alone. Note that, in the far right-hand lane of the blot displayed in Fig. 7A, a lysate sample derived from cultured human umbilical vein endothelial cells that were collected one passage before all of the other cells used served as a positive control for eNOS expression.

To ensure that observed changes in eNOS immunoreactivity were not skewed by unequal loading of total protein between lanes, the same cells samples analyzed by Western blotting were also resolved on a parallel SDS polyacrylamide gel and then stained with Coomassie Blue R-250. The total protein staining intensity observed in cells that were collected one passage before all of the other cells used served as a positive control for eNOS expression.
were briefly treated (10 min) with the competitive NOS inhibitor L-NAME or the purinergic agonist ATP evoked increases in cellular fluorescence that were reproducible upon a second agonist exposure (Fig. 1A). In the absence of agonist stimulation, basal fluorescence from DAF-FM-loaded cells did not noticeably change over a period of 5 to 10 min. The addition of the direct NO donor spermine nonoate (10 μM) produced a much larger fluorescence signal in cells compared with ATP or histamine, consistent with the spontaneous release of NO produced by this compound (Feelisch, 1998). Similar results were observed with the clinical nitrovasodilator sodium nitroprusside (10 μM) (data not shown). Treatment (~10 min) of dye-loaded cells with the competitive eNOS inhibitor L-NAME (Knowles and Moncada, 1994) after the initial agonist exposure abolished subsequent increases in fluorescence upon readdition of the same agonist (e.g., histamine or ATP) (Fig. 1B). However, L-NAME-treated cells still produced a qualitatively similar increase in fluorescence upon exposure to spermine nonoate, indicating that L-NAME treatment did not compromise cell viability or the responsiveness of the intracellular DAF-FM diacetate fluorescent reporter. Under the experimental conditions used to detect agonist-stimulated NO synthesis in single endothelial cells (see Materials and Methods), the evoked DAF-FM fluorescence increases were found to be transient in nature. Likewise, Qiu et al. (2001) have reported that DAF-2 fluorescence signals may be transient in populations of stimulated bovine aortic endothelial cells detected using a real-time imaging strategy; this phenomenon probably reflects photobleaching of the NO-bound form of the dye. However, as photobleaching seems to affect primarily the triazole or NO-modified form of DAF (Kojima et al., 1998), which represents only a small fraction of the total intracellular pool (Leikert et al., 2001), the large excess of unconverted dye in the cytoplasm remains fully sensitive to de novo NO synthesis, thereby allowing repeated measurements of stimulated NO production from the same cell(s) (Fig. 1, A and B).

There is now ample evidence implicating a causative role for elevated plasma glucose, as seen in types I and II diabetes mellitus, in the pathogenesis of endothelial dysfunction, which is strongly associated with impaired NO availability (Brownlee, 2001; Creager et al., 2003). The use of DAF-FM diacetate as a real-time reporter of NO synthesis provides the opportunity to directly examine how prolonged exposure to elevated glucose impacts agonist-evoked NO synthesis. Cells maintained in 5 mM glucose displayed progressive increases in the NO fluorescence signal in response to increasing concentrations of ATP (Fig. 2A). However, agonist-evoked fluorescence signals in cells treated with 20 mM glucose were significantly blunted compared with those observed with 5 mM glucose treatment (Fig. 2B). Quantification of the observed concentration-dependent increases in NO fluorescence evoked by ATP in 5 and 20 mM glucose-treated cells is plotted in Fig. 2D along with responses observed in cells treated with an intermediate glucose concentration (10 mM). Over the concentration range of 1 to 100 μM, ATP evoked similar increases in NO-associated fluorescence in 5 and 10 mM glucose-treated cells; however, fluorescence signals were significantly lower in cells treated with 20 mM glucose. In the continued presence of elevated glucose, the blunted NO fluorescence signals observed in 20 mM glucose-treated cells were largely reversed by a ~24-h exposure to vitamin C (150 μM), a potent antioxidant (Frei et al., 1989), and L-sepiapterin (20 μM), an endogenous precursor that can be converted to the eNOS cofactor BH4 via a cellular “salvage” pathway (Fig. 2C) (Werner-Felmayer et al., 1993). Similar findings have been reported in murine mesangial cells treated by 25 mM glucose, in which vitamin C and BH4 were shown to reverse the impairment of cytokine-induced NO production (Prabhakar, 2001). In contrast to these effects observed under high glucose conditions, exposure to vitamin C and L-sepiapterin did not enhance ATP-evoked increases in NO synthesis in endothelial cells treated with either 5 or 10 mM glucose (Fig. 2E) and seemed to somewhat dampen the maximal production of NO in response to agonist stimulation. Previous studies have reported that excess BH4/L-sepiapterin may autoxidize to generate superoxide radicals, thereby reducing NO availability and endothelium-dependent vasodilation (Kirsch et al., 2003; Mitchell et al., 2004).

To rule out that the observed blunted response to ATP was...
somehow selective for purinergic agonists, we further examined NO synthesis in response to histamine. As shown in Fig. 3, A and B, histamine-evoked increases in NO-associated fluorescence were also depressed in cells treated with 20 mM glucose compared with those treated with 5 mM glucose. As in the case of ATP, the addition of vitamin C and L-sepiapterin in the continued presence of 20 mM glucose largely reversed the blunted response to histamine but produced no enhancement of agonist-evoked NO production in cells exposed to either 5 or 10 mM glucose (Fig. 3, C to E).

Given the effectiveness of vitamin C and L-sepiapterin to improve agonist-evoked increases in NO production in high glucose-treated cells, we examined the effect of each agent individually on NO production in response to ATP. In glucose-treated cells exposed separately to either vitamin C (Fig. 4A) or L-sepiapterin (Fig. 4B), agonist-induced increases in NO synthesis were only partially restored, in contrast to the results obtained with combined vitamin C/L-sepiapterin treatment (see Figs. 2E and 3E).

Because disruption of agonist-evoked NO synthesis by elevated glucose could potentially be explained by altered calcium handling, we performed fluorescence-based measurements of ATP- and histamine-evoked cytosolic calcium transients in glucose-treated cells. Figure 5 shows fluorescence tracings of calcium transients evoked by either ATP (panels A and C) or histamine (panels B and D) in single endothelial cells treated with either 5 or 20 mM glucose, as monitored with the membrane-permeable calcium-sensitive dye Fluo-3 (Kao et al., 1989). Quantitative analyses of these signals indicated no significant differences in the magnitudes of agonist-induced calcium transients in cells treated by 5, 10, or 20 mM glucose (Fig. 5, E and F).

Based on these observations, we next examined the direct calcium-dependent activation of eNOS using the Ca^{2+} ionophore calcimycin A23187, which induces elevation of cytosolic Ca^{2+} by directly releasing intracellular Ca^{2+} stores and promoting the entry of external calcium. Similar to the results observed with ATP and histamine (see Figs. 2 and 3),
stimulation of NO production by calcimycin A23187 (0.1–1 μM) was significantly lower in cells treated with high glucose versus those exposed to either 5 or 10 mM external glucose (Fig. 6A). Furthermore, the addition of 150 μM vitamin C and 20 μM L-sepiapterin to glucose-treated cells improved calcimycin A23187-induced NO synthesis in EA.hy926 cells treated with 20 mM glucose (Fig. 6B), similar to the recovery of NO production in response to either ATP (Fig. 2E) or histamine (Fig. 3E). Finally, we observed that exposure to either vitamin C or L-sepiapterin alone only partially restored the calcimycin A23187-induced NO response in 20 mM glucose-treated cells (data not shown), similar to the data presented in Fig. 4. Mechanistically, these observations suggest that glucose-induced impairment of stimulated NO production occurs subsequent to the elevation of cytosolic free Ca²⁺ and may possibly involve either a disruption of eNOS activity itself or a decrease in the availability of newly synthesized NO.

Earlier studies have reported that chronic elevated glucose may alter the cellular expression of eNOS protein (Cosentino et al., 1997; Chakravarthy et al., 1998; Ding et al., 2000), which may negatively impact upon NO production. Using
Western blot analyses, endogenous eNOS was detected as a single ~140-kDa immunoreactive band in EA.hy926 human endothelial cells under all three glucose treatment conditions and in either the absence or presence of vitamin C and/or L-sepiapterin (Fig. 7A). Using densitometric image analysis (see Materials and Methods), we found that the levels of eNOS immunoreactive protein in cells treated by either 10 or 20 mM glucose alone were 96.9 ± 8.0 and 98.1 ± 3.6% (mean ± S.E., n = 6), respectively, of the eNOS immunoreactivity detected in 5 mM glucose-treated cells (set to 100%). Figure 7B plots the percent difference in eNOS immunoreactivity calculated between glucose-treated cells without exposure to either vitamin C or L-sepiapterin (control, set to 100%) and cells exposed to these agents at the same glucose concentration. Although modest differences in eNOS immunoreactivity were observed in cells exposed to vitamin C and/or L-sepiapterin, none of these changes was found to be statistically significant.

The observed improvement in agonist-induced NO production in high glucose-treated cells after the addition of vitamin C (Figs. 2, 3, 4, and 6) suggested that actively lowering cellular oxidants, such as superoxide radicals, may itself be beneficial. Elevated glucose is often associated with increased oxidative stress in the vascular wall (Giugliano et al., 1996), and this effect can be reduced by treatment with agents, such as SOD, that scavenge superoxide anions (Ammar et al., 2000; Nishikawa et al., 2000). To examine this possibility, glucose-treated EA.hy926 cells were incubated for 3 h with superoxide dismutase (200 U/ml) in the continued presence of 5, 10, or 20 mM glucose and then immediately utilized for recordings of DAF-FM fluorescence. As shown in Fig. 8, the addition of SOD reversed the impairment of ATP-stimulated NO production typically observed in EA.hy926 cells treated with 20 mM glucose; however, SOD seemed to have little or no effect on agonist-induced NO production in cells treated by 5 or 10 mM glucose (compare data in Fig. 2D). Thus, these observations consistent with an increased presence of superoxide radicals in cells undergoing prolonged exposure to elevated glucose.

**Discussion**

It is now recognized clinically that chronic elevation of plasma glucose, characteristic of types I and II diabetes mellitus, leads to impaired NO-dependent vasorelaxation (i.e., endothelium dysfunction) as a result of decreased synthesis and/or bioavailability of NO. Clinical studies examining endothelial dysfunction associated with hypertension or coronary artery disease have reported that the severity of dysfunction in patients can be reduced by administration of vitamin C (ascorbic acid) (Levine et al., 1996; Taddei et al., 1998). Likewise, in rodent and human diabetic models of endothelial dysfunction, administration of either L-sepiapterin (Pannirselvam et al., 2003) or BH4 (Pieper, 1997; Shinozaki et al., 1999; Heitzer et al., 2000) is reported to improve endothelium-dependent vasorelaxation. However, it remains unclear from the majority of these reports what aspect(s) of vascular function and/or properties are affected by such treatments. In the present study, we have utilized the NO-sensitive fluorescent dye DAF-FM diacetate (Kojima et al., 1998) to examine directly, in real-time, how agonist-induced NO production is affected by elevated extracellular glucose in cultured human vascular endothelial cells and how vitamin C and L-sepiapterin influence this process. It is noteworthy that agonist-evoked increases in DAF-FM fluorescence were inhibited by pretreatment of dye-loaded cells with L-NAME, a competitive inhibitor of eNOS (Knowles and Moncada, 1994), whereas L-NAME had no effect on the fluorescence increase produced by the addition of the direct NO donor spermine nonoate (Feelisch, 1998). Thus, these data are consistent with the reported properties of DAF-FM diacetate in endothelial cells (Nakatsubo et al., 1998) and support the conclusion that the increases we have observed in DAF-FM diacetate fluorescence reflect agonist-stimulated elevations in cellular NO.
In the presence of either normal (i.e., 5 mM, ~90 mg/dl) or modestly elevated extracellular glucose (i.e., 10 mM, ~180 mg/dl), both ATP and histamine produced similar concentration-dependent increases in DAF-FM fluorescence (Figs. 2A and 3A). However, NO synthesis was markedly blunted in response to the same concentrations of these agonists in cells exposed to a higher concentration (i.e., 20 mM, 360 mg/dl) of extracellular glucose. Likewise, NO production stimulated by calcimycin A23187, which directly elevates the cytosolic free \([\text{Ca}^{2+}]\) by promoting release from intracellular stores and calcium influx, was also decreased by 20 mM glucose treatment (Fig. 6). Thus, these data demonstrate that above a threshold concentration, elevated external glucose interferes with stimulated NO production at the level of individual vascular endothelial cells.

Although prolonged exposure to elevated glucose may depress endothelial cell NO production by altering a number of cellular properties, an obvious candidate is altered release of intracellular \([\text{Ca}^{2+}]\) stores, which would be expected to have a direct impact on eNOS activation and NO synthesis. Using Fluo-3 to monitor agonist-stimulated elevations in cytosolic free \([\text{Ca}^{2+}]\) in glucose-treated cells, we did not detect any apparent differences in either the magnitude or kinetics of intracellular \([\text{Ca}^{2+}]\) transients evoked by brief exposure to either ATP or histamine (Fig. 5). Such observations provide important insights regarding the integrity of cellular function in these different treatment groups. First, the similar concentration dependence for evoked \([\text{Ca}^{2+}]\) transients by either ATP or histamine suggest that high glucose exposure does not alter receptor/G-protein activation or the signaling pathway leading to release of intracellular \([\text{Ca}^{2+}]\) stores. Second, the cellular mechanisms responsible for maintaining intracellular \([\text{Ca}^{2+}]\) stores and promoting entry of external \([\text{Ca}^{2+}]\) after store depletion do not seem to be compromised by prolonged treatment with elevated glucose. Collectively, these observations suggest that high glucose does not impair the signal transduction events leading to the generation of intracellular \([\text{Ca}^{2+}]\) transients in human endothelial cells but rather point to a defect(s) downstream of this event that may be responsible for decreased NO availability.
Based on steady-state measurements of NO metabolites, such as nitrites, it has been suggested that agonist-stimulated NO synthesis may be lower in arterial vessels from diabetic animals (Shinozaki et al., 1999). An important finding of our study is that the observed impairment of stimulus-evoked NO production by 20 mM external glucose could be largely reversed by the addition of vitamin C (150 μM), an effective antioxidant in plasma and tissues (Frei et al., 1989), and L-sepiapterin (20 μM), a biosynthetic precursor of the eNOS cofactor BH4 (Werner-Felmayer and Gross, 1996). The administration of vitamin C has been clinically shown to improve endothelium-dependent vasorelaxation in diseased humans (Levine et al., 1996; Ting et al., 1996; Taddei et al., 1998; Timimi et al., 1998), and similar beneficial effects have been reported for BH4 or its biosynthetic precursor, L-sepiapterin.
Reversal of Impaired NO Synthesis in Endothelial Cells

Fig. 8. SOD restores ATP-induced NO synthesis in high glucose-treated endothelial cells. SOD (from bovine erythrocytes) was added to the culture medium of EA.hy926 cells treated with 5, 10, or 20 mM glucose at a final concentration of 200 U/ml. Cells were pretreated with SOD for approximately 3 h immediately before recordings of DAF-FM fluorescence. Data points represent the means ± S.E. of agonist-induced changes in DAF-FM fluorescence recorded from five different populations of cells treated at the indicated concentrations of glucose.


tions (Pieper, 1997; Heitzer et al., 2000; Maier et al., 2000; Tiefenbacher et al., 2000; Pannirselvam et al., 2003). However, under normal physiologic conditions, administration of these compounds does not further enhance endothelial function (Ting et al., 1996; Pieper, 1997; Taddei et al., 1998; Timimi et al., 1998; Heitzer et al., 2000; Tiefenbacher et al., 2000; Beckman et al., 2001). Our results demonstrating that vitamin C and l-sepiapterin do not increase agonist-evoked NO synthesis in endothelial cells treated with either 5 or 10 mM glucose (Figs. 2 and 3) are entirely consistent with these earlier reports. Although it has not been readily apparent which cell type(s) is primarily affected by these therapeutic agents in whole animal or isolated vessel studies, our results provide clear evidence that vitamin C and l-sepiapterin act directly on vascular endothelial cells to improve agonist-stimulated NO synthesis and/or availability.

It is now well recognized that high glucose produces a number of metabolic changes in human cells, including the production of advanced glycation end products, the activation of protein kinase C, and elevated production of superoxide dismutase for (O2•−) (Squadrito and Pryor, 1995). Per- oxyxynitrite can cause oxidation of BH4 (Werner-Felmayer and Gross, 1996), and under conditions of limited BH4 levels, eNOS itself may be capable of generating superoxide anions (Pou et al., 1992; Vasquez-Vivar et al., 2002). Such a process would be expected to increase the formation of peroxynitrite, thereby contributing to the progression of endothelial dysfunction. Our results (see Fig. 8) showing that prior addition of superoxide dismutase for 3 h reversed the impairment of agonist-stimulated NO synthesis in high glucose-treated endothelial cells are thus consistent with an elevated level of oxidative stress in these cells (Nishikawa et al., 2000). Furthermore, vitamin C, a potent antioxidant, is reported to enhance eNOS enzyme activity and NO synthesis by stabi-
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