Acute Host-Mediated Endothelial Injury After Adenoviral Gene Transfer in Normal Rabbit Arteries
Impact on Transgene Expression and Endothelial Function

Keith M. Channon, HuSheng Qian, Scot A. Youngblood, Ercument Olmez, Geetha A. Shetty, Valentina Neplioueva, Michael A. Blazing, Samuel E. George

Abstract—Acute injury after adenoviral vascular gene transfer remains incompletely characterized. Here, we describe the early response (≤days) in 52 New Zealand White rabbits undergoing gene transfer (β-galactosidase or empty vector) or sham procedures to both carotid arteries. After gene transfer, arteries were either left in vivo for 1 hour to 3 days (in vivo arteries) or were excised immediately after gene transfer and cultured (ex vivo arteries). Within 1 hour, in vivo arteries receiving infectious titers of $\approx 4 \times 10^6$ plaque-forming units (pfu)/mL showed endothelial activation, with an acute inflammatory infiltrate developing by 6 hours. Ex vivo arteries showed endothelial activation but no inflammatory infiltrate. There were also significant differences in transgene expression between in vivo and ex vivo arteries. Ex vivo arteries showed titer-dependent increases in β-galactosidase expression through $2 \times 10^{10}$ pfu/mL, whereas in in vivo arteries, titers above $4 \times 10^9$ pfu/mL merely increased acute inflammatory response, without increasing transgene expression. In vivo arteries showed significant time- and titer-dependent impairment in endothelium-dependent relaxation, with no effect on contraction or nitroprusside-induced relaxation. Interestingly, however, if rabbits were made neutropenic with vinblastine, their arteries maintained full endothelium-dependent relaxation, even after very high titer vascular infection (up to $1 \times 10^{11}$ pfu/mL). These findings show that recombinant adenovirus triggers an early inflammatory response, and it is the inflammatory response that in turn causes functional endothelial injury. This occurs at much lower titers than previously appreciated (though the precise threshold will undoubtedly vary between laboratories). However, titers below the inflammatory threshold produce excellent transgene expression without inflammation or vascular injury. (Circ Res. 1998;82:1253-1262.)

Key Words: adenovirus • gene transfer • endothelium • inflammation • neutrophil

Recombinant adenovirus shows promise as a tool for vascular research and therapy,1-3 but significant limitations are clearly apparent. Most prominent are the long-term problems4-5: in vivo transgene expression declines from initially high levels to virtually nothing within ∼2 weeks,6 and an adenovirus-induced chronic inflammatory response produces significant endothelial injury and neointimal proliferation that confound data interpretation and counter any potential therapeutic effect.7 These untoward effects are largely attributable to a virus-induced host immune response.

Acute vascular effects of adenoviral gene transfer—those occurring within 3 days of gene transfer—have also been described but are less well characterized: (1) in normal rat arteries, complete endothelial denudation after high-titer ($2 \times 10^9$ pfu/mL) gene transfer but no apparent injury at lower titers ($\approx 10^9$ pfu/mL),8 (2) in balloon-injured rat arteries, an acute medial inflammatory infiltrate and smooth muscle cell loss in arteries receiving $10^9$ pfu/mL,9 and (3) in normal rabbit carotid arteries, a medial inflammatory infiltrate, an impaired response to contractile agonists, and complete loss of endothelium-dependent vasodilation after moderately high-titer ($4 \times 10^{10}$ pfu/mL) gene transfer.10

These observations have led to 2 general hypotheses about adenovirus-induced acute injury. One is that the adenovirus itself is directly toxic to the vessel (“direct viral toxicity”),8,11 a view supported by the cytotoxic effects of high-multiplicity recombinant adenovirus infections in cell culture and the known in vitro cytotoxicity of some adenoviral proteins, such as the penton base.12,13 The second is that the observed injury is a host-mediated effect, largely secondary to acute inflammatory cell infiltrate, that develops after high-titer gene transfer.14 A better understanding of adenovirus-induced acute effects and the cellular mechanisms through which they are produced may be particularly important for vascular gene transfer, since these effects may have an untoward impact on transgene expression6 and the subsequent development of neointimal proliferation.7

Accordingly, we undertook the present study to define more thoroughly the acute vascular effects of adenovirus and to answer the following general questions about adenoviral...
gene transfer in normal rabbit arteries: (1) What is the extent of acute vascular inflammation, and what is its time course and titer dependence? (2) What is the impact of acute vascular inflammation on transgene expression? (3) To what extent does adenoviral gene transfer functionally impair the vessel, and if functional impairment is present, what is its time course and titer dependence? (4) What is the relative contribution of “direct viral toxicity” and host-mediated inflammatory effects to the observed functional deficits?

The present study shows that a titer-dependent acute inflammatory response that significantly limits transgene expression and endothelial vasomotor function develops within hours of vascular gene transfer. Moreover, our data suggest that the host response, rather than direct viral toxic effects, is largely responsible for the observed endothelial injury.

Materials and Methods

Animals
Male New Zealand White rabbits (2 to 2.5 kg) were maintained on a normal diet. Anesthesia was induced using ketamine (Ketastat, 60 mg/kg, Bristol Laboratories) and xylazine (Anased, 6 mg/kg, Lloyd Laboratories) subcutaneously. All animal care and procedures were approved by Duke University Institutional Animal Care and Use Committee and complied with the Guide for the Care and Use of Laboratory Animals (National Institutes of Health publication 80-23, revised 1985).

Preparation of Adenovirus Vector
We generated a recombinant adenovirus, Ad β-Gal, derived from the in340 mutant strain of Ad5, containing a nuclear-targeted β-Gal transgene and expression cassette in the E1 region, as previously described.13 Virus was purified from infected 293 cells by lysis in virus storage medium (20 mmol/L Tris [pH 7.4], 150 mmol/L NaCl, 5 mmol/L KCl, and 1 mmol/L MgCl2), followed by ultracentrifugation of the lysate on a 1.3 to 1.4 g/mL cesium chloride step gradient at 100,000 g for 20 minutes at 4°C. Virus was harvested, and residual cellular RNA was removed by incubation with RNase A (100 μg/mL, Sigma Chemical Co) for 30 minutes at room temperature. Pooled virus was ultracentrifuged overnight on a second cesium chloride gradient at 4°C. Pure virus was harvested and desalted by serial gel filtration on Sepharose CL-6B spin columns (Pharmacia) in virus storage buffer. Gel-filtered virus was diluted 1:1 with 80% normal rabbit serum/20% glycerol (virus storage medium) and immediately frozen in aliquots. Viral concentration was initially estimated spectrophotometrically by absorbance at 260 nm, and infectious titers of all viral stocks were determined by at least 3 independent plaque assays on 293 cells using standard techniques (1-hour infection at 37°C, without rocking).16

Screening of Preparations to Exclude Wild-Type Adenovirus Contamination
Wild-type contamination was shown to be <1 in 107 by PCR analysis, using primers designed to amplify a 560-bp product corresponding to Ad5 base pairs 690 to 1250 (sense primer, 5’-ACGAACGTATGATTAGACGG 3’ [Ad5 base pairs 690 to 711]; antisense primer, 5’-AGGCTCGATTACAGACAGG 3’ [Ad5 base pairs 1250 to 1229]). As a positive control, serial 10-fold dilutions of Ad5 adenovirus DNA, ranging from 1 ng to 1 fg (106 to 1 copy of the in340 adenovirus genome) were used as template in the PCR. A single copy of Ad5 DNA produced a clearly visible 560-bp band. No recombinant preparations produced a positive PCR result, unless >106 copies of the recombinant adenovirus DNA were present in the PCR. In addition, no recombinant preparation produced cell death on cultured human vascular smooth muscle cells, despite high multiplicity of infection levels (≥100 pfu/cell) and observation periods of up to 10 days. In contrast, Ad5 preparations rapidly induced cell death in human vascular smooth muscle cells (within 3 days at a multiplicity of infection of 1).

Carotid Artery Gene Transfer
Rabbits underwent gene transfer to both carotid arteries in an identical manner. High-titer viral stock, maintained on dry ice until immediately before use, was thawed and diluted with DMEM/virus storage medium to ensure equal composition of virus solutions at different viral titers. Mock infections were carried out using DMEM/virus storage medium alone. At surgery, the right and left carotid arteries were carefully exposed through a midline neck incision. Heparin (700 IU IV) was administered, and gene transfer was performed by isolating the exposed vessel segment between microvascular clamps. A 24-gauge polytetrafluoroethylene (Teflon) cannula was inserted through a proximal arteriotomy, and the lumen of the vessel was cleared of blood by gentle flushing with DMEM. Approximately 200 μL of virus solution was instilled into the vessel lumen and incubated for 20 minutes. The arteriotomy was then repaired using 100 nylon sutures.

Induction of Neutropenia With Vinblastine
To induce neutropenia, animals received intravenous vinblastine according to previous protocols.17,18 Two doses of 1.5 mg vinblastine were given: 3 days before and, again, 1 day before surgery and gene transfer. A peripheral blood sample was taken immediately before each dose, on the day of surgery, and at the harvest of the vessels to ensure that profound neutropenia had been induced by the time of surgery and had been maintained throughout the experimental period. Peripheral blood counts were determined by Coulter counter, and absolute counts of neutrophils and lymphocytes were also determined by manual counting of blood smears. During vinblastine treatment, animals received a single daily dose of enrofloxacin (Baytril, 15 mg, Miles Inc) subcutaneously.

Vessel Harvesting and Analysis
Vessels were harvested at time points from 1 hour to 72 hours after surgery. Animals were anesthetized and heparinized (700 IU IV), and the carotid arteries were dissected free. Animals were killed with an intravenous overdose of pentobarbital sodium, and vessels were excised and washed in PBS. At the same time, ex vivo vessel rings and the carotid arteries were harvested at time points from 1 hour to 72 hours after surgery. Animals were anesthetized and heparinized (700 IU IV), and the carotid arteries were dissected free. Animals were killed with an intravenous overdose of pentobarbital sodium, and vessels were excised and washed in PBS. At the same time, ex vivo vessel rings were removed from the incubator and processed in parallel. Segments from all vessels were immediately frozen at −80°C for protein extraction or were rapidly frozen for processed sections and immunohistochemistry.

β-Gal and total protein concentration was quantified in frozen vessel segments using an ELISA kit (5 Prime-3 Prime) and a Bradford protein assay. β-Gal protein quantity was determined as nanograms β-Gal per milligram of vessel protein.

Immunohistochemistry and Image Analysis
Vessel segments were briefly equilibrated in 30% sucrose in PBS at 4°C, embedded in optimal cutting temperature compound (Miles Scientific), frozen in liquid nitrogen, and sectioned (6 μm) onto
silane-coated glass microscope slides. Vessel sections were thawed, dried, and then stained for β-Gal by incubation at room temperature in X-Gal solution for 4 hours (20 mMol/L Tris [pH 7.4], 150 mMol/L NaCl, 5 mMol/L potassium ferricyanide, 5 mMol/L potassium ferrocyanide, and 2 mMol/L MgCl2 containing 0.5 mg/mL X-Gal). Immunohistochemistry to identify CD18 leucocytes, T lymphocytes, or macrophages was performed using primary antibodies directed against rabbit CD18 (Serotec), rabbit CD43 (T11/135, Serotec), or rabbit RAM 11 (Dako), respectively. VCAM-1 and ICAM-1 were identified using monoclonal antibodies raised against rabbit VCAM-1 and ICAM-1β (a generous gift of Dr M. Cybulsky, University of Toronto). Immunostaining of smooth muscle cells (HHF 35, Dako) and endothelial cells (anti-von Willebrand factor, Atlantic Antibodies) was also performed. Briefly, frozen sections were fixed for 10 minutes in cold acetone and then equilibrated in PBS. Blocking solution (1.5% horse serum in PBS) was applied for 1 hour at room temperature. Antibodies were diluted in blocking solution at concentrations determined in preliminary experiments and were applied to tissue sections for 1 hour. This was followed by sequential incubation with biotinylated anti-mouse IgG (except for von Willebrand factor staining) and ABC reagent (Vectastain ABC kit, Vector Laboratories, Inc). Immune complexes were localized using the chromogenic alkaline phosphatase substrate Vector Red (Vector Laboratories, Inc). The sections were lightly counterstained with hematoxylin, dehydrated, and mounted with Permount (Fisher Scientific). In all experiments an adjacent section was incubated with an irrelevant murine IgG monoclonal antibody to serve as a negative control. Staining intensity was quantified using an image analysis system (Olympus IX70 inverted microscope, Optromics DEI-750 image capturing hardware, PowerTowerPro 180 CPU). Images were captured using Adobe Premiere and quantified using NIH Image 1.61 software.

Endothelial inflammatory cell infiltration was assessed by counting the total number of CD18 or CD43 leucocytes on the luminal surface of arterial cross sections. Counting was performed at 3,200 magnification, in a blinded fashion, using a pointing device and a manual counter. The mean number of luminal inflammatory cells was calculated from counting multiple vessel cross sections (range, 4 to 20; median, 8 sections/vessel).

Vasomotor Studies

Freshly harvested vessels were cleaned of fat and connective tissues, cut into helical strips, and mounted in 30-mL organ baths containing Krebs-Henseleit buffer (mmol/L: NaCl 120, KCl 4.7, CaCl2 2.5, MgSO4 1.2, KH2PO4, NaHCO3, and glucose 5.5 mMol/L, pH 7.4) maintained at 37°C and oxygenated with 95% O2/5% CO2. Vessels were equilibrated for 60 minutes, with changes of bathing fluid every 15 minutes. Isometric tension studies were performed using a Grass model 7D polygraph. Optimal resting tension was determined in baseline studies, and the response to vasoactive drugs was then determined. Cumulative dose–response curves to PE (10-8 to 10-4 mol/L) were established. The vessels were then submaximally precontracted with PE (typically 3×10-8 mol/L), and endothelial function was evaluated by vascular relaxation to ACh (10-8 to 10-4 mol/L). NO mediation of ACh-induced relaxation was blocked by L-NAME (1 mmol/L), a specific non-selective inhibitor of NO synthase. After they were washed, the vessels were again precontracted, and endothelium-independent relaxation responses to SNP (10-4 to 10-4 mol/L) were determined. Contractile responses were measured from the polygraph chart and expressed as a percentage of the maximal contraction or, for relaxations, as a percentage of the precontracted tension. Statistical significance of the differences between responses was assessed by ANOVA.

Results

Host Factors Limit Adenovirus-Mediated Transgene Expression In Vivo

We measured β-Gal transgene expression as a function of infective titer and compared expression between (1) “in vivo arteries,” ie, carotid arteries left in situ after gene transfer until harvest 3 days later, and (2) “ex vivo arteries,” ie, the contralateral artery from the same rabbit, which was excised immediately after gene transfer and cultured ex vivo for 3 days.

A total of 19 carotid artery pairs were studied. They were infected with titers ranging from 4×108 to 5×1011 pfu/mL (Figure 1).

The in vivo arteries showed a striking plateau in transgene expression. The β-Gal protein was detectable at the lowest titer evaluated and rose to near-maximal levels at a titer of 1.6×1010 pfu/mL. However, β-Gal levels showed no significant increase from 2×108 through 1×1011 pfu/mL, and a further increase in titer (to 5×1011 pfu/mL) significantly reduced β-Gal expression. In ex vivo arteries, transgene expression was higher than in the paired contralateral in vivo arteries at all titers studied. In addition, expression in ex vivo arteries increased steadily as infecting titers were increased from 1.6×109 to 2×1010 pfu/mL. Thus, the gap between ex vivo and in vivo expression became progressively larger in this titer range (reaching a 6-fold difference at 2×1010 pfu/mL). This suggested that some host factor(s) may be limiting transgene expression in vivo.

Adenovirus-Mediated Gene Transfer Provokes Time- and Titer-Dependent Endothelial Activation

We examined arteries for evidence of endothelial activation and acute inflammation after from 1 to 72 hours after infection with recombinant adenovirus. Cryosections were evaluated by immunohistochemistry to identify VCAM-1, ICAM-1, CD18+, and CD43+ leucocytes (T lymphocytes). CD18+ leucocytes were identified as PMNs, as they had multilobed nuclei and did not stain with RAM 11, which would identify CD18+ monocytes.
ICAM-1 was detectable at 6 hours after adenoviral infection in both the adventitia and endothelium (Figure 2). ICAM-1 immunostaining increased through 24 hours and remained at high levels at 72 hours. VCAM-1 was detectable as early as 1 hour and, like ICAM-1, increased through 24 hours and remained at high levels at 72 hours. However, VCAM-1 staining was confined to the endothelium. Mock-infected arteries showed no endothelial ICAM-1 or VCAM-1 expression (Figure 2, bottom panels), nor did arteries infected with low-titer adenovirus (1.6 \times 10^9 pfu/mL, not shown).

Thus, high-titer recombinant adenoviral gene transfer induces endothelial activation very soon after infection.

The degree of endothelial activation was also titer dependent, as judged by immunohistochemistry combined with image analysis (Figure 3). When the infectious titer was held below 4 \times 10^9 pfu/mL, neither ICAM-1 nor VCAM-1 showed significantly increased expression above that observed in sham-infected arteries. However, as titers met or exceeded that threshold, there was a steady increase in endothelial expression of both adhesion molecules. We observed a sigmoidal relationship between the log of infectious titer used and relative staining intensity, with the steepest increase in staining intensity occurring between 4 \times 10^9 and 2 \times 10^{10} pfu/mL.

We next compared the degree of inflammation in mock-infected vessels and in low-titer (1.6 \times 10^9 pfu/mL) and moderate-titer (2 \times 10^{10} pfu/mL) adenovirus-infected arteries. Arteries were harvested 72 hours after gene transfer, then cryosectioned, and (1) stained with X-Gal to demonstrate \(\beta\)-Gal–expressing cells, followed by (2) immunostaining for CD18 (Figure 4, all panels). We observed the following: (1) Mock-infected arteries showed no \(\beta\)-Gal–positive nuclei

![Figure 2. Time dependence of ICAM-1 and VCAM-1 expression.](image-url)
(Figure 4A), whereas arteries infected with moderate-titer (Figure 4B) and low-titer (Figure 4C) adenovirus showed approximately equal amounts of transduced endothelial cells (>80% endothelial cell nuclei positive for β-Gal). (2) In mock-infected arteries (Figure 4A) and low-titer–infected arteries (Figure 4C), endothelial inflammatory cells were observed only occasionally. (3) In contrast, vessels infected with moderate-titer adenovirus (Figure 4B) showed extensive endothelial infiltration by PMNs. Thus, low-titer– and moderate-titer–infected vessels differed primarily in the degree of endothelial inflammatory cell infiltrate and were not distinguishable in terms of transgene expression.

To quantify further the extent of inflammation, we counted endothelium-adherent CD18+ and CD43+ (pan T-lymphocyte) cells in cryosections (Figure 5). As was observed for endothelial activation, the degree of inflammatory infiltrate showed both time and titer dependence. A significant inflammatory infiltrate developed as early as 6 hours after high-titer adenovirus infection (1×10^11 pfu/mL) and progressed to near-maximal levels by 12 hours after gene transfer (Figure 5, left). Next, we examined the effect of viral titer on inflammation at 72 hours after infection. At or below 1.6×10^9 pfu/mL, the number of endothelial inflammatory cells was not increased relative to mock-infected vessels (Figure 5, right). However, at ≥4×10^9 pfu/mL, the inflammatory infiltrate progressively increased. Numbers of PMNs continued to increase with titers up to 5×10^11 pfu/mL, whereas CD43+ T lymphocytes were less numerous than PMNs and did not show progressive increase with viral titer.

To determine whether β-Gal transgene expression was contributing to the observed inflammation, we infected 4 arteries with 5×10^10 pfu/mL of an “empty vector” (identical to Ad.β-Gal but the β-Gal transgene was absent) and 4 arteries with 5×10^9 pfu/mL of Ad.β-Gal and compared the degree of adhesion molecule expression and inflammatory cell infiltration between the 2 groups (Table 1). Empty vector-infected arteries and Ad.β-Gal–infected arteries were not distinguishable with regard to any of the parameters studied, suggesting that β-Gal expression did not contribute significantly to the observed inflammation.

**Adenovirus-Mediated Vascular Gene Transfer Results in Functional Endothelial Injury**

To assess the functional impact of adenovirus-mediated gene transfer, we excised rabbit carotid arteries 3 days after gene transfer and evaluated their response to vasoactive agonists. Regardless of the adenovirus titer received, all vessels showed essentially identical contraction in response to PE (Figure 6A). Similarly, all vessels relaxed in response to treatment with the NO donor SNP (Figure 6C). These observations show that adenoviral gene transfer did not harm the contraction and relaxation responses of vascular smooth...
Acute Endothelial Injury in Adenoviral Gene Transfer

Figure 5. Adenovirus-mediated endothelial inflammation is time and titer dependent. Left, Rabbit carotid arteries were infected in vivo with 1 \times 10^{11} pfu/mL of Ad.\beta-Gal and harvested at various times after infection. The numbers of CD18⁺ leukocytes (PMNs) and CD43⁺ leukocytes (T lymphocytes) on the endothelial surface were counted in vessel cryosections stained by immuno-histochemistry. hpf indicates high-power field. Bars represent the means of at least 3 (range, 3 to 6) vessels analyzed at each viral titer. Error bars indicate SEM. Right, Similar experiment is shown, except titer was varied as indicated and all vessels were harvested at 72 hours after infection.

We also evaluated the time course of vasomotor function at 6, 12, 24, and 72 hours after infection with 1 \times 10^{11} pfu/mL. ACh-induced relaxation was significantly impaired as early as 6 hours after infection, with further injury progressing through 72 hours (Figure 7). There was no significant impact on either PE-induced contraction or SNP-induced relaxation at any time after gene transfer (data not shown). Thus, adenovirus induces time- and titer-dependent endothelial dysfunction but does not impair vascular smooth muscle function.

TABLE 1. Endothelial Activation and Inflammation Induced by Empty Vector and Ad.\beta-Gal

<table>
<thead>
<tr>
<th>Vector</th>
<th>ICAM-1, (\mu mol/L²/hpf)</th>
<th>VCAM-1, (\mu mol/L²/hpf)</th>
<th>CD18⁺, Cells/hpf</th>
<th>CD43⁺, Cells/hpf</th>
</tr>
</thead>
<tbody>
<tr>
<td>Empty vector</td>
<td>83 ± 14</td>
<td>79 ± 8</td>
<td>20.1 ± 3.9</td>
<td>10.5 ± 3.0</td>
</tr>
<tr>
<td>Ad.\beta-Gal</td>
<td>89 ± 16</td>
<td>76 ± 6</td>
<td>23.2 ± 5.5</td>
<td>11.9 ± 3.7</td>
</tr>
</tbody>
</table>

hpf indicates high-power field. A total of 8 rabbit carotid arteries were infected with 5 \times 10^{10} pfu/mL of either an empty vector or Ad.\beta-Gal (4 each), harvested 3 days later, and immunostained for the indicated markers. Areas of positive ICAM-1 and VCAM-1 endothelial staining were quantified by image analysis, and endothelium-adherent CD18⁺ and CD43⁺ cells were counted by an observer blinded to the experimental conditions. Scores from 4 randomly selected sections from each artery were determined. Values are mean ± SEM. P = NS (>0.05) for all comparisons between empty vector and Ad.\beta-Gal, by 2-tailed t test.

Neutrophil Inflammation Mediates Functional Endothelial Injury

We hypothesized that inflammatory cell infiltration may play a role in the pathogenesis of adenovirus-related endothelial injury. To investigate this possibility, we induced neutropenia in rabbits undergoing carotid artery gene transfer. Four rabbits received vinblastine (1.5 mg IV) on days 3 and 1 before surgery. All animals survived until the designated time of harvest without evidence of infection. At surgery, all
Vinblastine-treated rabbits were profoundly neutropenic (15-fold reduction compared with pretreatment) and remained so at the time of harvest (Table 2). Peripheral blood lymphocyte and platelet counts were modestly reduced at surgery (2-fold and 2.5-fold, respectively), with further reductions noted by the time of harvest.

Vinblastine pretreatment had no apparent effect on either VCAM-1 or ICAM-1 expression after gene transfer; arteries from vinblastine-treated animals still mounted a vigorous adhesion molecule response after adenoviral gene transfer (Figure 8A and 8B; compare with Figure 2 at 24 hours). However, vinblastine pretreatment strikingly reduced endothelial inflammatory cell infiltration (Figure 8C and 8D; compare with Figure 4B). Endothelium-adherent PMNs were reduced by 25-fold (Figure 9A; \(P \leq 0.01\)), whereas endothelium-adherent T-lymphocytes were reduced by 2-fold (\(P = \text{NS}\)) 3 days after adenoviral gene transfer. Thus, vinblastine treatment did not affect endothelial cell activation and only modestly reduced T-lymphocyte infiltration but virtually abrogated endothelial PMN infiltration in infected arteries.

We next sought to determine whether the marked reduction in endothelial PMNs favorably affected endothelial vasomotor function after adenoviral gene transfer. We examined vasomotor function in arteries from 4 groups of rabbits: (1) no vinblastine, mock-infected; (2) no vinblastine, high-titer gene transfer (\(1 \times 10^{11} \text{ pfu/mL}\)); (3) vinblastine-treated, mock-infected; and (4) vinblastine-treated, high-titer gene transfer. Vinblastine treatment did not alter sensitivity to PE and modestly reduced sensitivity to SNP, reflecting a slight reduction in

![Figure 8](http://circres.ahajournals.org/)

Figure 8. Vinblastine-induced neutropenia abolishes endothelial inflammatory cell infiltration. Rabbits were rendered neutropenic by vinblastine pretreatment, and carotid arteries were infected with Ad,\(\beta\)-Gal \((1 \times 10^{11} \text{ pfu/mL})\). Vessels were harvested 72 hours later, and serial tissue sections were immunostained for the adhesion molecules VCAM-1 (A) or ICAM-1 (B) or for CD18\(^+\) or CD43\(^+\) inflammatory cells (C and D, respectively). Counterstaining with X-Gal revealed blue nuclei in transduced endothelial cells expressing \(\beta\)-Gal (outlined arrows).
sensitivity to NO (for unknown reasons). Therefore, to standardize comparisons between vinblastine-treated and untreated animals, we expressed ACh-induced relaxation as a percentage of maximal SNP-induced relaxation. With this correction, ACh-induced relaxation was virtually identical in mock-infected arteries, regardless of vinblastine treatment.

We next compared ACh-induced relaxation in arteries from untreated high-titer gene transfer rabbits with: (1) the contralateral sham-infected carotid from the same animal and (2) arteries from vinblastine, high-titer gene transfer rabbits (Figure 9B). In untreated rabbits, sham-infected arteries relaxed by >75% to ACh, whereas high-titer adenovirus markedly impaired ACh-induced relaxation. But in vinblastine-treated rabbits, ACh-induced relaxation was virtually identical, regardless of whether the artery was mock-infected or uninfected. Thus, high-titer adenovirus by itself did not impair endothelial vasomotor function, if the rabbit was first made neutropenic with vinblastine. It is host-mediated inflammation, rather than direct effects of the virus, that induces the observed deficit in endothelial vasomotor function.

Discussion

The present study shows that adenoviral gene transfer acutely induces endothelial activation, inflammatory cell infiltration, and endothelial dysfunction. All of these effects are directly related to infectious titer, and all become apparent within 6 hours of gene transfer. Although superficially discouraging, these findings are tempered considerably by the existence of a therapeutic window—a range of infectious titers that induce near-maximal transgene expression but little or no acute vascular injury. In our hands, this window lies roughly between 1 and 4×10⁹ pfu/mL. Previously published therapeutic window estimates, based on expression data and morphological observations (ie, abrupt loss of transgene expression and endothelial denudation after very high-titer gene transfer⁹), were substantially higher; our downward revision is made possible by more detailed immunohistochemistry and studies of vasomotor function. These approaches appear to be substantially more sensitive than morphology alone as indicators of acute vascular injury.

The precise boundaries of the therapeutic window will be affected by a number of variables. For example, our boundaries apply to rabbit carotids exposed to virus for 15 minutes, but they may be quite different, for example, for other species, shorter or longer exposures, and different organ systems. Moreover, the titer determinations themselves may vary considerably between laboratories. Thus, therapeutic window boundaries must be determined on a case-by-case basis.

We show that adenovirus-induced inflammation is well developed as early as 6 hours after vascular gene transfer. This onset is too soon to attribute to 2 key adenovirus life cycle events: adenoviral viral DNA replication and late antigen expression.¹¹ This has important implications for vascular gene transfer with newer adenoviral vectors, which are designed to reduce or eliminate viral replication and antigen expression.¹²,¹³ Our data suggest that acute vascular injury may be primarily determined by events surrounding the infection itself. If so, second-generation vectors will continue to induce titer-dependent acute inflammation, and strict attention to the therapeutic window will continue to be important.

Reduced ACh-induced vascular relaxation reflects loss of endothelial NO production,²⁵ and that, in turn, may facilitate the long-term chronic inflammation and vascular injury that is known to occur in this model.¹ Endothelial NO production, and related molecules reduce the expression of adhesion molecules and proinflammatory cytokines,²⁶,²⁷ inhibit platelet aggregation and adhesion,²⁸,²⁹ and directly inhibit vascular smooth muscle cell proliferation and migration.³⁰ Thus, the detrimental effects of early endothelial injury may extend beyond acute loss of ACh-induced relaxation and may contribute to the long-term vascular injury induced by recombinant adenovirus.

The observed vasomotor impairment has a number of striking parallels to the inflammatory cell infiltrate in terms of temporal development, dependence on titer, and spatial distribution (ie, both inflammation and vasomotor impairment affect the endothelium and spare the vascular media). These tight parallels suggest the possibility of a causal relationship. Our results with cytopenic animals further support this hypothesis: vinblastine-induced cytopenia (1) virtually eliminated endothelial cellular infiltration and (2) prevented the loss of ACh-induced vascular relaxation that otherwise occurs after exposure to high-titer adenovirus. Moreover, it is noteworthy that vinblastine treatment had no discernible effect on endothelial ICAM-1 or VCAM-1 expression. This result shows that vasomotor impairment requires additional events beyond those necessary for endothelial activation. Again, this would implicate cellular infiltration as playing a causal role.

Our observations regarding vasomotor function contrast sharply with those of Lafont et al.¹⁰ They described complete loss of endothelium-dependent relaxation and substantial loss of PE-induced contraction in rabbit ear and femoral arteries.
days after adenoviral gene transfer at $4 \times 10^{10}$ pfu/mL. In contrast, our carotid artery data suggest that adenoviral gene transfer does not affect vascular smooth muscle function at any titer and does not harm endothelial function if one uses titers within the therapeutic window. Finally, our data show that vasomotor dysfunction induced by high-titer adenovirus can be prevented by prior treatment with vinblastine.

Vinblastine treatment induced neutropenia, lymphopenia, and thrombocytopenia. Any of these cytopenias may play an important role in reducing endothelial injury after gene transfer. The fact that PMNs were the most affected by vinblastine treatment, both in terms of reduced peripheral counts and reduced endothelial infiltration, suggests that neutrophils have the most significant role. Certainly, their ability to release proinflammatory mediators (eg, superoxide, tumor necrosis factor-$\alpha$, and interleukin-1$\beta$) and to generate tissue injury lends support for this view. However, a more targeted experimental approach is necessary to establish definitively whether PMNs are the agents of functional endothelial injury in this model.

Important questions remain to be answered about the pathogenesis of acute effects. What aspects of recombinant adenovirus infection trigger endothelial activation? Does the initial infection represent the sole stimulus for subsequent infection? Does adenovirus infection trigger endothelial activation? We show that neutrophils may mediate acute effects. What aspects of recombinant endothelial injury in this model.

Acknowledgments

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References


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