Current therapies for the treatment of atherosclerotic vascular disease are aimed at either disrupting or bypassing flow-limiting lesions. Preventative strategies are necessary to decrease the burden of disease but are limited by genetic predispositions to certain diseases and the body's innate response to injury. Gene therapy, defined as the purposeful therapeutic overexpression or attenuation of a gene product, has enormous potential benefits in vascular disease prevention and treatment strategies. This article reviews the scientific considerations involved in the development of gene therapy strategies and outlines some of the gene products that are currently being used. These interventional genetic approaches will be reviewed in the context of specific vascular disease processes, including atherosclerosis, restenosis, and thrombosis. Gene therapy will serve an enhancing and adjuvant role to evolving surgical therapies.

Atherosclerotic cardiovascular disease is the leading cause of morbidity and mortality in the United States and Europe, and gene therapy has become a potentially important therapeutic tool in the treatment of cardiovascular disease. Gene therapy is often defined as the transfer of nucleic acids to the somatic cells of an individual to elicit a beneficial therapeutic effect. These nucleic acids are in the form of genes that either replace a specific genomic deficit, as with single gene mutations, or encode proteins that may have therapeutic applications. Gene therapy also includes the transfer of nucleic acids to alter patterns of gene expression. Instead of full coding sequences, DNA molecules called oligodeoxynucleotides, which encode sequences that are complementary to those of specific messenger RNA, can be used to block the expression of certain genes. A transferred gene can be targeted to specific tissues, organs, or the entire body. The delivery of a gene can be likened to the administration of a drug in classic pharmacology. However, a theoretical advantage of gene transfer is that a single administration of a gene can result in highly specific, long-lasting therapeutic effects with reduced systemic toxicity.

Several hurdles must be overcome in the development of cardiovascular gene transfer strategies. First, there must be a disease process that is amenable to treatment with a gene product. Such targets for cardiovascular gene therapy may include postangioplasty restenosis, angiogenesis, atherogenesis, thrombogenesis, and transplantation allograft vasculopathy. Second, the therapeutic gene of interest must be identified and cloned. Third, gene therapy uses vectors that serve as vehicles to facilitate the efficient transfer of genetic material into targeted cells. Finally, gene therapy strategies must consider the accessibility of the targeted tissue to vector delivery. The advent of catheter-based delivery systems and other technologies contributed to the feasibility of cardiovascular gene therapy as a clinical application. Ultimately, the advancement of cardiovascular gene therapy will rely on our ability to improve on current vectors and delivery systems.

HISTORY

Although the phrase “genetic engineering” was first coined in the 1930s in reference to the application of genetic principles to animal and plant breeding, the concept of selective breeding predates this by centuries. Our current definition
of genetic engineering evolved during the 1950s and 1960s when genes were first transferred to bacterial and mammalian cell lines. As gene transfer technology developed over the ensuing decades, efforts were originally focused on its use for the correction of inherited disorders stemming from single gene mutations. However, as our application of gene transfer broadened to include the concept of a genetic means of drug delivery (ie, the use of genes expressing therapeutic proteins), acquired diseases, such as cancer and atherosclerosis, also became candidates for gene therapy. The first report of gene therapy in the cardiovascular system was by Nabel et al in 1989, in which retrovirally transduced endothelial cells were seeded onto porcine iliac arteries. Although these engineered cells were detected on the vessel wall, this was clearly an inefficient method of in vivo gene delivery and a far reach from clinical application. Since this report, many technological advances have been made that enable the use of gene therapy in the care of patients with cardiovascular disease.

VECTORS

When “naked” DNA comes into contact with a cell membrane, only a minute amount of it will pass into the cell, and, once in the cell, the DNA is rapidly degraded by cytoplasmic nucleases. Naked DNA gene transfer is a highly inefficient process and certainly one that would be prohibitively limiting for human gene therapy. Therefore, mechanisms of facilitating DNA entry into cells were developed, namely through the use of vectors. An ideal vector should enable efficient delivery of genetic material to a targeted tissue with minimal local or systemic toxicity while allowing a desired level of gene expression for a specific duration of time. Thus far, no single vector possesses all these characteristics, and vector design is an active area of research. The vectors used in vascular gene therapy, as well as gene therapies directed at other diseases, include viral vectors, such as retroviruses and adenoviruses, and nonviral vectors, such as polymers, cationic liposomes, and liposome-viral conjugates (Table 1). An understanding of the advantages and shortcomings of current vector systems is critical to the design of any clinical gene therapy strategy.

Viral Vectors

Viruses are commonly used as vectors in cardiovascular gene therapy research and clinical trials. Their popularity centers on the natural life cycle of viruses, which involves the infection of mammalian cells to propagate viral genomic material and produce infectious viral offspring. Often, however, these life cycles result in lytic death of the host cell. Recombinant DNA technology has allowed the reengineering of these viral genomes such that the majority of the viral coding sequences necessary for replication are deleted and foreign therapeutic DNA sequences are inserted. Disrupting the normal reproductive pathways of these viruses allows the safe infection of mammalian cells. Propagation of these modified viruses requires the use of specially engineered “packaging” cells that carry the deleted viral genes.

Gene delivery for overexpression of therapeutic proteins vs oligonucleotides to inhibit expression of deleterious host proteins. In gene delivery by a generic vector (A), the vector gets internalized into the cell and releases its nucleic acids (containing transgene). The nucleic acids are translocated into the nucleus, where they may remain distinct or become incorporated into the host DNA. Vector (transgene) messenger RNA (mRNA) is transcribed in the nucleus then translated by ribosomal complexes in the cytoplasm to yield the final transgene protein product. It is the overexpression of this protein that is intended to be of therapeutic value. Antisense oligonucleotides are single-stranded nucleic acids (B), antisense oligonucleotides can prevent protein synthesis at several different levels in the gene expression pathway. They can hybridize to host DNA to form a triple helix or to host mRNA and thus prevent mRNA transcription or splicing and modification, respectively. Additionally, they can prevent mRNA export to the cytoplasm and ribosomal translation into protein. Decoy oligonucleotides are double-stranded nucleic acids (C). These oligonucleotides contain consensus sequences for transcription factor–binding sites. When transfected into cells, transcription factors will bind to these consensus sequences on the decoy oligonucleotides in the cytoplasm and will be prevented from translocating into the nucleus. This will prevent binding to host DNA and activation of host transcription.

One of the original viral vectors was the retrovirus. Retroviruses are RNA viruses that infect cells by a specific receptor–ligand interaction. Once inside a host cell, the viral RNA is reverse-transcribed to DNA, which then undergoes stable integration into the host genome. Theoretically, retrovirally transferred genes can be expressed for the lifetime of the organism treated. Nabel et al have shown expression of a marker transgene in arteries as long as 5 months after gene delivery. However, the integra-
mediated vascular gene transfer. These strategies use ruses that have been used more effectively for ex vivo cell transgenes, measuring up to 8 kilobases (kb). Retrovirus vectors, adenoviruses have a very complex genome and are more difficult to manipulate using recombinant technology. In their natural environment, both endothelial and vascular smooth muscle cells have low proliferative activity and are very poor targets for retroviral infection. Transfection efficiencies may be as low as 0.1% to 1.0% in vivo in these cells. Additionally, because retroviral integration occurs randomly, there is the theoretical potential for insertional mutagenesis with malignant transformation, although this has never been reported to date. The retrovirus genome is easily manipulated and replication-deficient retroviruses can hold large transgenes, measuring up to 8 kilobases (kb). Retroviruses have been used more effectively for ex vivo cell-mediated vascular gene transfer. These strategies use harvested endothelial cells that can be proliferated and transduced in vitro. Such techniques have been used in cardiovascular gene therapy for seeding stents, grafts, or injured arteries.

Lentiviruses are a class of retrovirus that can infect quiescent, terminally differentiated cells. The ability to generate stable gene expression in nontargeting cells with minimal immunogenicity is promising for gene therapy in the cardiovascular system. The human immunodeficiency virus is a member of this family and, as may be expected, there are a number of safety concerns about contamination or possible mutation of these recombinant viruses back to a pathogenic phenotype. The use of lentiviruses for gene therapy is on the horizon, and they may be the preferred vectors of the future.

Adenoviruses are DNA viruses that enter the cell via specific receptor interactions and are typically associated with the transmission of the common cold. After infection, adenoviral DNA enters the nucleus, where it remains episomal. The lack of genomic integration enables adenoviruses to efficiently infect proliferating and nonproliferating cells. In addition, there is no risk of insertional mutagenesis. Compared with recombinant retroviruses, adenoviral vectors have high gene transfer efficiencies in susceptible cells. Also in contrast to retroviruses, adenoviruses have a very complex genome and are more difficult to manipulate using recombinant technology. Significant limitations of our current “first-generation” adenoviral vectors are the resultant immunologic and cytotoxic responses that are generated against adenoviral proteins within the infecting virus and the low-level viral protein expression in the infected cell. Most people have been exposed to natural adenovirus infection, and the production of viral proteins by recombinant adenovirus can stimulate a cellular immune response that eliminates transfected cells. The immune response and the lack of gene integration limit the duration of transgene expression, which usually lasts 1 to 2 weeks.

Several strategies are being explored to improve adenoviral vectors for gene therapy. Many researchers are creating “gutless” adenoviruses by removing nearly all the native adenoviral genes. This reduces the immune response, creates room for larger transgenes, and has been shown to improve the duration of expression in vivo. Others are altering the viral capsid to improve virus-receptor interaction or using polymer-coated adenoviruses to shield them from antibodies and permit more selective targeting.

Adeno-associated viruses (AAVs) are small DNA viruses that gain entry into cells by binding to heparan sulfate proteoglycan receptors. Viral DNA then localizes to the nucleus where it is integrated into the host genome. This occurs preferentially at chromosome 19q. Because AAV is not capable of replication on its own, it is dependent on coinfection with a helper virus, either an adenovirus or a herpesvirus. Additionally, AAV is not associated with any known human disease or insertional mutagenesis. Integration of the recombinant viral genes leads to stable expression within the host cell and, therefore, long-term recombinant gene expression. This is a very important property that makes AAV particularly attractive for the treatment of chronic disorders resulting from single gene mutations as well as acquired disorders, such as atherosclerosis. Other advantages of AAVs are that they can infect proliferating and nonproliferating cells, it is relatively nonimmunogenic, and the genome is small and easy to manipulate. A disadvantage of the small AAV genome is that it also limits the size of the transgene to a maximum of only 4.9 kb. To date, there

<table>
<thead>
<tr>
<th>Vector</th>
<th>Advantages</th>
<th>Disadvantages</th>
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<tbody>
<tr>
<td>Retroviruses</td>
<td>Integrates into host genome; months of gene expression</td>
<td>Potential for insertional mutagenesis</td>
</tr>
<tr>
<td></td>
<td>Relatively nonimmunogenic</td>
<td>Low titers</td>
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<tr>
<td></td>
<td>Easily manipulated</td>
<td>Infects proliferating cells only</td>
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<tr>
<td>Adenoviruses</td>
<td>High transduction efficiencies</td>
<td>Low transfection efficiency of endothelial and smooth muscle cells</td>
</tr>
<tr>
<td></td>
<td>Infects replicating and nonreplicating cells</td>
<td>Limited by host immune response</td>
</tr>
<tr>
<td></td>
<td>High titers</td>
<td>Large genome; difficult to manipulate</td>
</tr>
<tr>
<td></td>
<td>High level of gene expression</td>
<td>Lack of integration and immune response limit duration to &lt;2 wk</td>
</tr>
<tr>
<td>Adeno-associated viruses</td>
<td>Infects replicating and nonreplicating cells</td>
<td>Only small transgenes</td>
</tr>
<tr>
<td></td>
<td>Nonpathogenic in humans</td>
<td>Difficult to produce in large quantities</td>
</tr>
<tr>
<td></td>
<td>Easily manipulated</td>
<td>Potential for insertional mutagenesis (not documented)</td>
</tr>
<tr>
<td></td>
<td>Stable integration</td>
<td>Nonimmunogenic</td>
</tr>
<tr>
<td></td>
<td>Nonimmunogenic</td>
<td></td>
</tr>
<tr>
<td>Cationic liposomes</td>
<td>Easy to manipulate</td>
<td>Low transduction efficiency</td>
</tr>
<tr>
<td></td>
<td>Nonpathogenic</td>
<td>Days of gene expression, in general</td>
</tr>
<tr>
<td></td>
<td>No size limit</td>
<td></td>
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<tr>
<td></td>
<td>Transfects all cell types</td>
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</table>
is no accepted packaging cell line for recombinant AAV
propagation, and it is difficult to produce viral stocks in
high concentrations with adequately low levels of con-
taminating helper virus. These problems with AAV pro-
duction will soon be overcome, and it is becoming a very
attractive vector for human gene therapy.

Nonviral Vectors

Plasmids are circular DNA molecules that were origi-
nally found to transfer antibiotic-resistance genes be-
tween bacteria. The regions carrying the antibiotic re-
sistance were deleted and replaced with recombinant
genomes, and these plasmids have been employed in the bulk
preparation of a variety of proteins for pharmacologic use.
Methods to deliver gene-carrying plasmids to mamma-
lian cells for gene therapy include direct microinjec-
tion, liposomes, calcium phosphate, electroporation, or
DNA-coated particle bombardment. Liposomes are the
most common nonviral form of gene transfer. This method
takes advantage of cationic lipid bilayers that incorpo-
rates the nucleic acids and facilitate cell entry. Liposome-
coated DNA will enter the nucleus and remain extra-
chromosomal, although a very small amount will undergo
spontaneous genomic integration. Transfection efficiencies
vary with DNA/liposome ratio, cell type, and the pro-
liferation status of cells.\textsuperscript{18} The advantages of liposome-
mediated gene transfer include the ease of plasmid
construction, the lack of the risks associated with viral
vectors, and the simplicity of liposome preparation for
clinical use. However, limitations of this method of gene
transfer, such as low gene transfer efficiencies and tran-
sient durations of gene expression, are significant. Ad-
vances are being made to improve transfection effi-
ciency\textsuperscript{19} and enhance the specificity of DNA delivery. An
example of such a modification is the combination of li-
posomes with proteins of the hemagglutinating virus of
Japan.\textsuperscript{20} These proteins mediate cell attachment and mem-
brane fusion and can dramatically improve gene trans-
fer efficiency. Hemagglutinating virus of Japan–li-
posome constructs carrying antisense oligonucleotides\textsuperscript{21}
or therapeutic genes\textsuperscript{22} have been used in vascular gene ther-
pautes to prevent intimal hyperplasia (IH).

LOCAL GENE DELIVERY

One of the important considerations in developing cardio-
vascular gene transfer as a therapy is our ability to de-
lever the vector, viral or plasmid, to the desired tissue in
a safe fashion. This is not a problem in peripheral ves-
sels but proves to be quite a challenge in the coronary
arteries. In peripheral circulation, vessels can be trans-
duced at the time of surgical exposure for intervention,
and extremities also tolerate quite well the periods of is-
chemia necessary to perform the gene transfer. In con-
trast, in the coronary bed, we must be able to access the
lesion and occlude the vessel for an adequate amount of
time to allow vector attachment and uptake without sig-
nificantly compromising myocardial perfusion. With the
evolving technology in angioplasty and endovascular de-
vices, these hurdles are surmountable. The various types
of catheters include double-balloon, channel-balloon, mi-
croporous, hydrogel-coated, and infiltrating.\textsuperscript{23} Cath-
ters can be subdivided based on the mechanism of de-
ivery of the genetic material, either by passive diffusion,
pressure facilitation, or mechanical facilitation.\textsuperscript{18} The pur-
pose of all these devices is to deliver the vector to an iso-
olated segment of the artery. Still in the developmental
phase are stents coated with a hydrogel containing viral
or plasmid vectors that can be used for gene delivery, but
these devices are limited by production concerns and the
ability to stabilize the stents without destroying the vec-
tors. Bypass grafts, such as saphenous veins, can be eas-
ily transduced ex vivo prior to implantation into the ar-
terial circulation. Prosthetic grafts can also be modified
with autogenous vascular smooth muscle or endothelial
cells that have been engineered in vitro to express re-
combinant genes prior to implantation. In the clinical set-
ting, the barrier of atherosclerotic plaques can signifi-
cantly lower gene transfer efficiency, and devices have
been designed that allow vectors to be injected directly
into the arterial wall, penetrating these plaques.\textsuperscript{24}

An alternative to intraluminal gene delivery is trans-
duction of the outer wall, or adventitia, of blood vessels.
Numerous studies have demonstrated that adventitial gene
derivery results in equivalent levels of biological effect
in reducing IH in injury models of restenosis. Certainly,
this method of vascular gene transfer obviates the inher-
ent problems of transient interruption in blood flow
through a targeted blood vessel and access to the intra-
vascular space. Biodegradable polymers mixed with vec-
tors and placed on the outside of vessels have been used
to deliver antisense oligonucleotides,\textsuperscript{25} plasmid DNA,\textsuperscript{26}
and adenovirus.\textsuperscript{27} Other investigators have used biode-
gradeable cuffs that isolate vector solutions to the adventi-
titial space,\textsuperscript{28,29} or direct adventitial injection.\textsuperscript{31} Adventi-
tial gene delivery is a particularly attractive route of gene
transfer for the surgeon who has direct access to blood
vessels during operative exposure.

In angiogenesis, intravascular gene delivery is not
needed. Instead, direct intramuscular injection of the de-
sired vector into ischemic tissues, such as skeletal muscle
or myocardium, allows local angiogenic factor expres-
sion to stimulate collateral blood vessel development.\textsuperscript{30-32} Researchers have modified this by injecting mi-
crospheres coupled to plasmids or growth factors.\textsuperscript{33} The
microspheres can allow for slow release of the recombi-
nant material into the surrounding tissue.

VASCULAR GENE THERAPIES

Prevention of IH

Common interventional therapies for atherosclerotic vas-
cular disease focus on physically disrupting or bypass-
ning hemodynamically limiting lesions. These treat-
ments produce perturbations in normal flow dynamics
and induce injury, both of which provide stimuli for cel-
lar proliferation and IH. Clinically significant in-stent
stenosis occurs in 20% to 40% of patients within 6 months
of balloon dilation and stenting of coronary vessels.\textsuperscript{34,35}
The proliferative process is more protracted in vein grafts,
and significant stenosis typically occurs in 50% of grafts
by 5 years. Pharmacologic agents, such as antiplatelet and
Table 2. Clinical Therapeutic Targets in Cardiovascular Disease

<table>
<thead>
<tr>
<th>Disease</th>
<th>Clinical Therapeutic Targets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Angiogenesis</td>
<td>VEGF, FGF, angiotensin, HIF, Del-1, PDGF</td>
</tr>
<tr>
<td>Thrombogenesis</td>
<td>Tissue factor inhibitors, thrombomodulin, CDX, t-PA</td>
</tr>
<tr>
<td>Atherosclerosis/dyslipidemia</td>
<td>LDL receptor, LPL, ApoE, ApoA, antioxidative enzymes, LCAT</td>
</tr>
<tr>
<td>Plaque rupture</td>
<td>TIMPS, CDX, leukocyte adhesion blockers</td>
</tr>
<tr>
<td>Restenosis/in-stent stenosis</td>
<td>Cytoxic genes</td>
</tr>
<tr>
<td></td>
<td>tKinsacnclenictu, CDI, 5-fluorouracine, Fas ligand</td>
</tr>
<tr>
<td></td>
<td>Cell cycle regulators</td>
</tr>
<tr>
<td></td>
<td>Proto-oncogenes: c-myc, c-myb</td>
</tr>
<tr>
<td></td>
<td>Cell cycle genes: CDKs, cyclins, p16, p21, p27, PCNA</td>
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<tr>
<td></td>
<td>Tumor suppressor genes: p53, Rb</td>
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<tr>
<td></td>
<td>Transcription factors</td>
</tr>
<tr>
<td></td>
<td>Gax, NfXb, E2F</td>
</tr>
<tr>
<td></td>
<td>Intracellular signal transducers</td>
</tr>
<tr>
<td></td>
<td>Ras, Raf, Bcl, CNIP</td>
</tr>
<tr>
<td></td>
<td>Cytokines/growth factors</td>
</tr>
<tr>
<td></td>
<td>Interferon β, VEGF, FGF, PDGF, IGF</td>
</tr>
<tr>
<td></td>
<td>INOS/eNOS/endothelial NOS</td>
</tr>
</tbody>
</table>

*VEGF indicates vascular endothelial growth factor; FGF, fibroblast growth factor; HIF, hypoxia-inducible factor; Del-1, developmentally regulated endothelial locus; PDGF, platelet-derived growth factor; CDX, cyclo-oxidase; t-PA, tissue plasminogen activator; LDL, low-density lipoprotein; LPL, lipoprotein lipase; Apo, apolipoprotein; LCAT, lecithin-cholesterol acyltransferase; TIMPS, tissue inhibitor of metalloproteinase; TK, thymidine kinase; CD, cysteine deaminase; CDK, cyclin-dependent kinase; PCNA, proliferating cell nuclear antigen; Rb, retinoblastoma; NfXb, nuclear factor X; B; CNP, c-type natriuretic peptide; IGF, insulin-like growth factor; INOS, inducible nitric oxide synthase; and eNOS, endothelial NOS.

anticoagulant drugs, that have generally been unsuccessful at preventing neointima formation. Instead, the use of gene therapy technology that locally modifies the vascular wall has been applied to prevent IH, including those encoding for a variety of gene products that can arrest cell cycle progression, DNA synthesis, cell viability, and cytoprotection.

Many gene therapy studies have focused on the modulation of cellular proliferation through regulation of the cell cycle. Cell cycle progression is controlled by the phosphorylation of cyclin/cyclin-dependent kinase (CDK) complexes. Activated cyclin/CDK complexes will then phosphorylate and inactivate the retinoblastoma protein that results in the release of transcription factors E2F and ELF1. Inhibitors of CDK (CDKIs) are endogenous inhibitors of the cyclin/CDK complexes and can arrest cell cycle progression. Gene therapy strategies have included manipulation of the expression of several of these cell cycle regulatory proteins. An example is the overexpression of the CDKI p21(Cip1/Waf1). In 1995, Chang et al32 infected rat carotid arteries following balloon injury with an adenoviral vector carrying the p21 CDNA and demonstrated histologically that p21-expressing carotid arteries had a 46% reduction in the intima-media ratio at 20 days postinjury as compared with control treated arteries. This has been reproduced in both rat and pig models.37,38 Chang et al also used gene transfer of a constitutively active retinoblastoma protein to dramati-

cally inhibit IH in both rat and pig models of arterial injury. Similarly, regulators of p21 expression, such as gax39 and p53,40 as well as other CDKIs, such as p16, p27, and CDKI fusion proteins,41,42 have successfully inhibited neointima formation.

Another interesting approach to inhibiting the cell cycle uses E2F decoy oligonucleotides. Decoy oligonucleotides are double-stranded DNA molecules that mimic the chromosomal binding sites of transcription factors, thus depleting transcriptional factors that activate or suppress target genes (Figure). In 1995, Morishita et al43 expressed an E2F decoy in vein grafts. These grafts were found to have reduced IH, increased resistance to diet-induced atherosclerosis, and enhanced medial hypertrophy following implantation into the arterial circulation, all of which improves graft patency. A small-scale human clinical trial using E2F decoys in saphenous vein grafts in the peripheral circulation suggested therapeutic benefit and warranted further investigation.44 Many other genes have been applied to prevent IH, including those encoding for the death-signaling Fas ligand (FasL).45,46 the cytotoxic herpes simplex virus–thymidine kinase (HSV-tk),47 and cytosine deaminase48 (Table 2).

An important consideration in developing gene therapy is gene transfer efficiency. If a gene product is an intracellular protein, higher gene transfer efficiency will be essential to target as many cells as possible because each cell will have to express its own gene product to benefit from the actions of the transgene. In contrast, a secreted gene product can diffuse outside an infected cell and can affect a whole population of cells. This type of gene product will more likely be beneficial at lower gene transfer efficiencies. In gene therapy strategies that use nonsecreted gene products, such as the cell-cycle proteins, transcription-factor decoys, and even cytokine proteins, the efficacy is limited by the in vivo gene transfer efficiency. Other gene therapy strategies that focus on the synthesis of growth factors, cytokines, intracellular-signaling molecules, and matrix proteins, for example, may be more clinically relevant.

One very promising gene therapy regimen involves the delivery of nitric oxide synthase (NOS) to the vasculature as a means of augmenting local nitric oxide levels. Nitric oxide is a diffusable molecule that, once synthesized, can target a whole population of cells. Nitric oxide has been shown to play an important role in many processes throughout the cardiovascular system, including normal maintenance functions, atherosclerosis, hypertension, vasospasm, and ischemia-reperfusion.49 Nitric oxide inhibits platelet aggregation, leukocyte chemotaxis, and smooth muscle cell proliferation and migration and promotes endothelial cell regeneration. Because of these vasoprotective properties, methods of delivering nitric oxide to sites of vascular injury were devised, including supplementing dietary L-arginine, the substrate for NOS activity, and using nitric oxide donor compounds. These methods all resulted in reduced IH in rodent models of vascular injury. In 1995, von der Leyen et al50 transduced endothelial NOS (eNOS) into rat carotid arteries following balloon injury using hemagglutinating virus of Japan modified liposomes and reported a 70% reduction in the intima-media ratio compared with

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control arteries at 14 days. These results have been reproduced by other investigators using eNOS gene transfer by either liposomal or adenoviral gene delivery methods; eNOS was a natural candidate for these studies because it is believed that vascular injury results in the loss of eNOS function and, therefore, nitric oxide. This enzyme produces nitric oxide in low levels in response to mechanical and agonist stimulation. In contrast, the inducible NOS (iNOS) is expressed following cellular stress and is capable of producing significantly greater quantities of nitric oxide. A theoretical advantage of iNOS for gene therapy is its ability to produce adequate local concentrations of nitric oxide in the vasculature with lower gene transfer efficiencies. This is an important consideration in the coronary circulatory system, where even short periods of blood flow disruption can result in myocardial injury. In 1996, Tzeng et al performed ex vivo delivery of retroviral human iNOS to balloon-injured pig arterial segments and essentially abolished myointimal thickening, despite a very low (1%) gene transfer efficiency. Subsequently, adenoviral delivery of iNOS to balloon-injured rat carotid arteries using low titers of virus resulted in a 97% inhibition of IH compared with controls at 2 weeks. This therapy was similarly effective in a porcine model of iliac artery injury where iNOS gene transfer reduced IH by more than 50%. Finally, iNOS gene transfer into jugular vein grafts implanted into the pig carotid circulation also protected against graft IH by 35%. These studies suggest the great potential utility of NO gene therapy for the prevention of IH and have fueled the approval by the National Institutes of Health (Bethesda, Md) and the Food and Drug Administration (Rockville, Md) of iNOS gene transfer in a clinical trial to treat in-stent stenoses following coronary angioplasty or stenting.

These studies demonstrate that a number of different approaches can be effective in preventing IH by targeting smooth muscle cell proliferation. This discussion is by no means complete and many other studies have been performed using genes directed against extracellular matrix deposition, cytokines, and other antiproliferative agents. Further investigations into vascular biology and delineation of molecular mechanisms will help to identify additional targets for gene therapy as well as improve on our current strategies.

Angiogenesis

The treatment of ischemic disease with the goal of increasing the number of small vessels within ischemic tissue is termed therapeutic angiogenesis. Studies from tumor neovascularization and cardiovascular development have helped to identify vascular endothelial growth factors (VEGF) and fibroblast growth factors (FGF) as potent mediators of angiogenesis. The VEGF family is large but VEGF-A is the best-characterized form in the study of angiogenesis. Hypoxia and several cytokines induce VEGF expression, which then signals through tyrosine kinase receptors to mediate downstream effects. A mitogen for endothelial cells, VEGF also promotes cell migration and is a potent hyperpermeability factor. It has been shown to improve collateral vessel development in animal models of hind limb ischemia and myocardial ischemia. Earlier studies with FGF demonstrated similar results. In the clinical setting, Baumgartner et al treated 9 patients with limb-threatening lower-extremity ischemia with intramuscular injections of plasmid DNA containing the VEGF complementary DNA (cDNA). This treatment improved blood flow to the ischemic limbs as evidenced by angiographic evaluation, improved hemodynamic indices, relieved rest pain, and improved ulcers and limb salvage when evaluated at an average of 6 months posttreatment. Other clinical trials, however, failed to show such definitive benefit, and additional trials are ongoing using claudication as the treatment criterion as opposed to limb-threatening ischemia. Trials are also being carried out using VEGF administration, either liposome-mediated or adenoviral-mediated, to stimulate angiogenesis in ischemic myocardium. Patients are still being evaluated for these trials.

Despite these studies, many concerns have been raised regarding these therapies. Although gene therapy with FGF, VEGF, and other growth factors has led to angiogenesis, additional studies have not shown the formation of functional collateral vessels that persist after the withdrawal of the growth factor. There are many unanswered questions and concerns. The biological effects of VEGF are remarkably dose-dependent. The potential risks of therapeutic angiogenesis include hemangioma formation, formation of nonfunctional leaky vessels, and the acceleration of incidental tumor growth. Accelerated tumor growth was observed in a patient with an occult lung tumor receiving VEGF therapy and resulted in the halting of that trial by the Food and Drug Administration. This event brought to light the need to be extremely cautious about the clinical application of these gene therapies and the need to be rigorous about the screening of the patients we subject to such experimental therapies.

Prevention of Atherosclerosis

The origin of atherosclerotic lesions is multifactorial and involves many genes. Before we can treat this process in the vasculature, there has to be a better understanding of the precise roles of the gene products involved in this progression. For this reason, vascular-directed gene therapy approaches to treating atherosclerosis are still early in the development phase. On the other hand, certain inherited defects that lead to accelerated atherosclerosis may potentially be treated with systemic therapies. For example, low-density lipoprotein–receptor deficiency may be treated by low-density lipoprotein–receptor gene transfer to the liver to increase low-density lipoprotein uptake and clearance. Similarly, patients with specific defects in enzymes of lipoprotein metabolism, such as lipoprotein lipase or hepatic lipase, could be treated with gene therapies to express functional forms of these defective enzymes in the liver or even the skeletal muscle.

Prevention of Thrombosis

A thrombus forms in the vasculature when there is a local defect in the normal antithrombotic function of the
vessel. This typically occurs at sites of vascular injury, either from disease states or secondary to therapeutic maneuvers. Gene therapy approaches have been developed to prevent thrombus formation. Examples of such genes include tissue plasminogen activator (t-PA), which activates plasminogen to plasmin that can then mediate fibrinolysis,5,6,69; tissue factor pathway inhibitor, because tissue factor is the primary stimulator of the coagulation pathway,67; and hirudin,58,69 These genes may be very useful in preventing early thrombosis following bypass surgical or angioplasty procedures.

FUTURE DIRECTIONS AND SURGERY

Research in the field of human genetics will continue to affect our understanding of the molecular mechanisms involved in disease. Technological advances, such as DNA microarrays and proteomics, continue to help us study the molecular responses of tissue to vascular injury and all disease processes. The Human Genome Project will help link specific genes to disease, identify new genes, and discover single nucleotide variations (polymorphisms) within a gene that alter phenotype and, thus, physiological behavior. These advances will enable physicians to better predict and diagnose disease. For the surgeon, this may translate into optimal timing for some surgical therapies and identifying patients at higher risk for complications both before and after surgical intervention. Gene-based strategies will improve late complications that have limited the surgical outcomes for patients, such as neointima formation, graft failure, and transplant arteriosclerosis. More important, gene therapy and molecular medicine have tremendous potential to advance our ability to prevent the onset of disease. From a physiological standpoint, it is predicted that these advances will enable physicians to better predict and diagnose disease. As with any therapy, further studies and clinical trials will ensure the safety of vascular gene therapy.

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