USE OF BACULOVIRUS VECTORS IN GENE THERAPY

Field of the Invention

This invention relates to gene delivery using a viral vector.

Background of the Invention

Efficient gene transfer would be a beneficial tool for the treatment of vascular diseases, such as post-angioplasty restenosis, post-bypass atherosclerosis, peripheral atherosclerotic disease, stenosis of vascular prosthesis anastomoses, and thrombus formation. Various techniques have been developed for this purpose; see, for example, Yla-Herttuala *et al*, J. Clin. Invest. 95:2692-8 (1995), and Laitinen *et al*, Hum. Gene. Ther. 8:1645-50 (1997).

WO-A-98/20027 discloses a periadventitial collar that can be used for arterial gene transfer during vascular surgery. However, there is a continuous need for more facile and efficient gene transfer vectors. Only a temporary expression of the transgene may be required to achieve a beneficial biological effect in cardiovascular applications; see Yla-Herttuala *et al*, Lancet 355:213-222 (2000).

Baculoviruses have long been used as biopesticides and as tools for efficient recombinant protein production in insect cells. They are generally regarded as safe, due to the naturally high species specificity and because they are not known to propagate in any non-invertebrate host. Although the virions have been shown to enter certain cell lines derived from vertebrate species, no evidence of viral gene expression has been detected using natural viruses. However, the *Autographa californica* multiple nuclear polyhedrosis virus (AcMNPV), containing an appropriate eukaryotic promoter, is able to transfer and express target genes efficiently in several mammalian cell types; see, for example, Hofmann *et al*, PNAS USA 92:10099-10103 (1995). In addition, Barsoum *et al*, Hum. Gene. Ther. 8:2011-8 (1997), has reported that baculovirus having the vesicular stomatitis virus C glycoprotein in its envelope significantly increases the efficiency of transduction of human hepatoma cell lines and broadens the range of mammalian cell types that can be transduced by baculoviruses. Stable transduction of mammalian cells by baculoviruses has been achieved by either including an expression cassette encoding a dominant selectable marker into baculovirus genome or by using hybrid baculovirus-adeno-associated virus vector; see Condreay *et al*, PNAS USA 96:127-132 (1999), and Palombo *et al*, J. Virol. 72:5025-34 (1998).

Sandig *et al*, Hum. Gene Ther. 7:1937-45 (1996), reported unsuccessful attempts to use baculoviruses for *in vivo* gene delivery in mice and rats by systemic or

intraportal application as well as by direct injection into the liver parenchyma. One reason for this is presumably the inactivation of baculoviruses by the classical pathway of serum complement system.

WO-A-00/05394 discloses baculovirus vectors and their use for gene transfer to the nerve cells of vertebrates.

Summary of the Invention

It has now been found that the inactivation of baculoviruses can be avoided. In particular, it has been shown that baculoviruses are able to mediate periadventitial gene transfer to rabbit carotid arteries with an efficiency comparable to adenoviruses. The ease of manipulation and rapid construction of recombinant baculoviruses, their lack of cytotoxicity in mammalian cells even at a high multiplicity of infection, their inherent incapability to replicate in mammalian cells, and their large capacity for the insertion of foreign sequences, make baculoviruses very suitable tools for *in vivo* gene therapy.

This invention is able to use the advantageous properties of baculoviruses, in a suitable vector, from which the gene is expressed, if administered (*in* or *ex vivo*) to a body site at which there is no blood, or which is essentially free of blood. Thus, periadventitial or, more specifically, collar-mediated local gene delivery allows gene transfer essentially in the absence of serum, thus avoiding deleterious effects of serum components. The novel method also avoids two other major problems encountered in systemic gene delivery, i.e. a rapid redistribution of the virus from the injection site and a drop in the local concentration of the virus.

Description of the Invention

Suitable delivery systems, active materials, formulations, dosages etc, are illustrated in WO-A-98/20027 and also WO-A-99/55315 (the contents of which are incorporated herein by reference). Thus, by way of example only, the delivery vehicle may be a collar or wrap. By comparison with those publications, the vector for gene delivery is a baculovirus.

Baculoviruses are of course known, and the skilled person will be able to construct any suitable vector for use in this invention. It will also be evident that the broad knowledge of baculovirus biology and AcMNPV genome will aid engineering of the improved second-generation viruses for gene transfer applications. The ease of construction, and capacity to accept large foreign DNA-fragments (>20 kbp), allows the development of baculoviruses having enlarged or targeted cell tropism along with more stable, temporal and cell type-specific control of transgene expression. A recombinant

baculovirus for use in the invention may be formulated into a medicament for therapeutic use, in known manner.

Routes and sites of administration for the invention include intra-ocular application, intra-articular application, superficial intra-dermal application, ureters, bladder, Fallopian tubes, gall bladder, spinal cord, cerebrospinal fluid compartment, pleural cavity and intraperitoneal cavity. Sites that have been used (see the Examples) are arteries, brain and skeletal muscle, including, by way of example, mycocytes, satellite cells and regenerating myoblasts. Gene delivery may be done *via* direct injection or various types of catheters.

If appropriate, body parts can be made "bloodless" during surgery. This technique is often used in leg or arm surgery by putting tight pressure around arm or thigh, thus preventing blood flow. The body part may then be perfused with saline to remove blood, and baculovirus transfection can then be done.

The invention can be used for the delivery of an agonist of a VEGF receptor, e.g. described in more detail in WO-A-98/20027. Further, by suitable choice of the gene, it may be used in the treatment of cancer, e.g. in the brain.

A further aspect of the invention relates to transplant organs and vessels which can be perfused with saline *ex vivo* and subjected to *ex vivo* baculovirus injection.

The following experimental work illustrates the invention.

Example 1

Preparation of recombinant baculoviruses

Viruses were constructed by using the transfer vector pFASTBac1 (pFB) (Gibco BRL, Life Technologies, Gaithersburg, MD, USA). A nuclear targeted β-galactosidase (β_{nt}-Gal) cassette with a cytomegalovirus (CMV) promoter was inserted into the *Stu*I site of pFB in reverse orientation with respect to the polyhedrin promoter, generating plasmid pFBCMV-β_{nt}.

Recombinant viruses were generated by using a BacTo-Bac™ Baculovirus Expression System (Gibco BRL). Viruses were amplified in *Spodoptera frugiperda* 9 (Sf9) suspension cultures (SF-900 medium, Gibco BRL) for 3 days using cell density of 2×10^6 cells/ml. For 50 ml of culture, 200 µl of primary transfection supernatant was used as an inoculum. To obtain 1 litre of amplified virus, 2 ml of amplified virus stock was used as an inoculum. The cell culture medium was centrifuged at 16,000 g for 20 min at room temperature to remove cell debris. The clarified supernatant was transferred to ultracentrifuge tubes underlaid with 1.5 ml of 25% sucrose in phosphate-buffered saline (PBS) and the viruses were concentrated by centrifugation (120,000 g,

4°C, 1.5 h). The virus pellets were resuspended into 35 ml of ice-cold PBS, transferred into ultracentrifuge tubes containing 3 ml of 25% sucrose in PBS and centrifuged as above. Final virus pellet was resuspended into 10 ml of cold PBS, filtered through the 0.45 µm filter and kept at 4°C protected from light for further use. Virus titer was determined by a plaque assay on Sf9 cells. Virus preparations were analyzed for lipopolysaccharide and bacteriological contaminants.

Preparation of recombinant adenoviruses

Nuclear-targeted *Lac*Z encoding adenoviruses (pCMVnls*lac*ZAd5) were constructed and prepared as described by Laitinen *et al*, *supra*. Virus preparations were analyzed for replication-competent viruses, lipopolysaccharide and bacteriological contaminants as described by Laitinen *et al*, Hum. Gene Ther. 9:1481-6 (1998).

Gene transfer in vitro

Rabbit aortic cells (RAASMC; Yla-Herttuala *et al* (1995), *supra*) and human carcinoma/ endothelial cell-like ECV-304 cells (ATTC CRL-1998) were plated at the density of 10,000 cells per well (Falcon Culture Slide, Becton Dickinson, Meylan, France). Cells were allowed to attach for 3 h before transduction in serum-free medium (DMEM, 100 units/ml of penicillin and 100 µg/ml of streptomycin, Gibco BRL). Viruses were added to medium at MOIs of 200 or 1000, and cells were incubated for 90 min at 37°C. After transduction, growth medium containing 10% fetal bovine serum was added either with or without 10 mM n-butyric acid (Sigma, St. Louis, MD, USA). After 18 h incubation, the media were removed and cells were washed three times with PBS. Cells were fixed with 1.25% glutaraldehyde for 15 min and washed three times with PBS. X-Gal (MBI Fermentas, Lithuania) staining solution (1 mg/ml, 2 mM $MgCl_2$, 5 mM $K_3Fe(CN)_6$, 5 mM $K_4Fe(CN)_6$, 1 x PBS) was added to the cells and incubated for 3 h at 37°C. Cells were then washed with PBS and further fixed with 4% paraformaldehyde (PFA) for 10 min. After washing with PBS, cells were counter-stained with Mayers Carmalum for 5 min. Blue X-Gal positive cells were counted and the transduction efficiencies were expressed as the percentage of positive cells of the total number of cells.

ONPG assay

*lac*Z-encoded β-galactosidase activity in transduced RAASMC cells was measured using a colorimetric substrate, *o*-nitrophenyl β-D-galactopyranoside (ONPG, Sigma), as described by Ruponen *et al*, Biochim. Biophys. Acta 1415:331-41 (1999).

In vitro toxicity assay

Cells were plated in 96-well plates at a density of 20,000 cells per well in 100 µL of growth medium consisting of DMEM with 10% fetal bovine serum and antibiotics (100 units/mL of penicillin and 100 µg/mL of streptomycin). Virus transductions were performed as for the transduction efficiency assay and cells were incubated for 48 h at 37°C. Growth medium was removed and cells were washed with PBS. Serum-free DMEM without phenol red, containing MTT solution (3-(4,5-dimethylthiazolyl-2)-2,5-diphenyl tetrazolium bromide, 5 mg/mL, final concentration 0.3 mg/mi) was then added and cells were incubated for 2 h. To dissolve the dark blue formazan crystals, MTT solution was removed, 150 µl of 1 M DMSO was added to each well and mixed thoroughly. Absorbance was measured at 570 nm. Survival percentage was calculated as compared with absorbance of the no virus- or no butyrate wells (100% survival).

Animal experiments

Male New Zealand White (NZW) rabbits (*n* = 12; 2.8-3.7 kg) were used. Fentanyl-fluanisone (0.3 ml/kg, s.c.; Janssen Pharmaceutica, Beerse, Belgium) and midazolam (1.5 mg/kg, i.m., Roche, Basel, Switzerland) were used for anesthesia. Left and right carotid arteries were exposed using midline neck incision. The artery was carefully separated from the surrounding tissue and a 3 cm long silastic collar (see Laitinen *et al* (1997), *supra*) was positioned around it. Rabbits were re-anesthetized for gene transfer, which was performed 5 days after the installation of the collar exactly in the same way as described by Laitinen *et al* (1997), *supra*, comparing the transfection efficiency of plasmid/liposomes, pseudotyped retroviruses and adenoviruses. The collars were opened and filled with 500 µl of the gene transfer solution containing I x 10^9 pfu of adenovirus or baculovirus. In each animal, the left carotid artery was used for adenovirus and the right carotid artery for baculovirus treatment. Four rabbits were killed 3, 7 and 14 days after the gene transfer and arteries were removed for histological analyses. All animal procedures were approved.

Histological analysis

Collared arteries were divided into three equal parts: the proximal third was immersion-fixed in 4% PFA/15% sucrose (pH 7.4) for 4 h, rinsed in 15% sucrose (pH 7.4) overnight and embedded in paraffin. The medial part was immersion-fixed in 4% PFA/PBS (pH 7.4) for 30 min, rinsed in PBS (pH 7.2) and embedded in OCT compound (Miles Scientific, Naperville, IL, USA). The distal part was snap-frozen in liquid nitrogen and stored at -70°C for mRNA isolation and reverse transcriptase polymerase chain reaction (RT-PCR).

Randomly selected frozen sections (10 μm) from each rabbit were stained with X-Gal (MBI Fermentas) for 18 h to identify β-galactosidase positive cells. Gene transfer efficiency was calculated as X-Gal positive cells per mm^2 of adventitia or whole artery wall in eight randomly selected sections by two independent observers. Mean values ± standard error of mean (SEM) of the results are reported. Paraffin sections were used for immunocytochemical detection of endothelium (CD-31; 1:50 dilution; Dako, Hamburg, Germany), macrophages (RAM-11; 1:100 dilution; Dako), smooth muscle cells (HHF-35; 1:50 dilution; Dako), and T cells (MCA-805; 1:100 dilution; Dako) as described by Yla-Herttuala (1995), *supra*. Controls for the immunostainings included sections where the first antibody was omitted and sections incubated with class and species matched immunoglobulins. Morphometry and image analysis were done using hematoxylin-eosin-stained paraffin sections and Image-Pro Plus™ software with Olympus AX70 microscope (Olympus Optical, Japan).

RT-PCR

Total RNA was extracted from transduced carotid artery segments using Trizol Reagent (Gibco-BRL) and treated with excess RQ1 RNAse-free DNAse (Promega, Madison, WI, USA). M-MuIV reverse transcriptase (MBI Fermentas) was used for cDNA synthesis. Primers (20 pmol each) for *lac*Z were designed to distinguish between endogenous and transduced genes by selecting the 5' primers from the CMV promoter and the 3' primers from the coding region. Dynazyme polymerase (Finnzymes, Espoo, Finland) was used for amplification.

For *lac*Z amplification, the primers were SEQ ID NO:1 for adenovirus (A) and SEQ ID NO:2 for baculovirus (B) as forward primers, and SEQ ID NO:3 for both as a reverse primer. Hot start (95°C 5 min; 58°C 3 min) was followed by 39 cycles, each consisting of 95°C 1 min, 58°C 2 min, 72°C 3 min with the final extension of 10 min at 72°C. 5 μl of the first PCR product was used for the second PCR with forward primers SEQ ID NO:4 (A) and SEQ ID NO:5 (B). The reverse primer for both was SEQ ID NO:6. The first PCR cycle was 95°C for 5 min followed by 20 cycles as in the first PCR.

Gene transfer in vitro

In order to test the baculovirus stock, RAASMC and ECV-304 cells were transduced at a multiplicity of infection (MOI) of 200 or 1000 pfu per cell in the absence or presence of 10 mM sodium butyrate and the percentage of X-Gal positive cells were counted. The results were compared to cells transduced with *lac*Z-adenovirus under identical conditions (Table 1). In agreement with published results, (Condreay *et al*, *supra*) addition of butyrate to cell cultures increased remarkably the expression of the

transgene, especially with baculoviruses. The RAASMC cells seemed to be more susceptible to baculovirus transduction (91% infected at MOI 1000) than ECV-304 cells (21% infected at MOI 1000). Levels of β-galactosidase activity in the RAASMC cells were also measured by a quantitative biochemical assay with *o*-nitrophenyl β-D-galactopyranoside (ONPG). The results were in line with X-Gal staining showing an increase in the transgene expression after butyrate treatment in the baculovirus-transduced cells.

In vitro toxicity

3-(4,5-Dimethylthiazol-2-yl)-2,5-diphenyltetrazolium bromide (MTT)-assay was used to measure the cytotoxicity of virus preparations (Table 2). Neither baculoviruses nor adenoviruses showed any major cytotoxicity to RAASMC cells in the absence of butyrate at MOI 200 or 1000. However, together with butyrate, some cytotoxicity was detected in these cells with baculoviruses at a MOI of 1000. Similar results were obtained with primary WHHL (Watanabe heritable hyperlipidemic) rabbit fibroblasts except that no cytotoxic effects were detected for baculoviruses in the presence of butyrate at a MOI of 1000 (data not shown).

Gene transfer in vivo

In order to determine whether baculoviruses can be used for *in vivo* gene transfer, NZW rabbits were killed 3, 7 and 14 days after gene transfer. Due to the nuclear targeting of the β-galactosidase expression, intense X-Gal staining was located in the nuclei of the transduced cells. The number of cells positive for β-galactosidase activity was calculated from the baculovirus-transduced (1×10^9 pfu per artery) carotid arteries and was compared with similarly treated adenovirus-transduced arteries. Both viruses mediated delivery of the marker gene to the vessel wall. The numbers of transgene positive cells for baculovirus- and adenovirus-treated arteries at day 3 were 12 ± 5 and 23 ± 7 β-galactosidase positive cells/mm^2 of adventitia (11 ± 4 and 19 ± 6/mm^2 of the whole artery wall), respectively. At day 7, the corresponding values were 17 ± 6 and 22 ± 7 (15 ± 5 and 18 ± 6). At day 14, the values were 0.1 ± 0 and 0.2 ± 0.1 (0.1 ± 0 and 0.1 ± 0.1). The baculovirus-mediated gene expression was thus transient with a similar efficiency and time pattern as that of the adenovirus-mediated gene transfer. Transgene expression in the arterial wall was also verified with RT-PCR.

The mean value of intima/media ratio (all arteries) was 0.18 ± 0.03 for baculovirus and 0.12 ± 0.01 for adenovirus-treated arteries, which indicates that the procedures did not damage the vessel wall. Histology of the arteries, 7 days after gene transfer, detected no β-galactosidase activity outside adventitia. For both viruses,

macrophage infiltrates and some T cells were detected in the transduced arteries by RAM-11 and MCA-805 immunostainings, respectively. The arterial structure and endothelium remained intact throughout the experiments. Histological findings at all time-points are summarized in Table 3.

Table 1 Transduction of RAASMC and ECV-304 cell lines with baculoviruses and adenoviruses

Cell line	MOI	Butyrate (mM)	Positive cells (%)	
			Baculovirus	Adenovirus
RAASMC	200	0	1.0 ± 0.3	1.7 ± 0.8
		10	52.5 ± 0.8	42.1 ± 1.1
	1000	0	5.3 ± 1.3	48.0 ± 5.8
		10	90.6 ± 1.6	87.6 ± 2.3
ECV-304	200	0	0	44.2 ± 2.9
		10	2.6 ± 1.7	89.4 ± 1.9
	1000	0	0.3 ± 0.3	87.51 ± 4.0
		10	20.8 ± 7.7	97.6 ± 1.4

± s.e.m.

Table 2 MTT assay for cytotoxicity of baculoviruses and adenoviruses in RAASMC cells

MOI	Butyrate (mM)	Baculovirus (%)*	Adenovirus (%)*
200	0	82 ± 3	98 ± 4
	10	78 ± 2	101 ± 2
1000	0	81 ± 1	99 ± 1
	10	65 ± 1	90 ± 3

* Survival percentage of RAASMC cells as compared with mock-transduced cells. ± s.e.m.

Table 3 Summary of histological findings in transduced arteries 3, 7 and 14 days after gene transfer

Time-point	Virus	Macrophages	PMN cells	Endothelium intact
3d	adeno	++	+	Yes
	baculo	++	++	Yes
7d	adeno	+	+	Yes
	baculo	+	+	Yes
14 d	adeno	++	-	Yes
	baculo	++	-	Yes

-, absent; + mild; ++ moderate and +++ severe infiltrates as compared with control arteries.

PMN, polymorphonuclear.

Example 2

Using essentially the same procedure as in Example 1, it has been shown that baculovirus gene transfer works also in brain and skeletal muscle. Using baculovirus/*lac*Z, rat brain shows positive transfection in various types of brain cells, especially in choroid plexus cells in ventricles and endothelial cells. The profile of transfected cells is clearly different from that of adenoviruses.

Further, baculovirus transfection has been demonstrated in rabbit skeletal muscle. Baculovirus encoding *lac*Z (1.8×10^{10} PFU) was directly injected into the adductor muscle of NZW rabbit *via* a 25 G needle. The injection volume was 0.5 ml. Tissue samples were collected 7 days after the gene transfer, and X-Gal staining was performed overnight. These results clearly indicate that baculovirus can be used for transfection of several cell types in mammalians, i.e. not only arterial cells.

The accompanying drawing illustrates the construction of a nuclear-targeted β-galactosidase-encoding baculovirus transfection cassette. In principle, this is a standard public domain baculovirus with polyhedrin promoter, into which have been cloned restriction sites and the CMV-NT *lac*Z expression cassette. The *lac*Z expression cassette is oriented opposite to the polyhedrin promoter. The sequence of the CMV-nt *lac*Z expression cassette is in SEQ ID NO:7.

CLAIMS

1. A method for the delivery of a gene product, wherein the gene is provided in a baculovirus vector and the vector is applied to a body compartment free, or usually free, of blood.

2. A method according to claim 1, wherein delivery is periadventitial.

3. A method according to claim or claim 2, wherein the gene product is an agonist of a VEGF receptor.

4. A method according to any preceding claim, for the treatment of intimal hyperplasia.

5. A method according to claim 1 or claim 2, wherein the compartment comprises arterial cells.

6. A method according to claim 1 or claim 2, wherein the compartment comprises brain cells.

7. A method according to claim 1 or claim 2, wherein the compartment comprises skeletal muscle.

8. A device for the periadventitial delivery of a gene product, wherein the gene is provided in a baculovirus vector from which the gene may be expressed.

9. A device according to claim 8, in the form of a collar.

10. A device according to claim 8, in the form of a wrap.

11. A device according to any of claims 8 to 10, wherein the gene product is an agonist of a VEGF receptor.