CARBON MONOXIDE IMPROVES OUTCOMES IN TISSUE AND ORGAN TRANSPLANTS AND SUPPRESSES APOPTOSIS

Statement as to Federally Sponsored Research

This invention was made with Government support under National Institutes of Health Grant Nos. HL 58688. The Government has certain rights in this invention.

Technical Field

This invention relates to the field of enhancing cell survival.

Background

Carbon monoxide (CO) gas is poisonous in high concentrations. However, it is now recognized as an important signaling molecule (Verma *et al.*, Science 259:381-384, 1993). It has also been suggested that carbon monoxide acts as a neuronal messenger molecule in the brain (*Id.*) and as a neuro-endocrine modulator in the hypothalamus (Pozzoli *et al.*, Endocrinology 735:2314-2317, 1994). Like nitric oxide (NO), carbon monoxide is a smooth muscle relaxant (Utz *et al.*, Biochem Pharmacol. 47:195-201, 1991; Christodoulides *et al.*, Circulation 97:2306-9, 1995) and inhibits platelet aggregation (Mansouri *et al.*, Thromb Haemost. 48:286-8, 1982). Inhalation of low levels of CO has been shown to have anti-inflammatory effects in some models.

Islet cell transplantation is a viable treatment for the amelioration of type I diabetes (Lacy *et al.*, Annu. Rev. Immunol., 2:183-98, 1984; Weir *et al.*, J. Am. Optom. Assoc. 69:727-32, 2000; Berney *et al.*, Langenbechs Arch. Surg. 385: 378-8, 2000; Shapiro *et al.*, N Engl. J. Med., 343:230-8, 2000). However, the processes of clinical islet transplantation are made difficult by a number of factors. One factor is primary nonfunction (PNF) of the graft. Another is the need for high numbers of donor islets needed for a successful reversal of diabetes (Shapiro *et al.*, N Engl. J. Med., 343:230-8, 2000). Both situations reflect the same pathophysiology: the substantial cell loss in the graft within the first weeks after transplantation. After transplantation, islets suffer a variety of stress factors such as hypoxia before secondary vascularization (Carlsson *et al.*, Diabetes 47:1027-32, 1998) and exposure to pro-inflammatory cytokines and free radicals released from macrophages in the microenvironment of the transplant (Rabinovitch *et al.*,

Diabetes 48:1223-9, 1999; Kaufman *et al.*, J Exp Med. 772:291-302, 1990; Corbett *et al.*, Proc. Natl. Acad. Sci USA 90:1731-5, 1993) and from resident islet macrophages (Mandrup-Poulsen *et al.*, J. Immunol. 739:4077-82, 1987; Arnush *et al.*, J. Clin Invest. 702:516-26, 1998). The toxic effects of immunosuppressive drugs as well as rejection (Weir *et al.*, Diabetes 46:1247-56, 1997) also contribute to islet cell loss. The existence of PNF after experimental syngeneic islet transplantation (Nagata *et al.*, Transplant Proc. 22:855-6, 1990; Arita *et al.*, Transplantation 65:1429-33, 1998) indicates that non-specific inflammation plays a major role in this scenario.

Survival of a transplanted organ is thought to relate mainly to the success of immunosuppression, in terms of blocking the immune response that leads to graft rejection. However, it has previously been shown that transplanted organs can protect themselves from vascular injury leading to rejection through the expression of "protective genes" (see, *e.g.*, Bach *et al.*, Nature Med. 3:196-202 (1997); and Soares *et al.*, Nature Med. 4:1073-1077, 1998). One such gene, heme oxygenase-1 (HO-1), catabolizes heme into biliverdin, free iron and CO (Tenhunen *et al.*, Proc Natl Acad Sci USA 61:748-755, 1968).

SUMMARY

The present invention is based, in part, on the observations that CO promotes the survival and/or function of organ, tissue, and individual cell transplants.

Accordingly, in one aspect, the present invention provides a method of administering to a transplant donor a pharmaceutical composition containing carbon monoxide, obtaining an organ, tissue or cells from the donor, and transplanting the organ, tissue or cells into a recipient, where the amount of carbon monoxide administered to the donor is sufficient to enhance survival or function of the organ, tissue, or cells after transplantation into the recipient.

The pharmaceutical composition can be administered to a live donor, to a brain-dead donor, or to the donor prior to and following brain death.

Optionally, the organ can be treated *in situ* in the donor and/or *ex vivo* with a pharmaceutical composition comprising carbon monoxide.

The method can also or alternatively include the step of administering to the recipient a second pharmaceutical composition that includes carbon monoxide, before and/or during and/or after the step of transplanting the organ or tissue into the recipient.

In this or any of the methods described herein, the organ or tissue can be any organ or tissue which can be transplanted, e.g., a liver, a kidney, a heart, a pancreas, a lung, small intestine, and/or skin, and the donor can be of a species different from that of the recipient, or the donor and the recipient can be of the same species. The donor and the recipient can both be non-human animals or humans. Alternatively, the donor can be a non-human animal such as pig, and the recipient can be a human.

In another aspect, the invention provides a method of transplanting an organ, tissue or cells which includes providing an organ, tissue or cells of a donor, administering *ex vivo* or *in situ* to the organ, tissue or cells a pharmaceutical composition that includes carbon monoxide, and transplanting the organ, tissue, or cells into a recipient, wherein the amount of carbon monoxide is sufficient to enhance survival or function of the organ, tissue or cells in the recipient. In one embodiment, the pharmaceutical composition is administered by perfusing the organ or tissue *in situ* while the organ or tissue is in the donor.

Optionally, the method can include the step of administering to the recipient a second pharmaceutical composition containing carbon monoxide before and/or during and/or after transplantation of the organ or tissue into the recipient.

In yet another aspect, the invention provides a method of transplanting an organ, tissue or cells that includes the steps of providing an organ, tissue or cells of a donor, transplanting the organ, tissue or cells into a recipient, and before, and/or during, and/or after the step of transplanting the organ, tissue or cells into the recipient, administering to the recipient an amount of a pharmaceutical composition containing carbon monoxide sufficient to enhance survival and/or function of the transplanted organ, tissue or cells in the recipient.

In one embodiment, the pharmaceutical composition can be administered to the recipient within 0 to 20 days, e.g., within 1, 2, 4, 6, 8, 10, 12, 14, 18, or 20 days, after the organ has been transplanted into the recipient. In another embodiment, the pharmaceutical composition is administered to the recipient at least once, e.g., multiple times or continuously, from the time beginning 21 days after the step of transplanting the organ or tissue into the recipient for as long as needed to ensure survival of the graft. The pharmaceutical composition can be administered to the recipient upon determination that the transplanted organ or tissue is undergoing or about to undergo rejection, e.g., chronic rejection or acute rejection.

Optionally, the method can further include the step of administering to the donor a second pharmaceutical composition containing carbon monoxide prior to obtaining the organ, tissue or cells from the donor. The second pharmaceutical composition can be administered to a live donor or to a brain-dead donor.

The method can include the step of administering to the organ a second pharmaceutical composition containing carbon monoxide *in situ* in the donor and/or *ex vivo*.

In another aspect, the invention provides a method of enhancing the survival and/or function of a donor organ, tissue or cell which includes providing an organ, tissue or cell of a marginal donor and exposing the organ, tissue or cell to an amount of a pharmaceutical composition containing carbon monoxide sufficient to enhance the survival and/or function of the donor organ, tissue or cell.

In another aspect, the invention provides a method of maintaining an animal cell *in vitro* that includes providing a vessel containing a pressurized gas that includes carbon monoxide gas, providing an isolated cell *in vitro*, wherein the cell is a primary cell or stem cell, releasing the pressurized gas from the vessel to form an atmosphere that includes carbon monoxide gas, and maintaining the animal cell *in vitro* in the presence of the atmosphere that includes carbon monoxide gas.

If desired, the cell can then be transplanted into a recipient. The cell may be obtained from a donor that is not the recipient, or it may be obtained from the recipient. Further, a carbon monoxide composition can be administered to the recipient prior to, and/or during, and/or after the transplantation step. This composition will typically be in the form of an inhaled gas.

In another embodiment, the animal cell is obtained from a donor by a method that includes administering a composition comprising carbon monoxide to the donor and obtaining the cell from a tissue of the donor.

The invention also provides a method of maintaining an animal cell *in vitro* that includes providing a culture medium containing an effective amount of carbon monoxide, for example, at least 0.0001 g CO/100 g medium, and maintaining an isolated cell in the medium. The medium can contain, for example, at least 0.0002, 0.0004, 0.0006, 0.0008, 0.0010, 0.0013, 0.0014, 0.0015, 0.0016, 0.0018, 0.0020, 0.0021, 0.0022, 0.0024, 0.0026, 0.0028, 0.0030, 0.0032, 0.0035, 0.0037, 0.0040, 0.0042, or 0.0044 g CO/100 g medium.

Further, the invention provides a method of enhancing survival of an animal cell after removal from a donor that includes administering to a live or brain-dead donor a pharmaceutical composition comprising carbon monoxide, and obtaining an isolated cell from the donor. The pharmaceutical composition can be, for example, supplied in the form of a pressurized gas suitable for inhalation by the donor.

The method can further include the step of maintaining the cell *in vitro* in the presence of a second composition containing carbon monoxide.

While *in vitro* the cell may be disposed in a liquid medium. In such a case, the step of exposing the cell to the second carbon monoxide composition can be performed by providing a source of pressurized carbon monoxide gas and contacting the liquid medium with carbon monoxide gas released from the source. The liquid medium itself may also be provided as a carbon monoxide composition, i.e., with carbon monoxide dissolved therein.

Further, the invention provides a method of transplanting an animal cell that includes the steps of administering to a live or brain-dead donor a pharmaceutical composition comprising carbon monoxide, obtaining an isolated cell from the donor, and transplanting the cell into a recipient. The animal cell may be obtained from a donor that is not the recipient, or it may be obtained from the recipient. If desired, a carbon monoxide composition can be administered to the recipient prior to and/or during and/or after the transplantation step.

The invention also provides a method of enhancing survival or function of an animal cell transplanted into a recipient that includes the steps of transplanting an animal cell into a recipient and before, during, and/or after the transplanting step, causing the recipient to inhale an amount of carbon monoxide gas sufficient to enhance survival or function of the transplanted cell in the recipient. The carbon monoxide gas can be supplied in the form of a vessel containing pressurized gas that includes carbon monoxide. In one embodiment, the cell is maintained *in vitro* in an atmosphere comprising carbon monoxide prior to the transplant step. For example, the animal cell can be maintained in a liquid medium that includes at least at least 0.0001 g carbon monoxide/100 g medium (e.g., at least about 0.0002, 0.0004, 0.0006, 0.0008, 0.0010, 0.0013, 0.0014, 0.0015, 0.0016, 0.0018, 0.0020, 0.0021, 0.0022, 0.0024, 0.0026, 0.0028, 0.0030, 0.0032, 0.0035, 0.0037, 0.0040, 0.0042, or 0.0044 g CO/100 g medium).

The method can optionally include the step of exposing the cell to a carbon monoxide composition *ex vivo*, prior to the transplanting step.

The carbon monoxide gas can be administered to the recipient prior to and/or during and/or after the transplantation step. The animal cell may be obtained from a donor that is not the recipient, or it may be obtained from the recipient. A pharmaceutical composition comprising carbon monoxide can be administered to the donor prior to and/or during removal of the cell from the donor.

In another aspect, the invention provides a method of improving survival of a transplanted cell in a recipient that includes administering to the recipient before and/or during and/or after transplantation of the cell into the recipient, an effective amount of a pharmaceutical composition comprising carbon monoxide gas.

In any of the above methods of the invention, the survival effect may be enhanced by inducing the enzyme hemeoxygenase-1 (HO-1) in a donor or recipient, e.g., induced with heme, heavy metals, cytokines, hormones, nitric oxide, endotoxins, UV irradiation, or glutathione depletors; or via heat shock. In the donor, such induction can occur prior to or during removal of the organ, tissue, or cells. In the recipient, such induction can occur, prior to, during, or following transplantation. Alternatively, the enzyme can be induced in the organ, tissue, or cells *ex vivo*, prior to transplantation into the recipient.

The invention further provides an article of manufacture that includes a vessel containing pressurized gas, that contains at least 0.001 ppm, e.g., at least about 1, 10, 50, 100, 150, 200, 250, 300, 500, 1000, 2000, 5000, 10,000, 100,000, 200,000, 300,000, 400,000, 500,000, and up to 1,000,000 ppm carbon monoxide, and a label describing use of the gas to enhance survival of isolated animal cells, tissues, or islets before, during or after transplantation of the cells, tissues, or islets into a patient.

Also within the invention is a sterile cell medium that includes nutrients suitable for maintaining an animal cell in culture and at least about 0.0001 g carbon monoxide/100 g medium, e.g., at least 0.0002, 0.0004, 0.0006, 0.0008, 0.0010, 0.0013, 0.0014, 0.0015, 0.0016, 0.0018, 0.0020, 0.0021, 0.0022, 0.0024, 0.0026, 0.0028, 0.0030, 0.0032, 0.0035, 0.0037, 0.0040, 0.0042, or 0.0044 g CO/100 g medium. It may also contain animal cells.

A method of maintaining an animal cell *in vitro* and then transplanting it is also provided. The method includes the steps of providing a vessel containing pressurized gas containing carbon monoxide gas; providing an isolated animal cell *in vitro,* wherein the cell is disposed in a medium that contains dissolved carbon monoxide; releasing the pressurized gas from the vessel

to form an atmosphere comprising carbon monoxide gas; maintaining the cell in the presence of the atmosphere; and transplanting the cell into a recipient.

In any of the above aspects or embodiments of the invention, the cell can be any cell. For example, the cell can be an animal cell such as a primary, secondary, or cell line cell. As another example, the cell can be part of a pancreatic islet, e.g., a é-cell. The cell can also be, e.g., a liver cell, a fibroblast, a bone marrow cell, a neuronal cell, a myocyte, a lymphocyte, or a stem cell. In each of the *ex vivo* methods of the invention, the tissue is preferably not blood and contains little if any whole blood, and the cells are preferably not red blood cells and are not accompanied by a significant number of red blood cells.

Unless otherwise defined, all technical and scientific terms used herein have the same meaning as commonly understood by one of ordinary skill in the art to which this invention belongs. Although methods and materials similar or equivalent to those described herein can be used in the practice or testing of the present invention, suitable methods and materials are described below. All publications, patent applications, patents, and other references mentioned herein are incorporated by reference in their entirety. In case of conflict, the present specification, including definitions, will control. The materials, methods, and examples are illustrative only and not intended to be limiting.

Other features and advantages of the invention will be apparent from the following detailed description, and from the claims.

DESCRIPTION OF DRAWINGS

Fig. 1A is a bar graph that illustrates the effect of treatment of βTC3 cells with increasing concentrations of TNF–α.

Fig. 1B is a graphical representation illustrating a FACScan™ analysis of DNA fragmentation in βTC3 cells following treatment with TNF–α.

Fig. 1C is a bar graph that illustrates the effect of co-transfecting βTC3 with a β–gal expressing vector (pcDNA3/β–gal) plus control (pcDNA3), and treatment with either the caspase–3 inhibitor Z–DEVD–FMK (C3–i) or the caspase–8 inhibitor IETD–CHO (C8–i). Gray histograms represent untreated β–cells and black histograms represent β–cells treated with TNF–α for 24 hours. Results shown are the mean ± standard deviation from duplicate wells taken from one representative experiment out of three.

Fig. 2A is a bar graph showing that exogenous carbon monoxide can substitute for HO–1 (hemeoxygenase-1) when HO–1 activity is blocked. Gray histograms represent untreated β–cells and black histograms represent β–cells treated with TNF–α or etoposide or subjected to serum deprivation. Results shown are mean ± standard deviation from duplicate wells taken from one representative experiment out of three.

Fig. 2B is a graphical representation of a FACScan™ analysis of DNA fragmentation in βTC3 cells following 24 hour treatment with carbon monoxide after treatment with TNF–α.

Fig. 2C is a bar graph illustrating that exogenous carbon monoxide protects β–cells from apoptosis in the absence of HO–1. βTC3 cells were transfected with β–gal expressing vectors and were exposed to exogenous carbon monoxide. Gray histograms represent untreated β–cells and black histograms represent β–cells treated with TNF–α or etoposide or subjected to serum deprivation as indicated. Results shown are mean ± standard deviation from duplicate wells taken from one representative experiment out of three.

Fig. 3 is a DNA fragmentation analysis by FACScan™ that indicates that exogenous carbon monoxide protects murine islets of Langerhans from apoptosis. CHX = cycloheximide.

Fig. 4A is a bar graph illustrating that the anti-apoptotic effect of exogenous carbon monoxide is mediated by guanylate cyclase activation. ODQ = guanylyl cyclase inhibitor ODQ.

Fig. 4B is a bar graph illustrating that cGMP analogue can substitute for carbon monoxide in protecting cells from apoptosis. 8–Br–cGMP=cGMP analogue 8–Br–cGMP.

Fig. 4C is a bar graph illustrating that cGMP-dependent protein kinases (cGK) mediate the anti-apoptotic effect of carbon monoxide. βTC3 cells were co-transfected with β–gal expressing vector. For Figs. 4A-C, gray histograms represent untreated β–cells and black histograms represent β–cells treated with TNF–α. Results shown are mean ± standard deviation from duplicate wells taken from one representative experiment out of three. KT=protein kinase G inhibitor KT5823.

Fig. 5A is a bar graph showing that one hour of carbon monoxide exposure is sufficient to prevent apoptosis.

Fig. 5B is a bar graph showing that carbon monoxide protects β–cells after induction of apoptosis.

Fig. 5C is a bar graph showing that preincubation with carbon monoxide prevents β–cell apoptosis. For Figs. 5A-C, gray histograms represent untreated β–cells and black histograms represent β–cells treated with TNF–α. Results shown are mean ± standard deviation from duplicate wells taken from one representative experiment out of three.

Fig. 6A is a line graph indicating that exposure of murine islets to carbon monoxide improves survival and function following transplantation.

Fig. 6B is a line graph that indicates the probability of recovery (blood glucose level below 200 mg/dl) for animals receiving islets pre-exposed to carbon monoxide or control islets. $*P = 0.001$ versus control.

Fig. 7 is a bar graph that illustrates expression of HO-1 in mouse hearts transplanted into CVF plus CsA-treated rats. Mouse hearts were transplanted into rats treated at the time of transplantation with cobra venom factor (CVF) plus daily treatments after transplantation with cyclosporin A (CsA). Expression of HO-1 and β-actin mRNA were detected by RT-PCR. The symbol -/- indicates RNA from HO-1 -/- mouse hearts used as a negative control. Histograms represent relative level of HO-1 mRNA expression normalized for expression of β-actin mRNA.

Fig. 8 is a set of bar graphs illustrating that SnPPIX inhibits HO-1 enzymatic activity *in vivo*. Mouse hearts were transplanted into untreated rats (II) or into rats treated with, CVF and CsA (III) plus FePPIX (IV) or SnPPIX (V). Total HO activity in donor and recipient hearts was measured 2 days after transplantation and compared with basal HO activity in normal mouse and rat hearts, respectively (I). Results shown are the mean ± standard deviation (SD) of three animals analyzed for each treatment. Statistical analyses were conducted by using unpaired Welsh *t* test.

Fig. 9 is a set of line graphs illustrating that SnPPIX and FePPIX do not interfere with the generation of anti-graft antibodies (Abs). Mouse hearts were transplanted into rats treated with CVF plus CsA, as described above. Serum level of anti-graft IgM Abs was evaluated by a cellular ELISA. Binding of rat complement component C3 to mouse endothelial cells was evaluated by cellular ELISA. Complement hemolytic activity (CH50) was evaluated by a standard hemolytic assay. Results shown are the mean ± SD ($n = 3$).

Fig. 10A is a set of bar graphs illustrating that exogenous CO does not affect the ability of SnPPIX to suppress HO-1 enzymatic activity. Mouse hearts were transplanted into rats treated with CVF plus CsA plus SnPPIX (II) or SNPPIX and CO (III). Total HO activity was measured

in donors' and recipients' hearts as well as in recipients' livers 2 days after transplantation. HO activity in different specimens was compared with basal HO activity in normal mouse hearts (I), rat hearts (I), or livers (I), according to the sample analyzed. Results shown are the mean ± SD of three animals analyzed for each treatment. Statistical analyses were conducted by using unpaired Welsh *t* test.

Fig. 10B is a bar graph that illustrates that exogenous CO does not affect the ability of SnPPIX to suppress HO-1 activity. The animals used to generate the data of Fig. 10A were analyzed for carboxyhemoglobin content 2 days after transplantation. Results shown are the mean ± SD *(n* = 3).

Fig. 11 is a line graph illustrating that up-regulation of HO-1 in endothelial cells inhibits platelet activation. Mouse 2F-2B endothelial cells were left untreated (NT) or were treated with CoPPIX (50 μM, 16 h) to up-regulate HO-1 activity, SnPPIX to suppress HO-1 activity (50 μM, 16 h), or CoPPIX (50 μM, 12 h) plus SnPPIX (50 μM, 4 h) to control for the specificity of CoPPIX in up-regulating HO-1 activity. Rat platelets were isolated, overlaid onto the mouse endothelial cells for 5 min, and tested for aggregation after stimulation with 2 μM of adenosine diphosphate (ADP).

Fig. 12 is a bar graph illustrating that carbon monoxide suppresses endothelial cell apoptosis. Gray histograms represent cells treated with Act.D alone and black histograms represent cells treated with Act.D plus TNF-α. Where indicated, endothelial cells were treated with SnPPIX (50 μM) and exposed to exogenous CO (10,000 parts per million (ppm)).

DETAILED DESCRIPTION

The term "carbon monoxide" (or "CO") as used herein describes molecular carbon monoxide in its gaseous state, compressed into liquid form, or dissolved in aqueous solution. The terms "carbon monoxide composition" and "pharmaceutical composition comprising carbon monoxide" are used throughout the specification to describe a gaseous, liquid, solid, or semi-solid composition containing carbon monoxide that can be administered to a donor patient, cadaver, or animal; to an organ; or to a portion of an organ, e.g., tissues of the organ, or individual cell(s) that make up the organ, e.g., neurons, hepatocytes, myocytes, islets, or islet cells such as a pancreatic β-cell. The skilled practitioner will recognize which form of the

pharmaceutical composition, e.g., gaseous, liquid, or both gaseous and liquid forms, is preferred for a given application.

The terms "effective amount" and "effective to treat," as used herein, refer to an amount or concentration of carbon monoxide utilized for period of time (including acute or chronic administration and periodic or continuous administration) that is effective within the context of its administration for causing an intended effect or physiological outcome. Effective amounts of carbon monoxide for use in the present invention include, for example, amounts that are effective for enhancing survival and/or improving function of organs or cells *in vivo* and/or *in vitro*. Within the context of transplantation of individual cells or masses of cells, e.g., transplant donors and/or recipients, an effective amount of carbon monoxide is that amount administered to the transplant donor and/or recipient sufficient to enhance survival of the cell or mass of cells, e.g. to reduce loss of the cell, or mass of cells, and/or to improve functional performance of a transplanted cell or a mass of cells. Within the context of treating cells outside a body, e.g., islet cells to be cultured and/or used for transplantation, an effective amount of carbon monoxide is that amount with which the cells are incubated or stored in order to enhance preservation of the cells and/or to reduce cell loss, e.g., loss via apoptosis, and/or to enhance function. Within the context of transplantation of organs and tissues, e.g., transplant donors and/or recipients, an effective amount of carbon monoxide is that amount administered to the transplant donor and/or recipient sufficient to enhance survival of the organ, tissue or cells of interest, e.g., to reduce loss of cells from which the organ or tissue is composed, and/or to improve functional performance of an organ. Within the context of treating organs, tissues or cells *ex vivo* to be stored or used for transplantation, an effective amount of carbon monoxide is an amount sufficient to enhance survival and/or function of the organ or tissues. As used herein, the term "inhibiting" includes delaying the onset of, reducing, preventing, or alleviating a biological process, e.g., apoptosis. For gases, effective amounts of carbon monoxide generally fall within the range of about 0.0000001% to about 0.3% by weight, e.g., 0.0001% to about 0.25% by weight, preferably at least about 0.001%, e.g., at least 0.005%, 0.010%, 0.02%, 0.025%, 0.03%, 0.04%, 0.05%, 0.06%, 0.08%, 0.10%, 0.15%, 0.20%, 0.22%, or 0.24% by weight of carbon monoxide. Preferred ranges of carbon monoxide include about 0.001% to about 0.24%, about 0.005% to about 0.22%, about 0.01% to about 0.20%, and about 0.01% to about 0.1% by weight. Other preferred ranges include about 0.005% to about 0.24%, about 0.01% to about 0.22%, about

0.015% to about 0.20%, and about 0.025% to about 0.1% by weight. For liquid solutions of CO, effective amounts generally fall within the range of about 0.0001 to about 0.0044 g CO/100 g liquid, e.g., at least 0.0002, 0.0004, 0.0006, 0.0008, 0.0010, 0.0013, 0.0014, 0.0015, 0.0016, 0.0018, 0.0020, 0.0021, 0.0022, 0.0024, 0.0026, 0.0028, 0.0030, 0.0032, 0.0035, 0.0037, 0.0040, or 0.0042 g CO/100 g aqueous solution. Preferred ranges include, e.g., about 0.0010 to about 0.0030 g CO/100 g liquid, about 0.0015 to about 0.0026 g CO/100 g liquid, or about 0.0018 to about 0.0024 g CO/100 g liquid. A skilled practitioner will appreciate that amounts outside of these ranges may be used, depending upon the application.

The term "patient" is used throughout the specification to describe an animal, human or non-human, to whom treatment according to the methods of the present invention is provided. Veterinary applications are clearly anticipated by the present invention. The term includes but is not limited to birds, reptiles, amphibians, and mammals, e.g., humans, other primates, pigs, rodents such as mice and rats, rabbits, guinea pigs, hamsters, cows, horses, cats, dogs, sheep and goats. The term "donor" or "donor patient" as used herein refers to an animal (human or non-human) from whom an organ, tissue or individual cells can be obtained for the purposes of storage and/or transplantation to a recipient patient. The term "recipient" or "recipient patient" refers to an animal (human or non-human) into which an organ, tissue, mass of cells or individual cells can be transferred.

The term "diabetes" is a general term to describe diabetic disorders as they are recognized in the art, e.g., Diabetes Mellitus. Diabetes Mellitus is characterized by an inability to regulate blood glucose levels. The two most prevalent types of diabetes are known as Type I and Type II diabetes. In Type I, or insulin-dependent diabetes (IDDM), the pancreas makes little or no insulin because the insulin-producing beta cells have been destroyed. In Type II, or noninsulin-dependent diabetes (NIDDM), the pancreas makes some insulin but the insulin is not effective. The term also encompasses the myriad secondary disorders caused by diabetes, both acute and chronic, e.g., diabetic complications, e.g., hypoglycemia and hyperglycemia, retinopathy, angiopathy, neuropathy, and nephropathy.

The term "cell(s)" or "animal cell(s)" as used herein refers to any type of animal cells, including animal cells suitable for transplantation. The cells are typically primary cells obtained from an animal donor, but can be secondary cells or even cells of an established cell line. They are optionally transfected *ex vivo* with an expression vector that alters their function in some

way. The cells include, but are not limited to, e.g., islet cells, e.g., cells which are part of a pancreatic islet, and liver cells, fibroblasts, bone marrow cells, myocytes, and stem cells, and cells (e.g., neurons) of the central nervous system, including the spinal cord. The term "islet cell(s)" is used throughout the specification as a general term to describe the clumps of cells within the pancreas known as islets, e.g., islets of Langerhans. Islets of Langerhans contain several cell types that include, e.g., β-cells (which make insulin), α-cells (which produce glucagons), γ-cells (which make somatostatin), F cells (which produce pancreatic polypeptide), enterochromaffin cells (which produce serotonin), PP cells and D1 cells. The term "stem cell" is an art recognized term that refers to cells having the ability to divide for indefinite periods in culture and to give rise to specialized cells. Included within this term are, for example, totipotent, pluripotent, multipotent, and unipotent stem cells, e.g., neuronal, liver, muscle, and hematopoietic stem cells.

By "isolated cell" is meant that the cell is removed from the tissue or organ in which it (or its predecessor) naturally occurs. A cell can be just partially purified from its natural milieu and be deemed "isolated." For example, an intact islet of Langerhans is considered to be made up of "isolated" cells, once the islet is removed from a pancreas and can be physically separated from other islets. The cells of an intact organ such as a kidney or heart or a partial organ such as a piece of a blood vessel are not considered to be "isolated cells" while still part of the organ.

The term "organ(s)" is used throughout the specification as a general term to describe any anatomical part or member having a specific function in the animal. Further included within the meaning of this term are substantial portions of organs, e.g., cohesive tissues obtained from an organ. Such organs include but are not limited to kidney, liver, heart, intestine, e.g., large or small intestine, pancreas, and lungs. Further included in this definition are bones and blood vessels, e.g., aortic transplants.

The term "transplantation" is used throughout the specification as a general term to describe the process of implanting an organ, tissue, mass of cells, or individual cells into a patient. The term "transplantation" is defined in the art as the transfer of living tissues or cells from a donor to a recipient, with the intention of maintaining the functional integrity of the transplanted tissue or cells in the recipient (see, e.g., *The Merck Manual*, Berkow, Fletcher, and Beers, Eds., Merck Research Laboratories, Rahway, N.J., 1992). The term "cell transplantation" is used throughout the specification as a general term to describe the process of transferring at

least one cell, e.g., an islet cell(s), to a patient. For example, such transplantation can be performed by removing the β-cells (or intact islets) from a donor's pancreas and putting them into a recipient patient whose pancreas cannot produce sufficient insulin. The terms include all categories of transplants known in the art, except blood transfusions. Transplants are categorized by site and genetic relationship between donor and recipient. The term includes, e.g., autotransplantation (removal and transfer of cells or tissue from one location on a patient to the same or another location on the same patient), allotransplantation (transplantation between members of the same species), and xenotransplantation (transplantations between members of different species).

The terms "organ rejection", "transplant rejection" or "rejection" are art-recognized, and are used throughout the specification as a general term to describe the process of rejection of an organ, tissues, or cells in a recipient. Included within the definition are, for example, three main patterns of rejection that are usually identified in clinical practice: hyperacute rejection, acute rejection, and chronic rejection (see, e.g., *Oxford Textbook of Surgery*, Morris and Malt, Eds., Oxford University Press, 1994).

The terms "marginal donor(s)" and "marginal organ" are used herein as general terms to describe a donor or organ presenting with problems that render its use in a transplantation procedure less than optimal. For example, a marginal donor can include a donor that is older than 50 years old, or that is afflicted with a chronic disease that may affect graft function, e.g., diabetes, HTA and alcohol intake. A marginal organ is, for example, (1) an organ from such a donor, or (2) an organ that has experienced prolonged warm or cold ischemia times, or (3) an organ that presents with anatomical abnormalities (e.g., small and multiple vessels, e.g., in the kidney) that can render the vascular anastomosis difficult, or with evidence of atherosclerostic plaques on graft vessels.

Preparation of Gaseous Compositions

A carbon monoxide composition may be a gaseous carbon monoxide composition. Compressed or pressurized gas useful in the methods of the invention can be obtained from any commercial source, and in any type of vessel appropriate for storing compressed gas. For example, compressed or pressurized gases can be obtained from any source that supplies compressed gases, such as oxygen, for medical use. The pressurized gas including carbon

monoxide used in the methods of the present invention can be provided such that all gases of the desired final composition (e.g., CO and O_2, and optionally N_2, He, and/or CO_2) are mixed together in the same vessel. If desired, the methods of the present invention can be performed using multiple vessels containing individual gases. For example, a single vessel can be provided that contains carbon monoxide, with or without other gases, the contents of which can be optionally mixed with room air or with the contents of other vessels, e.g., vessels containing oxygen, nitrogen, carbon dioxide, compressed air, or any other suitable gas or mixtures thereof.

Gaseous compositions administered to a patient according to the present invention typically contain 0% to about 79% by weight nitrogen, about 21% to about 100% by weight oxygen and about 0.0000001% to about 0.3% by weight (corresponding to about 0.001 ppm (i.e., 1 ppb) to about 3,000 ppm) carbon monoxide. Preferably, the amount of nitrogen in the gaseous composition is about 79% by weight, the amount of oxygen is about 21% by weight and the amount of carbon monoxide is about 0.0001% to about 0.25% by weight. The amount of carbon monoxide is preferably at least about 0.001%, e.g., at least about 0.005%, 0.01%, 0.02%, 0.025%, 0.03%, 0.04%, 0.05%, 0.06%, 0.08%, 0.10%, 0.15%, 0.20%, 0.22%, or 0.24% by weight. Preferred ranges of carbon monoxide include about 0.001% to about 0.24%, about 0.005% to about 0.22%, about 0.010% to about 0.20%, and about 0.015% to about 0.1% by weight. It is noted that gaseous carbon monoxide compositions having concentrations of carbon monoxide greater than 0.3% (such as 1% or greater) may be used for short periods (e.g., one or a few breaths), depending upon the application. They are particularly useful for ex *vivo* applications, where carbon monoxide poisoning is not a risk. Where the gas is used to form an atmosphere for cultivation of cells *in vitro*, the gas can contain carbon dioxide as well, to help maintain the pH of the medium. The carbon dioxide can be present at, for example, 1% to 10%, commonly 5%, by weight.

A gaseous carbon monoxide composition may be used to create an atmosphere that comprises carbon monoxide gas. An atmosphere that includes appropriate levels of carbon monoxide gas can be created, for example, by providing a vessel containing a pressurized gas comprising carbon monoxide gas, and releasing the pressurized gas from the vessel into a chamber or space to form an atmosphere that includes the carbon monoxide gas inside the chamber or space. Alternatively, the gases can be released into an apparatus that culminates in a breathing mask or breathing tube, thereby creating an atmosphere comprising carbon monoxide

gas in the breathing mask or breathing tube and ensuring the patient is the only person in the room exposed to significant levels of carbon monoxide.

Carbon monoxide levels in an atmosphere or a ventilation circuit can be measured or monitored using any method known in the art. Such methods include electrochemical detection, gas chromatography, radioisotope counting, infrared absorption, colorimetry, and electrochemical methods based on selective membranes (see, e.g., Sunderman *et al.,* Clin. Chem. 28:2026-2032, 1982; Ingi *et al.,* Neuron 16:835-842, 1996). Sub-parts per million carbon monoxide levels can be detected by, e.g., gas chromatography and radioisotope counting. Further, it is known in the art that carbon monoxide levels in the sub-ppm range can be measured in biological tissue by a midinfrared gas sensor (see, e.g., Morimoto *et al.,* Am. J. Physiol. Heart. Circ. Physiol 280:H482-H488, 2001). Carbon monoxide sensors and gas detection devices are widely available from many commercial sources.

Preparation of Liquid Compositions

A carbon monoxide composition may also be a liquid carbon monoxide composition. A liquid can be made into a carbon monoxide composition by any method known in the art for causing gases to become dissolved in liquids. For example, the liquid can be placed in a so-called "CO_2 incubator" and exposed to a continuous flow of carbon monoxide until a desired concentration of carbon monoxide is reached in the liquid. As another example, carbon monoxide gas can be "bubbled" directly into the liquid until the desired concentration of carbon monoxide in the liquid is reached. The amount of carbon monoxide that can be dissolved in a given aqueous solution increases with decreasing temperature. As still another example, an appropriate liquid may be passed through tubing that allows gas diffusion, where the tubing runs through an atmosphere comprising carbon monoxide (e.g., utilizing a device such as an extracorporeal membrane oxygenator). The carbon monoxide diffuses into the liquid to create a liquid carbon monoxide composition.

The liquid can be any liquid known to those of skill in the art to be suitable for administration to patients (see, for example, Oxford Textbook of Surgery, Morris and Malt, Eds., Oxford University Press, 1994) or for maintaining organs, tissues or cells *ex vivo*. In general, the liquid will be an aqueous solution. Examples of solutions include Phosphate Buffered Saline (PBS), Celsior™ solution, Perfadex™ solution, Collins solution, citrate solution, and University

of Wisconsin (UW) solution (Oxford Textbook of Surgery, Morris and Malt, Eds., Oxford University Press, 1994). The liquid compositions can include carbon monoxide at concentrations in the range of about 0.0001 to about 0.0044 g CO/100 g liquid, e.g., at least 0.0002, 0.0004, 0.0006, 0.0008, 0.0010, 0.0013, 0.0014, 0.0015, 0.0016, 0.0018, 0.0020, 0.0021, 0.0022, 0.0024, 0.0026, 0.0028, 0.0030, 0.0032, 0.0035, 0.0037, 0.0040, or 0.0042 g CO/100 g aqueous solution. Preferred ranges include, e.g., about 0.0010 to about 0.0030 g CO/100 g liquid, about 0.0015 to about 0.0026 g CO/100 g liquid, or about 0.0018 to about 0.0024 g CO/100 g liquid. For water at $0^{O}C$, the saturation point is about 0.0044 g CO/100 g medium.

Any suitable liquid can be saturated to a set concentration of carbon monoxide via gas diffusers. Alternatively, pre-made solutions that have been quality controlled to contain set levels of carbon monoxide can be used. Accurate control of dose can be achieved via measurements with a gas permeable, liquid impermeable membrane connected to a carbon monoxide analyzer. Solutions can be saturated to desired effective concentrations and maintained at these levels. In both liquid and gaseous compositions, the inclusion of the inert gas helium can improve carbon monoxide delivery to the tissues of an organ.

Treatment of Patients with Carbon Monoxide Compositions

The present invention contemplates the use of carbon monoxide compositions to treat donors, recipients, organs, tissues, masses of cells, and/or individual cells at any step of the harvesting, storage and transplant process. An organ, a tissue, a mass of cells, or individual cells may be harvested from a donor, treated with a carbon monoxide composition *ex vivo* in accordance with the present invention, and transplanted into a recipient. Alternatively or in addition, the organ, tissue, mass of cells, or individual cells can be treated *in situ*, while still in the donor. Optionally, a carbon monoxide composition can be administered to the recipient prior to, during, and/or after the surgery: *e.g.*, after an organ is reperfused with the recipient's blood. The carbon monoxide composition may also be administered to the donor prior to or during the process of harvesting the organ, tissue, mass of cells, or individual cells.

Organs, tissues, masses of cells, and/or isolated cells can be harvested from a donor and transplanted by any methods known to those of skill in the art (see, for example, *Oxford Textbook of Surgery*, Morris and Malt, Eds., Oxford University Press (1994)). The skilled

practitioner will recognize that methods for harvesting and transplantation may vary depending upon many circumstances, such as the type of organ, tissue or cells and the type of donor.

It is further contemplated by the present invention that the methods described herein can be used with organs, tissue, masses of cells or isolated cells *ex vivo*, *e.g.*, bioartificial organs, such as a bioartificial liver, kidney or pancreas (see, *e.g.*, Sambanis *et al*, *Cytotechnology* 15:351-363, 1994). The organs, tissues, or cells (or masses of cells) can be treated with carbon monoxide either prior to putting them in the device, or while they are utilized in the device, or both. Alternatively or in addition, the donor animal can be administered carbon monoxide prior to removal of the organ, tissue, mass of cells, or individual cells for use in the device.

Alternatively or in addition, a cell can be cultured as described below and transplanted into a recipient.

A patient can be treated with a carbon monoxide composition by any method known in the art of administering gases and/or liquids to patients. The present invention contemplates the systemic administration of liquid or gaseous carbon monoxide compositions to patients (e.g., by inhalation and/or ingestion), and the topical administration of the compositions to the patient's organs or tissues *in situ* (e.g., by ingestion, insufflation, and/or introduction into the abdominal cavity).

Systemic Delivery of Carbon Monoxide

Gaseous carbon monoxide compositions can be delivered systemically to a patient, e.g., a patient undergoing or in need of a transplant. Gaseous carbon monoxide compositions are typically administered by inhalation through the mouth or nasal passages to the lungs, where the carbon monoxide is readily absorbed into the patient's bloodstream. The concentration of active compound (CO) utilized in the therapeutic gaseous composition will depend on absorption, distribution, inactivation, and excretion (generally, through respiration) rates of the carbon monoxide as well as other factors known to those of skill in the art. It is to be further understood that for any particular subject, specific dosage regimens be adjusted over time according to the individual need and the professional judgment of the person administering or supervising the administration of the compositions, and that the concentration ranges set forth herein are exemplary only and are not intended to limit the scope or practice of the claimed invention. Acute, sub-acute and chronic administration of carbon monoxide are contemplated by the present

invention, depending upon, e.g., the severity or persistence of the disorder in the patient. Carbon monoxide can be delivered to the patient for a time (including indefinitely) sufficient to treat the condition and exert the intended pharmacological or biological effect.

The following are examples of some methods and devices that can be utilized to administer gaseous carbon monoxide compositions to patients.

Ventilators

Carbon monoxide (concentrations can vary) can be purchased mixed with air or another oxygen-containing gas in a standard tank of compressed gas (e.g., 21% O_2, 79% N_2). It is non-reactive, and the concentrations that are required for the methods of the present invention are well below the combustible range (10% in air). In a hospital setting, the gas presumably will be delivered to the bedside where it will be mixed with oxygen or house air in a blender to a desired concentration. The patient will inhale the gas mixture through a ventilator, which will be set to a flow rate based on patient comfort and needs. This is determined by pulmonary graphics (i.e., respiratory rate, tidal volumes, etc.). Fail-safe mechanism(s) to prevent the patient from unnecessarily receiving greater than desired amounts of carbon monoxide can be designed into the delivery system. The patient's carbon monoxide level can be monitored by studying (1) carboxyhemoglobin (COHb), which can be measured in venous blood, and (2) exhaled carbon monoxide collected from a side port of the ventilator. Carbon monoxide exposure can be adjusted based upon the patient's health status and on the basis of the markers. If necessary, carbon monoxide can be washed out of the patient by switching to 100% O_2 inhalation. Carbon monoxide is not metabolized; thus, whatever is inhaled will ultimately be exhaled except for a very small percentage that is converted to CO_2. Carbon monoxide can also be mixed with any level of O_2 to provide therapeutic delivery of carbon monoxide without consequential hypoxic conditions.

Face Mask and Tent

A carbon monoxide-containing gas mixture is prepared as above to allow inhalation by the patient using a facemask or tent. The concentration inhaled can be changed and can be washed out by simply switching over to 100% O_2. Monitoring of carbon monoxide levels would

occur at or near the mask or tent with a fail-safe mechanism that would prevent too high of a concentration of carbon monoxide from being inhaled.

Portable inhaler

Compressed carbon monoxide can be packaged into a portable inhaler device and inhaled in a metered dose, for example, to permit intermittent treatment of a recipient who is not in a hospital setting. Different concentrations of carbon monoxide could be packaged in the containers. The device could be as simple as a small tank (e.g., under 5 kg) of appropriately diluted CO with an on-off valve and a tube from which the patient takes a whiff of CO according to a standard regimen or as needed.

Intravenous Artificial Lung

An artificial lung (a catheter device for gas exchange in the blood) designed for O_2 delivery and CO_2 removal can be used for carbon monoxide delivery. The catheter, when implanted, resides in one of the large veins and would be able to deliver carbon monoxide at given concentrations either for systemic delivery or at a local site. The delivery can be a local delivery of a high concentration of carbon monoxide for a short period of time at a specific site (this high concentration would rapidly be diluted out in the bloodstream), or a relatively longer systemic exposure to a lower concentration of carbon monoxide (see, e.g., Hattler *et al.,* Artif. Organs 18(11):806-812, 1994; and Golob *et al.,* ASAIO J. 47(5):432-437, 2001).

Normobaric chamber

In certain instances, it would be desirable to expose the whole patient to carbon monoxide. The patient would be inside an airtight chamber that would be flooded with carbon monoxide (at a level that does not endanger the patient, or at a level that poses an acceptable risk without the risk of bystanders being exposed). Upon completion of the exposure, the chamber could be flushed with air (e.g., 21% O_2, 79% N_2), and samples could be analyzed by carbon monoxide analyzers to ensure no carbon monoxide remains before allowing the patient to exit the exposure system.

Aqueous Solutions

The present invention further contemplates that aqueous solutions comprising carbon monoxide can be created for systemic delivery to a patient, e.g., for oral delivery and/or by injection into the body, e.g., intravenously, intra-arterially, intraperitoneally and/or subcutaneously.

Preservation buffers and culture media can be saturated to a set concentration of carbon monoxide via gas diffusers or pre-made stock solutions that have been quality controlled to contain set levels of carbon monoxide. Accurate control of dose can be achieved via measurements with a gas permeable, liquid impermeable membrane connected to a carbon monoxide analyzer. The buffers and solutions can be saturated to desired effective concentrations and maintained at these levels. For procedures that require perfusion of a given organ, tissue, or cell preparation, pre-made saturated solutions can be on hand to maintain the levels of carbon monoxide. If carbon monoxide levels drop, fresh solutions can be added to replace those where carbon monoxide concentrations have dropped. Once the preparation of the organ, tissue or cell has been accomplished, it can be maintained in the solution in an airtight container for transport. The presence of the inert gas helium makes uptake of carbon monoxide more efficient.

Topical Treatment of Organs, Tissues, and Isolated Cells with Carbon Monoxide *in situ* and *ex vivo*.

The present invention features methods of transplanting an organ(s), tissues, masses of cells and/or isolated cells. The methods can include a step of exposing the organ(s), tissues, mass of cells and/or isolated cells to a carbon monoxide composition prior to transplantation. Such exposures can occur *in situ* and/or *ex vivo*. The organ(s), tissues and/or isolated cells may be exposed to an atmosphere comprising carbon monoxide gas, to a liquid carbon monoxide composition, e.g., a liquid perfusate, storage solution, or wash solution having carbon monoxide dissolved therein, or both.

Exposure of an organ or tissue to liquid carbon monoxide compositions can be performed *ex vivo* and/or *in situ* by any method known in the art. For example, the exposure may be performed *ex vivo* in any chamber or space having sufficient volume for submerging the

organ or tissue, completely or partially, in the carbon monoxide composition. As another example, the organ may be exposed to a carbon monoxide composition by placing the organ in any suitable container, and causing the carbon monoxide composition to "wash over" the organ, such that the organ is exposed to a continuous flow of the carbon monoxide composition.

Alternatively, the organ may be perfused with a carbon monoxide composition. The term "perfusion" is an art recognized term, and relates to the passage of a liquid, e.g., a carbon monoxide composition, through the blood vessels of an organ or tissue. Methods for perfusing organs *ex vivo* and *in situ* are well known in the art. An organ can be perfused with a carbon monoxide composition *ex vivo*, for example, by continuous hypothermic machine perfusion (see *Oxford Textbook of Surgery*, Morris and Malt, Eds., Oxford University Press, 1994). Optionally, in *in situ* or *ex vivo* perfusions, the organ can be perfused with a wash solution, e.g., UW solution without carbon monoxide, prior to perfusion with the carbon monoxide composition, to remove the donor's blood from the organ. Such a process could be performed to avoid competition for carbon monoxide by the donor's hemoglobin. As another option, the wash solution can be a carbon monoxide composition. An appropriate liquid may be passed through tubing that allows gas diffusion; this tubing runs through an atmosphere comprising carbon monoxide (e.g., through a chamber, such as with extracorporeal membrane oxygenation), to create a liquid carbon monoxide composition, which may then be passed into an organ (e.g., perfused into the organ by connecting the tubing to the organ).

The organ or tissue may be placed, e.g., submerged, in a medium or solution that does not include carbon monoxide, and placed in a chamber that exposes thee medium or solution to a carbon monoxide-containing atmosphere. Alternatively or in addition, carbon monoxide can be "bubbled" into the medium or solution. *In situ* exposures can be performed by any method known in the art, e.g., by *in situ* flushing or perfusion of the organ with a liquid carbon monoxide composition (see *Oxford Textbook of Surgery*, Morris and Malt, Eds., Oxford University Press, 1994).

The present invention contemplates that any or all of the above methods for exposing an organ or tissue to a liquid carbon monoxide composition, e.g., washing, submerging, or perfusing, can be used in a given transplantation procedure.

The present invention further contemplates that a solid or semi-solid carbon monoxide composition can be created. For example, a liquid that is a carbon monoxide composition, as

described above, can be made into a solid or semi-solid composition, in which an organ or tissue may be overlaid or embedded. Alternatively, a semi-solid carbon monoxide composition can be infused into the organ. Solid or semi-solid compositions can be made, for example, by adding a solidifying agent such as a gellingagent (e.g., collagen or alginate) to the liquid.

Cell Culture

The present invention features a method of maintaining or culturing an animal cell *in vitro*. The method can include the steps of providing a vessel containing a pressurized gas comprising carbon monoxide gas, providing an animal cell *in vitro* and releasing the pressurized gas from the vessel to form an atmosphere that includes the carbon monoxide gas. The animal cell is then cultured or simply maintained in the presence of the atmosphere comprising carbon monoxide gas.

The method can be performed in any chamber or space suitable for creating an atmosphere that includes appropriate levels of carbon monoxide gas. Such chambers or spaces include, e.g., incubators, mixing cylinders, and any vessel suitable for culturing or holding cells, such as roller bottles, cell culture flasks, petri dishes, and test tubes. For example, a CO_2 incubator may be used, wherein carbon monoxide gas is supplied in a continuous flow from a vessel that contains the gas. As another example, a roller bottle may be used, wherein carbon monoxide is included to create an appropriate atmosphere inside the roller bottle.

The skilled practitioner will appreciate that culture conditions, e.g., temperature, can be selected and/or varied depending upon the type of cell to be cultured (see, for example, *Cells: A Laboratory Manual*, Spector and Leinwand, Eds., Cold Spring Harbor Laboratory Press, Cold Spring Harbor, New York, 1997). For example, the murine insulinoma cell line βTC3 (DSMZ, Braunschweig, Germany) can be incubated in humidified 5% CO_2/95% air at 37°C.

The animal cell may be disposed, e.g., suspended or bathed in, a liquid medium. The medium can be any medium known to those of skill in the art to be suitable for culturing, preserving, or washing the cells of interest (see, for example, *Cells: A Laboratory Manual*, Spector and Leinwand, Eds., Cold Spring Harbor Laboratory Press, Cold Spring Harbor, New York, 1997). Such types of media include, but are not limited to, various buffers, Eagle's minimal essential medium (MEM), Dulbecco/Vogt modified Eagle's minimal essential medium (DMEM), or Roswell Park Memorial Institute (RPMI) Medium. Such media may also comprise appropriate supplements, e.g., fetal bovine serum (FBS), individual amino acids, antibiotics,

and/or vitamins. For example, the medium can be RPMI medium 1640 (Life Technologies, Grand Island, New York) supplemented with 2 mM L-glutamine, 100 U/ml penicillin G, 100 U/ml streptomycin and 10% Fetal Calf Serum (FCS) (Life Technologies). In those embodiments of the present invention wherein the cells are in a liquid medium, the cells can be exposed to a carbon monoxide composition by contacting the liquid medium with pressurized gas comprising carbon monoxide, e.g., with carbon monoxide gas released from a source of pressurized gas in accordance with the methods of the invention.

In another embodiment of the present invention, the liquid medium itself is a carbon monoxide composition, created as described above. The medium can be infused with carbon monoxide before or following addition of the cells to the medium.

The present invention further contemplates that a solid or semi-solid medium can be created wherein the solid or semi-solid medium is a carbon monoxide composition. For example, a liquid medium that is a carbon monoxide composition, as described above, can be made into a solid or semi-solid medium, in which cells may be overlaid or embedded. Such a process can be carried out, for example, by adding a gelling agent such as collagen, alginate or agar to a medium.

Use of Hemoxygenase-1, Compounds Associated with Hemoxygenase-1, and Other Compounds and Treatments

Also contemplated by the present invention is the induction or expression of hemeoxygenase-1 (HO-1) in conjunction with administration of carbon monoxide. HO-1 can be provided to a patient by inducing or expressing HO-1 in the patient, or by administering exogenous HO-1 directly to the patient. As used herein, the term "induce(d)" means to cause increased production of a protein, e.g., HO-1, in isolated cells or the cells of a tissue, organ or animal using the cells' own endogenous (e.g., non-recombinant) gene that encodes the protein.

HO-1 can be induced in a patient, e.g., a donor and/or recipient, by any method known in the art. For example, production of HO-1 can be induced by hemin, by iron protoporphyrin, or by cobalt protoporphyrin. A variety of non-heme agents including heavy metals, cytokines, hormones, nitric oxide, $COCl_2$, endotoxin and heat shock are also strong inducers of HO-1 expression (Otterbein *et al.*, Am. J. Physiol. Lung Cell Mol. Physiol. 279:L1029-L1037, 2000; Choi *et al.*, Am. J. Respir. Cell Mol. Biol. 15:9-19, 1996; Maines, Annu. Rev. Pharmacol.

Toxicol. 37:517-554, 1997; and Tenhunen *et al.*, J. Lab. Clin. Med. 75:410-421, 1970). HO-1 is also highly induced by a variety of agents and conditions that create oxidative stress, including hydrogen peroxide, glutathione depletors, UV irradiation and hyperoxia (Choi *et al.*, Am. J. Respir. Cell Mol. Biol. 15: 9-19, 1996; Maines, Annu. Rev. Pharmacol. Toxicol. 37:517-554, 1997; and Keyse *et al.*, Proc. Natl. Acad. Sci. USA 86:99-103, 1989). A "pharmaceutical composition comprising an inducer of HO-1" means a pharmaceutical composition containing any agent capable of inducing HO-1 in a patient, e.g., any of the agents described above, e.g., hemin, iron protoporphyrin, and/or cobalt protoporphyrin.

HO-1 expression in a cell can be increased via gene transfer. As used herein, the term "express(ed)" means to cause increased production of a protein, e.g., HO-1 or ferritin, in isolated cells or the cells of a tissue, organ or animal using an exogenously administered gene (e.g., a recombinant gene). The HO-1 or ferritin is preferably of the same species (e.g., human, mouse, rat, etc.) as the transplant recipient, in order to minimize any immune reaction. Expression could be driven by a constitutive promoter (e.g., cytomegalovirus promoters) or a tissue-specific promoter (e.g., milk whey promoter for mammary cells or albumin promoter for liver cells). An appropriate gene therapy vector (e.g., retrovirus, adenovirus, adeno associated virus (AAV), pox (e.g., vaccinia) virus, human immunodeficiency virus (HIV), the minute virus of mice, hepatitis B virus, influenza virus, Herpes Simplex Virus-1, and lentivirus) encoding HO-1 or ferritin would be administered to the patient orally, by inhalation, or by injection at a location appropriate for treatment of transplant rejection. Particularly preferred is local administration directly to the donor's organ, tissue or cells to be transplanted, or to the site of the transplant in the recipient. Similarly, plasmid vectors encoding HO-1 or apo-ferritin can be administered, e.g., as naked DNA, in liposomes, or in microparticles.

Further, exogenous HO-1 protein can be directly administered to a patient by any method known in the art. Exogenous HO-1 can be directly administered in addition to, or as an alternative, to the induction or expression of HO-1 in the patient as described above. The HO-1 protein can be delivered to a patient, for example, in liposomes, and/or as a fusion protein, e.g., as a TAT-fusion protein (see, e.g., Becker-Hapak *et al.*, Methods 24:247–256, 2001).

Alternatively or in addition, any of the products of metabolism by HO-1, e.g., bilirubin, biliverdin, iron, and/or ferritin, can be administered to a patient in conjunction with, or instead of, carbon monoxide in order to prevent or treat the disorder. Further, the present invention

contemplates that iron-binding molecules other than ferritin, e.g., desferoxamine (DFO), iron dextran, and/or apoferritin, can be administered to the patient. Any of the above compounds can be administered to the patient topically and/or systemically.

Also contemplated by the present invention is the administration of nitric oxide (NO) to a patient, organ(s), tissue(s) and/or isolated cells in conjunction with administration of carbon monoxide, HO-1 and/or HO-1 associated compounds. This technique includes providing NO to the donor, the recipient, or the gorgan, tissue or cell *ex vivo*, in conjunction with the administration of HO-1 and/or any or all of the products of heme degradation, e.g., CO, biliverdin, bilirubin, iron, and ferritin.

The term "nitric oxide" (or "NO") as used herein describes molecular nitric oxide in its gaseous state or dissolved in aqueous solution. Gaseous compositions comprising NO are typically administered by inhalation through the mouth or nasal passages to the lungs, where the NO may exert its effect directly or be readily absorbed into the patient's bloodstream. Compressed or pressurized gas, e.g., NO (and/or CO, as described in further detail above), useful in the methods of the invention can be obtained from any commercial source, and in any type of vessel appropriate for storing compressed gas. If desired, the methods of the present invention can be performed using multiple vessels containing individual gases. Alternatively, CO and NO can be combined in a single vessel, diluted if desired in an inert gas.

NO for inhalation is available commercially (e.g., INOmax™, INO Therapeutics, Inc., Clinton, NJ). The gas may be obtained from commercial supplier typically as a mixture of 200-800 ppm NO in pure N_2 gas. The source of NO can be essentially 100% NO, or diluted with N_2 or any other inert gas (e.g., helium) to any desired concentration. It is vital that the NO be obtained and stored as a mixture free of any contaminating O_2 or higher oxides of nitrogen, because such higher oxides of nitrogen (which can form by reaction of O_2 with NO) are potentially harmful to lung tissues. If desired, purity of the NO may be demonstrated with chemiluminescence analysis, using known methods, prior to administration to the patient. Chemiluminescence NO-NO_x analyzers are commercially available (e.g., Model 14A, Thermo Environmental Instruments, Franklin, MA). The NO-N_2 mixture may be blended with an O_2-containing gas (e.g., 100% O_2 or air) just prior to inhalation by the patient, using, for example, a calibrated rotameter that has been validated previously with a spirometer. The final concentration of NO in the breathing mixture may be verified with a chemical or

chemiluminescence technique well known to those in the field (e.g., Fontijin *et al.*, Anal Chem 42:575, 1970). Alternatively, NO and NO_2 concentrations may be monitored by means of an electrochemical analyzer. Any impurities such as NO_2 can be scrubbed by exposure to NaOH solutions, baralyme, or sodalime. As an additional control, the FiO_2 of the final gas mixture may also be assessed.

Pharmaceutical compositions comprising NO can be administered using any method in the art for administering gases to patients. Safe and effective methods for administration of NO by inhalation are described in, e.g., U.S. Patent No. 5,570,683; U.S. Patent No. 5,904,938; and Frostell *et al.*, Circulation 83:2038-2047, 1991. Some exemplary methods for administering gases (such as CO) to patients are described in detail above, and can be used to administer NO. Examples of methods and devices that can be utilized to administer gaseous pharmaceutical compositions comprising NO to patients include ventilators, face masks and tents, portable inhalers, intravenous artificial lungs (see, e.g., Hattler *et al.*, Artif. Organs 18(11):806-812, 1994; and Golob *et al.*, ASAIO J., 47(5):432-437, 2001), and normobaric chambers. However, the properties of NO may allow/necessitate some modification of these methods. In a hospital or emergency field situation, administration of NO gas can be accomplished, for example, by attaching a tank of compressed NO gas in N_2, and a second tank of oxygen or an oxygen/N_2 mixture (such as air), to an inhaler designed to mix gas from two sources. By controlling the flow of gas from each source, the concentration of NO inhaled by the patient can be maintained at an optimal level. NO can also be mixed with room air, using a standard low-flow blender (e.g., Bird Blender, Palm Springs, CA). NO can be generated from N_2 and O_2 (i.e., air) by using an electric NO generator. A suitable NO generator is described in U.S. Patent No. 5,396,882. In addition, NO can be provided intermittently from an inhaler equipped with a source of NO such as compressed NO or an electric NO generator. The use of an inhaler may be particularly advantageous if a second compound (e.g., a phosphodiesterase inhibitor as described in further detail below) is administered, orally or by inhalation, in conjunction with the NO.

Preferably, in a pharmaceutical composition comprising NO gas, the NO concentration at the time of inhalation is about 0.1 ppm to about 300 ppm, e.g., 0.5 ppm to 290 ppm, 1.0 ppm to 280 ppm, 5 ppm to 250 ppm, 10 ppm to 200 ppm, or 10 ppm to 100 ppm, in air, pure oxygen, or another suitable gas or gas mixture. A suitable starting dosage for NO administered by inhalation can be 20 ppm (see, e.g., INOmax™ package insert), and the dosage can vary, e.g.,

from 0.1 ppm to 100 ppm, depending on the age and condition of the patient, the disease or disorder being treated, and other factors that the treating physician may deem relevant. Acute, sub-acute and chronic administration of NO are contemplated by the present invention. NO can be delivered to the patient for a time (including indefinitely) sufficient to treat the condition and exert the intended pharmacological or biological effect. The concentration can be temporarily increased for short periods of time, e.g., 5 min at 200 ppm NO. This can be done when an immediate effect is desired. Preferred periods of time for exposure of a patient to NO include at least one hour, e.g., at least six hours; at least one day; at least one week, two weeks, four weeks, six weeks, eight weeks, ten weeks or twelve weeks; at least one year; at least two years; and at least five years. The patient can be exposed to the atmosphere continuously or intermittently during such periods. The administration of pharmaceutical compositions comprising NO (and/or CO) can be via spontaneous or mechanical ventilation.

When inhaled NO is administered, it is desirable to monitor the effects of the NO inhalation. Such monitoring can be used, in a particular individual, to verify desirable effects and to identify undesirable side effects that might occur. Such monitoring is also useful in adjusting dose level, duration and frequency of administration of inhaled NO in a given individual.

Gaseous NO can be dissolved in aqueous solution, and utilized in that form. For example, such a solution could be used to bathe an organ, tissue or cells *ex vivo*, or used to perfuse an organ or tissue *in situ*. The solution can contain other active agents such as CO, HO-1, heme, biliverdin, and/or bilirubin.

It may be desirable to prolong the beneficial effects of inhaled NO within the patient. In determining how to prolong the beneficial effects of inhaled NO, it is useful to consider that one of the in vivo effects of NO is activation of soluble guanylate cyclase, which stimulates production of cGMP. At least some of the beneficial effects of NO may result from its stimulation of cGMP biosynthesis. Accordingly, a phosphodiesterase inhibitor can be administered in conjunction with NO inhalation to inhibit the breakdown of cGMP by endogenous phosphodiesterases.

The phosphodiesterase inhibitor can be introduced into a patient by any suitable method, including via an oral, transmucosal, intravenous, intramuscular, subcutaneous or intraperitoneal route. Alternatively, the inhibitor can be inhaled by the patient. For inhalation, the

phosphodiesterase inhibitor is advantageously formulated as a dry powder or an aerosolized or nebulized solution having a particle or droplet size of less than 10 μm for optimal deposition in the alveoli, and may optionally be inhaled in a gas containing NO.

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A suitable phosphodiesterase inhibitor is ZaprinastÕ (M&B 22948; 2-o-propoxyphenyl-8-azapurine-6-one; Rhone-Poulenc Rorer, Dagenham Essex, UK). ZaprinastÕ selectively inhibits the hydrolysis of cGMP with minimal effects on the breakdown of adenosine cyclic-monophosphate in vascular smooth muscle cells (Trapani *et al.*, J Pharmacol Exp Ther 258:269, 1991; Harris *et al.*, J Pharmacol Exp Ther 249:394, 1989; Lugnier *et al.*, Biochem Pharmacol 35:1743, 1986; Souness *et al.*, Br J Pharmacol 98:725, 1989). When using ZaprinastÕ according to this invention, the preferred routes of administration are intravenous or oral. The suitable dose range may be determined by one of ordinary skill in the art. A stock solution of ZaprinastÕ may be prepared in 0.05 N NaOH. The stock can then be diluted with Ringer's lactate solution to the desired final Zaprinast concentration, immediately before use.

This invention can be practiced with other phosphodiesterase inhibitors. Various phosphodiesterase inhibitors are known in the art, including Viagra® (sildenafil citrate) dipyridamole and theophylline. A suitable route of administration and suitable dose range can be determined by one of ordinary skill in the art.

Administration of NO with phosphodiesterase inhibitors can be performed as follows. The NO is administered at 20 ppm in air for 45 min. At the start of the 45 min period, 1.0 mg of ZaprinastÕ per kg body weight is administered by intravenous infusion over 4 min, followed by a continuous infusion of 0.004 mg/kg/min for the rest of the 45 min period. Alternatively, at the start of the 45 min period, 0.15 mg dipyridamole per kg body weight is administered over 4 min, followed by a continuous infusion of 0.004 mg/kg/min for the rest of the 45 min period. The ZaprinastÕ or dipyridamole is administered in a saline solution.

In the context of transplantation, the present invention further contemplates that other procedures known in the art for enhancing graft survival/function can be used along with the methods described herein. Such procedures include, but are not limited to immunosuppressive therapies and donor specific transfusions (DSTs). For example, a DST can be administered to a recipient prior to, during and/or after the administration of CO, HO-1, other heme-associated products, and/or NO to a recipient. Such administration, e.g., administration of DST(s) along with a treatment described herein, can be carried out prior to, during, and/or after transplantation.

Example I. Carbon Monoxide Protects Pancreatic Beta Cells from Apoptosis and Improves Islet Function/Survival After Transplantation

Cell cultures

The murine insulinoma cell line βTC3 (DSMZ, Braunschweig, Germany) was cultured in Dulbecco's Modified Eagle's Medium (DMEM) (Life Technologies, Grand Island, NY, USA) supplemented with 2mM L-glutamine, l00U/ml penicillin G, l00U/ml streptomycin and 10% Fetal Calf Serum (FCS) (Life Technologies) and incubated in humidified 5% CO_2/95% air at 37°C. This murine β-cell line, derived from transgenic mice carrying a hybrid insulin-promoter simian virus 40 tumor antigen, is known to maintain the features of differentiated β-cells for about 50 passages in culture. The cells produce mature insulin from proinsulin I and II in a manner comparable to β-cells *in vivo* and are inducible up to 30 fold by glucose (Efrat *et al.*, Proc. Natl. Acad. Sci. USA 85:9037-41, 1988). Compared to other frequently used transformed β-cell lines such as RIN-m5F and HIT, levels of secreted insulin are closer to normal β-cells in the βTC3 cell line. Thus, these cells are useful for studying β-cell regulation and gene expression (D'Ambra *et al.*, Endocrinology 726:2815-22, 1990).

Pancreatic islets of Langerhans of C57BL/6 mice were supplied by the islet isolation core facility of the Joslin Diabetes Center.

Crystal violet vital staining

βTC3 were seeded at 2 x 10^5 cells (Nunc, Marsh Products, Rochester, NY, USA). Cells were washed once with 500 μl PBS and stained with 200 μl 0.05% Crystal Violet in 20% ethanol for 10 min at RT. Crystal Violet was rinsed. To elute stain from cells, 100 μl 50% acetic acid were added to each well. 50 μl were transferred into a 96 well microtiter plate and read with a microtiter plate reader (EL 340 biokinetics reader, Bio-Tek Instruments) at an absorbance of 562 nm.

Expression plasmids

The β–galactosidase expression vector (Clontech Laboratories, Palo Alto, California) was cloned into the pcDNA3 vector (Sato *et al.*, J. Immunol. 166:4185-4194, 2001). (Invitrogen, Carlsbad, California). A 1.0 kbp X*ho*I-H*ind*III fragment encoding the full length rat HO–1 cDNA was cut from the prHO–1 vector (Shibahara *et al.*, J. Biochem. 113:214-218, 1993) and sub-cloned into the pcDNA3 vector.

Transient transfections

βTC3 were seeded at 3 x 10^5 cells in 16 mm wells and transfected 15 to 20 hours later using Lipofectamine plus™ reagents (Life Technologies) according to the manufacturer's instructions. Total DNA was maintained constant using empty pcDNA3 vector. The percentage of viable cells was assessed by normalizing the percentage of viable cells of each DNA preparation to the number of control-transfected cells without the apoptotic stimulus (100% viability) (Soares *et al.*, Nature Med. 4:1073-1077, 1998; Sato *et al.*, J. Immunol. 166:4185-4194, 2001).

Flow Cytometry

βTC3 cultures were incubated with recombinant TNF-α (500 or 1000 U/ml) (R&D Systems) for 24 hours and islet cultures were stimulated with TNF-É (5000U/ml) (R&D Systems) and cyclohexamide (CHX) (50 μg/ml) for 48 hours. βTC3 or islets were harvested,

dispersed, fixed in 70% ethanol, and suspended in DNA staining buffer (PBS, pH 7.4, containing 0.1% Triton X-100, 0.1 mM EDTA, 50 μg/ml propidium iodide, 50 mg/ml Rnase A). DNA content was analyzed on a FACScan™ analyzer equipped with Cell QuestÕ Software (Becton Dickinson, Palo Alto, CA). Cells with a normal DNA content (2N) were scored as viable, whereas cells with a hypoploid DNA content (<2N, termed A^0) were scored as apoptotic. To exclude debris and apoptotic cell-free fragments, all events with an FL-2 area profile below that of chicken erythrocyte nuclei were excluded from analysis.

Cell treatment and reagents

Murine recombinant TNF–α (R&D Systems) was dissolved in PBS with 1% bovine serum albumin and added to the culture medium (17.5 ng/ml = 500 U) 24 hours after transfection. The caspase–3 inhibitor Z–DEVD–FMK and the caspase–8 inhibitor IETD–CHO (Calbiochem, San Diego, California) were dissolved in dimethyl sulphoxide (DMSO, Sigma) and added to the culture medium (10 μM and 1 μM respectively) two hours before treatment with TNF–α. Tin protoporphyrin (SnPPIX) (Porphyrin Products, Logan, Utah) was dissolved (10 mM) in 100 mM NaOH and added 6 hours after transfection to the culture medium (50 μM). The guanylyl cyclase inhibitor 1H[1,2,4]oxadiazolo[4,3-α]quinoxalin-1 (ODQ; Calbiochem) was dissolved in DMSO and added to the culture medium (100 μM) 6 hours after transfection. The cGMP analogue 8-bromoguanosine-3'-5'-cyclic-monophosphate (8–Br–cGMP) (Sigma) was dissolved in water and added to the culture medium (10 μM) 30 minutes before induction of apoptosis. The protein kinase G inhibitor KT5823 (Calbiochem) was dissolved in DMSO and added to the culture medium (1.6 μM) 6 hours after transfection.

CO exposure

Cells and islets were exposed to 1% carbon monoxide in compressed air balanced with 5% CO_2, as described elsewhere (see, e.g., Otterbein *et al.*, Nature Med. 6:422-428, 2000). Islets were incubated in RPMI medium pre-saturated with carbon monoxide (4 °C overnight, 1% CO, 5% CO_2) for two hours at 37°C while treatment with 1% CO, 5% CO_2 was continued.

Mice and induction of diabetes

Male C57BL/6 were purchased from Charles River Laboratories (Wilmington,

Massachusetts) and housed in accordance with guidelines from the NIH. The experiments were approved by the Institutional Animal Care and Use Committee (IACUC). Recipient mice (8 weeks old) were rendered diabetic by a single intraperitoneal injection (220 mg/kg) of Streptozotocinõ (Sigma) dissolved in citrate buffer. Mice received transplants if 2 consecutive non-fasting blood glucose levels of greater than 350 mg/dl were obtained from a whole blood sample.

Islet isolation

Pancreatic islets of Langerhans (C57BL/6 mice) were provided by the Islet Core Laboratory of the JDRF Center for Islet Transplantation at Harvard Medical School and isolated as described previously (Gotoh *et al.*, Transplantation 40:437-438, 1985).

Syngeneic marginal mass islet transplantation

250 islets 150-250 îm in diameter were hand-picked using a dissecting microscope. Islets were transplanted under the kidney capsule as described previously (Kaufman *et al.*, J. Exp. Med. 172:291-302, 1990). From each islet preparation the same numbers of control and treatment animals were transplanted.

Graft functional outcome analysis

Graft function was defined as the point when the first of three consecutive days of non-fasting blood glucose levels <200mg/dl was reached. The primary endpoint of the experiment was defined as time to normoglycemia.

Statistical analysis

Blood glucose data were summarized as mean ± standard deviation of mice receiving untreated or treated islets. Time to recovery of islet function was calculated using Kaplan-Meier life tables and differences between groups tested using a log-rank test, with the three islet preparations treated as separate strata in the analysis, and the median time to recovery, with 95% confidence interval, reported.

TNF-α induces apoptosis in βTC3 cells

The effect of TNF-α on βTC3 cells was investigated. The following procedures were utilized to generate the data illustrated in Figs. 1A-C. Fig. 1A: βTC3 were treated with increasing concentrations of TNF–α. Viable cells were stained 24 hours after activation by crystal violet. The extinction was measured at 562 nm and normalized to untreated cells. Fig. 1B: βTC3 were treated with TNF–α, stained by propidium iodide 24 hours later and analyzed for DNA fragmentation (FACScan™). Fig. 1C: βTC3 were co-transfected with a β–gal expressing vector (pcDNA3/β–gal) plus control (pcDNA3). When indicated, cells were treated with the caspase–3 inhibitor Z–DEVD–FMK (C3–i) or the caspase–8 inhibitor IETD–CHO (C8–i). Gray histograms represent untreated β–cells and black histograms represent β–cells treated with TNF–α for 24 hours. Results shown are the mean ± standard deviation from duplicate wells taken from one representative experiment out of three.

TNF–α induced high levels of cell death in the insulinoma cell line βTC3, in a dose-dependent manner (Stephens *et al.*, Endocrinology 140:3219-3227, 1999) (Fig. 1A). DNA fragmentation was demonstrated by propidium iodide (PI) staining (Fig. 1B), suggesting that TNF-α induces β–cell death through apoptosis. TNF-α mediated apoptosis was strictly dependent on the activation of caspase–8 and partially dependent on that of caspase–3, as illustrated by the finding that blocking caspase–8 with a specific caspase–8 inhibitor (IETD–CHO) prevented apoptosis (96% inhibition) while blocking caspase–3 by a specific caspase–3 inhibitor (Z–DEVD–FMK) prevented apoptosis only partially (53% inhibition) (Fig. 1C).

Carbon monoxide protects βTC3 cells

Whether exogenous carbon monoxide could protect β–cells from apoptosis was investigated (Figs. 2A-C). The following procedures were utilized to generate the data illustrated in Figs. 2A-C. Fig. 2A: Exogenous CO can substitute for HO–1 when HO–1 activity is blocked. βTC3 were co-transfected with a β–gal expressing vector plus control or HO–1-expressing rector (Brouard *et al.*, J. Exp. Med. 192:1015-1026, 2000). When indicated, HO–1 enzymatic activity was inhibited by tin protoporphyrin (SnPP). When indicated, β–cells were exposed to exogenous carbon monoxide (1%) as described earlier (Otterbein *et al.*, Nature Med. 6:422-428, 2000).. Gray histograms represent untreated β–cells and black histograms represent

β–cells treated with TNF–α. Results shown are mean ± standard deviation from duplicate wells taken from one representative experiment out of three. Fig. 2B: Exogenous carbon monoxide protects β-cells from apoptosis in the DNA fragmentation analysis. βTC3 were treated with TNF–α. Directly after stimulation, βTC3 were exposed to exogenous carbon monoxide for 24 hours. Control βTC3 were treated in the same manner but not exposed to carbon monoxide. After 24 hours cells were stained by propidium iodide and analyzed for DNA fragmentation on a FACScan™. Fig. 2C: Exogenous carbon monoxide protects β–cells from apoptosis in absence of HO–1. βTC3 were transfected with β–gal expressing vectors and were exposed to exogenous carbon monoxide (Stephens *et al.*, Endocrinology 740:3219-27, 1999). Gray histograms represent untreated β–cells and black histograms represent β–cells treated with TNF–α or etoposide or subjected to serum deprivation as indicated. Results shown are mean ± standard deviation from duplicate wells taken from one representative experiment out of three.

To evaluate whether expression of HO–1 would protect β-cells from TNF-α mediated apoptosis, βTC3 cells were transiently transfected with a HO–1 expression vector and tested for their ability to survive when exposed to TNF-α. Over-expression of HO–1 protected βTC3 from TNF-α mediated apoptosis (Pileggi *et al.*, Diabetes 50:1983-1991, 2001) (87% survival versus 33% in control) (Fig. 2A). When HO–1 activity was blocked by tin protoporphyrin IX (SnPPIX) (Kappas *et al.*, Hepatology 4:336-341, 1994), the anti-apoptotic effect was suppressed (Fig. 2A), suggesting that the generation of at least one of the end products of heme catabolism by HO–1, i.e. iron, bilirubin and/or CO, is required for its anti-apoptotic function.

On the hypothesis that the anti-apoptotic effect of HO–1 could be mediated by carbon monoxide, whether exposure to exogenous carbon monoxide would substitute for HO–1 in protecting β–cells from apoptosis was tested. When the action of HO–1 was suppressed by SnPPIX, carbon monoxide exposure suppressed TNF–α mediated apoptosis to a similar extent as HO–1 (Fig. 2A). Exposure to exogenous carbon monoxide alone was protective (11.7% apoptotic cells versus 20.3% in controls not exposed to CO), as demonstrated by DNA fragmentation analysis (Fig. 2B). Similarly, β–cell apoptosis induced by etoposide or serum starvation was suppressed by carbon monoxide exposure (Fig. 2C).

Induction of HO-1 in Donors and Recipients Leads to Prolonged Islet Graft Survival

Whether induction of HO-1 in donors and recipients would protect islet cell grafts was investigated. The following procedures were utilized to generate the data illustrated in Table 1, below. A mouse model was utilized for the experiments. Donors of islet cells were treated with cobalt protoporphyrin (CoPP) (20 mg/kg) once per day before islet cell isolation. Recipients of islet cell grafts were treated with CoPP (20 mg/kg) once per day on days 1, 3, 5, 7 or with CoPP (10 mg/kg) once per day on days 1, 3, 5, 7, 9, 11, 13, 15, and 17. Treatment with CoPP induces expression of heme oxygenase-1 (HO-1).

Table I

Induction of HO-1 in Donors and Recipients Leads to Prolonged Islet Graft Survival

Treatment	No. of Islets	Rejection day	Mean±SD	Rejection/ Total
CoPP 20 mg/kg x 5	350-400	17, 33, 33, 48, >58x2, >67x1	44.85±17.81	4/7
CoPP 10 mg/kg x 10	350-400	30, 30, >51x2	40.5±12.12	2/4
Control	350-400	8,8,15,15,16,22,26	15.71±6.65	7/7

Listed under "rejection day" are the days to which islets survived. For instance, ">51x2", means that islets in 2 recipients were still surviving after 51 days. The mean date of rejection is shown in the fourth column. These data demonstrate that induction of HO-1 results in longer survival of islets after transplantation.

Exogenous carbon monoxide protects murine islet cells from apoptosis

Whether exogenous carbon monoxide protects murine islet cells from apoptosis was also investigated (Fig. 3). The following procedures were utilized to generate the data illustrated in Fig. 3. Apoptosis was induced in freshly isolated murine islets (C57BL/6) by stimulation with TNF–α and cycloheximide (CHX). Directly after stimulation, islets were exposed to exogenous carbon monoxide for 24 hours. Control islets were treated in the same manner but not exposed to carbon monoxide. After 48 hours cells were analyzed on a FACScan™ for DNA fragmentation. This experiment was done twice with indistinguishable results.

Exposure to carbon monoxide for 24 hours protected isolated murine (C57/BL6) islets of Langerhans from TNF–α plus cycloheximide (CHX) mediated apoptosis (11.7% apoptotic cells versus 20.3% in controls not exposed to CO) as assayed by DNA fragmentation analysis (Fig. 3).

The anti-apoptotic effect of exogenous carbon monoxide is mediated by guanylate cyclase activation and signals through cGMP-dependant protein kinases (cGK)

Whether the anti-apoptotic effect of carbon monoxide acted via activation of soluble guanylate cyclase (sGC) and generation of cGMP was investigated (Figs. 4A-C). The following procedures were utilized to generate the data illustrated in Figs. 4A-C. Fig. 4A: The anti-apoptotic effect of exogenous carbon monoxide is mediated by guanylate cyclase activation. βTC3 were transfected with β–gal expressing vectors and exposed to exogenous carbon monoxide (1%). Where indicated, βTC3 were treated with the guanylyl cyclase inhibitor ODQ. Fig. 4B: A cGMP analogue can substitute for carbon monoxide in protecting from apoptosis. βTC3 were transfected with β–gal expressing vectors. Where indicated, βTC3 were exposed to exogenous carbon monoxide. Where indicated, βTC3 were treated with the cGMP analogue 8–Br–cGMP but not exposed to carbon monoxide. Fig. 4C: cGMP-dependent protein kinases (cGK) mediate the anti-apoptotic effect of carbon monoxide. βTC3 were co-transfected with β–gal expressing vector. When indicated, βTC3 were exposed to exogenous carbon monoxide. When indicated, cells were treated with the protein kinase G inhibitor KT5823 (KT). Gray histograms represent untreated β–cells and black histograms represent β–cells treated with TNF–α. Results shown are mean ± standard deviation from duplicate wells taken from one representative experiment out of three.

Whether the anti-apoptotic effect of carbon monoxide acted via activation of soluble guanylate cyclase and generation of cGMP (as described in fibroblasts) was investigated (Petrache *et al.*, Am. J. Physiol. Lung Cell Mol. Physiol. 278:L312-319, 2000). Inhibition of sGC activity by oxadiazoloquinoxalin (ODQ) suppressed the anti-apoptotic effect of CO, suggesting that a soluble guanylate cyclase is a major mediator for carbon monoxide in this experimental system (Fig. 4A). The cGK activator/cGMP analogue, 8–Br–cGMP, suppressed βTC3 apoptosis to an extent similar to that seen with carbon monoxide (Fig. 4B). Also, inhibition of cGMP-dependent protein kinases by the specific inhibitor KT5823 suppressed the anti-apoptotic effect of exogenous carbon monoxide (Fig. 4C), suggesting that the anti-apoptotic effect of carbon monoxide is mediated through the activation of one or several cGMP-dependent protein kinases.

Exogenous carbon monoxide provided anti-apoptotic protection under various protocols

The ability of carbon monoxide to protect β-cells after induction of apoptosis was investigated (Figs. 5A-C). The following procedures were utilized to generate the data illustrated in Figs. 5A-C. Fig. 5A: one hour of carbon monoxide exposure is sufficient to prevent apoptosis. βTC3 were transfected with β–gal expressing vectors. Apoptosis of β–cells was induced by TNF–α. Immediately after TNF-α activation, cells were exposed to 1% carbon monoxide for varying periods (0-24 hours). Control βTC3 were treated in the same manner but were not exposed to carbon monoxide. Cell survival was determined 24 hours after application of TNF–α. Fig. 5B: carbon monoxide protects β–cells after induction of apoptosis. βTC3 were transfected with β–gal expressing vectors. Apoptosis was induced by TNF–α. After varying periods (0.5-12 hours, as indicated), βTC3 were exposed to 1% carbon monoxide (Otterbein *et al.*, Nat. Med, 6:422-428, 2000). Control βTC3 were treated in the same manner but were not exposed to carbon monoxide. Cell survival was determined 24 hours after application of TNF–α. Fig. 5C: Preincubation with carbon monoxide prevents β–cell apoptosis. βTC3 were transfected with β-gal expressing vectors and apoptosis was induced by TNF–α. βTC3 were pre-exposed to 1% carbon monoxide for one hour. Control βTC3 were treated in the same manner but were not exposed to carbon monoxide. 1–6 hours after termination of the pre-exposure, apoptosis was induced by TNF–α. Gray histograms represent untreated β–cells and black histograms represent β–cells treated with TNF–α. Results shown are mean ± standard deviation from duplicate wells taken from one representative experiment out of three.

βTC3 were exposed to carbon monoxide for different time periods (1–24 hours) immediately after the addition of TNF–α and tested for apoptosis 24 hours later. One hour of carbon monoxide exposure was sufficient to prevent β–cell apoptosis (Fig. 5A).

To investigate whether carbon monoxide exposure can block ongoing apoptosis, β–cells were exposed for one hour to CO, 0.5 to 12 hours after induction of apoptosis by TNF–α. Even when exposed two hours after TNF–α stimulation, carbon monoxide was still able to suppress β–cell apoptosis (Fig. 5B).

To investigate whether pre-incubation with carbon monoxide would protect β–cells from apoptosis, βTC3 were exposed to carbon monoxide for 0.5 to 3 hours before apoptosis induction. One hour pre-incubation in the presence of carbon monoxide was sufficient to prevent β–cell apoptosis (data not shown). To evaluate for how long this effect would last when the time

between pre-incubation and the apoptotic stimulus was extended, β–cells were preexposed for one hour to CO, one to six hours before induction of apoptosis with TNF–α (Fig. 5C). One hour of pre-incubation with carbon monoxide prevented β–cell apoptosis in cells stimulated with TNF–α even two to three hours after the end of the one-hour treatment with carbon monoxide. These data indicate that relatively brief treatment with carbon monoxide can act in an anti-apoptotic manner and that this anti-apoptotic effect will last for an extended time period.

Exposure of murine islets to carbon monoxide improves islet survival/function following transplantation

To determine whether carbon monoxide could also improve islet graft function *in vivo*, a marginal islet mass of 250 handpicked islets was transplanted in a syngeneic system, a model for primary non-function (Berney *et al.*, Transplantation 71:125-32, 2001); Kaufman *et al.*, Diabetes 43:778-83, 1994). Transplantation of a marginal (e.g., sub-optimal) number of islets (a "marginal mass") into a diabetic syngeneic recipient causes a delay in the return to normoglycemia without the effects of rejection or recurrence of auto-immune disease. In determining what would be a marginal islet mass in the C57/BL6 syngeneic system, it was observed that transplantation of 500 handpicked islets under the kidney capsule of the recipient led to rapid return to normoglycemia (1.5 ± 0.5 days (n=4)) whereas transplantation of 250 islets resulted in a significant delay (14.2 ± 2.94 days (n=9)). Thus, 250 islets were defined as a marginal mass. Using a marginal mass in this manner does not involve rejection or recurrence of auto-immune disease (Berney *et al.*, Transplantation 71:125-132, 2000).

Whether carbon monoxide pre-incubation of islet grafts prior to transplantation results in better functional performance *in vivo* was investigated (Figs. 6A-B). The following procedures were utilized to generate the data illustrated in Figs. 6A-B. Fig. 6A: Two hundred and fifty freshly isolated and hand-picked islets from C57BL/6 mice were incubated in medium pre-saturated with 1% carbon monoxide for two hours at 37°C. Control islets were treated in the same manner but were not exposed to carbon monoxide. The islets were transplanted under the kidney capsule of the diabetic syngeneic recipients as described previously. After transplantation, blood glucose levels were determined on a daily basis. A total of 16 animals (8 with pre-exposed islets; 8 controls) were transplanted. One animal receiving pre-exposed islets died on day 3 of non-exposure related technical reasons and was included in the statistical analysis as censored animal. The primary endpoint of these experiments was the first day of

normoglycemia. Data are shown as mean ± standard deviations. Fig. 6B: indicates the probability of recovery (blood glucose level below 200 mg/dl) for animals receiving islets pre-exposed to carbon monoxide or control islets. *$P = 0.001$ versus control.

Based on the observation that the effects of carbon monoxide treatment last for an extended time period (Figs. 5A and B) and that relatively brief pre-treatment with carbon monoxide (before the apoptotic stimulus is applied) is anti-apoptotic (Fig. 5C), whether pre-exposure of islets to carbon monoxide can improve islet survival and/or function following transplantation was evaluated. A marginal islet mass was transplanted under the kidney capsule of diabetic syngeneic recipients. The time needed to reach normoglycemia was reduced in a highly significant manner ($P = 0.0011$) when islets were pre-incubated for two hours in medium pre-saturated with carbon monoxide (7 days, 95% confidence interval: 6–8 days) as compared to control islets not pre-exposed to carbon monoxide (14 days, 95% confidence interval 12–18 days) (Fig. 6). In total, three different islet preparations were used for these experiments. There was no statistically significant difference in the time to normoglycemia for islets among these three preparations ($P > 0.25$).

Carbon monoxide exposures

For cell culture experiments, 5% CO_2 was present for buffering requirements. CO at a concentration of 1% (10,000 ppm) in compressed air was mixed with compressed air with or without CO_2 in a stainless steel mixing cylinder before delivery into the exposure chamber. Flow into the 3.70-ft^2 plexiglass animal chamber was maintained at 12 L/min and into the 1.2-ft^2 cell culture chamber at a flow of 2 L/min. The cell culture chamber was humidified and maintained at 37°C. A CO analyzer (Interscan, Chatsworth, CA) was used to measure CO levels continuously in the chambers. Gas samples were taken by the analyzer through a port in the top of the chambers at a rate of 1 L/min and analyzed by electrochemical detection, with a sensitivity of 10-600 ppm. Concentration levels were measured hourly. There were no fluctuations in the CO concentrations once the chamber had equilibrated (approximately 5 min).

Animals were exposed to > 98% O_2 or 98% O_2 + CO mixtures at a flow rate of 12 liters/min in a 3.70-cubic-foot glass exposure chamber. Animals were supplied food and water during the exposures. CO at a concentration of 1% (10,000 ppm) in compressed air was mixed with >98% O_2 in a stainless steel mixing cylinder prior to entering the exposure chamber.

By varying the flow rates of CO into the mixing cylinder, concentrations delivered to the exposure chamber were controlled. Because the flow rate was primarily determined by the O_2 flow, only the CO flow was changed to generate the different concentrations delivered to the exposure chamber. O_2 concentrations in the chamber were determined using a gas spectrometer.

Cell Isolation Procedure

The following example illustrates a protocol used for the isolation of islet cells from rats or mice. One bottle of Rat Liberase© (from Boehringer Manheim/Roche cat. # 1 815 032) was dissolved in 4 ml of sterile HBSS, chilled on ice for 30 min, aliquoted into 0.5 ml aliquots, and stored at -20°C. To each 0.5 ml aliquot, 33 ml of medium, e.g., M199, HBSS or RPMI 1640 without calf serum, was added.

Rats were overdosed with anesthesia (.1 ml plus .1 ml/100g body weight of Nembutol I.P.). For mice, 3ml syringes were prepared with 2 ml of Liberase solution with a 27 g-needle bent at a 90-degree angle. For the surgery, 2 pairs of scissors were used; one large pair for the abdominal cut and one fine pair to snip the bile duct. Two pairs of forceps were used for excision of the pancreas. One hemostat was used to clamp off the bile duct.

The abdomen was opened and the pancreas was exposed as much as possible by making a v cut from the lower abdomen. The pancreatic duct was clamped off (with a hemostat in rats or a small bulldog clamp in mice) at its duodenal insertion, taking care not to injure the surrounding pancreatic tissue. The bile duct was isolated at the proximal end. Fat was removed before inserting the cannula, making sure not to puncture the portal vein. The duct was cut with the fine scissors one third of the way across and the cannula was inserted in the duct. The cannula was held in the duct by clamping the duct lightly with forceps. Liberase© solution was injected rapidly. The pancreas appeared to be distended and fully dilated after 6 mls of fluid injection. In mice, the needle was inserted into the duct as proximal to the liver as possible and Liberase© solution was injected. The rat or mouse was then sacrificed by cutting the diaphragm and heart or aorta.

After Liberase© infiltration, the pancreas was removed, starting by removing from the intestines, then the stomach and then the spleen. When the pancreas was attached only by the bile duct, it was cut out of the rat. The pancreas was placed in a 50 ml conical tube, and placed in a water bath at 37°C for 30 min.

Following incubation, 20 ml of medium + NCS were added to each tube. The remainder of the isolation was completed on ice. Tubes were shaken by hand vigorously for 5-10 seconds to break up the tissue. The islets were washed several times to remove the LiberaseÕ in a clinical centrifuge at 800 rpm (approx. 180 xg) for 120 sec or 1200 rpm (approx. 200 xg) for 90 sec. The supernatant was poured off and 25-35 ml of medium was added and vortexed gently (about 1/2 max.). The centrifugation step was repeated, followed by washing 2-3 times. The tissue was resuspended in 20 ml of medium, and the suspension was filtered through a 400 îm diameter wire mesh (Thomas scientific mesh 35 cat. # 8321-M22) to remove the remaining undigested tissue, fat and lymph. 5-10 ml more was added to the tube to wash any remaining islets off and filter through the mesh.

The cells were pelleted by spinning at 1200 rpm for 90 sec. The supernatant was removed, leaving as little excess medium as possible.

To make the gradient, the pellet was resuspended in 10-15 ml Histopaque 1077Õ (Sigma cat # H 1077) and vortexed until the suspension was homogeneous (same as for washes). 10 ml of medium was overlaid, without NCS, being careful to maintain the sharp interface between the HistopaqueÕ and the medium. The medium was added by pipetting slowly down the side of the tube. The gradient was centrifuged for 20 minutes at 2400 rpm (900 g) at 10°C with very slow acceleration and no braking.

Following centrifugation, the islet layer was collected from the interface with a disposable 10cc serologic pipette (Falcon), and placed in 50 cc conical tubes. Islets were washed several times to remove the HistopaqueÕ by adding 25-35 ml of the medium + NCS. The initial centifugation was performed at 1200 rpm for 2 min., but the subsequent centrifugations were performed for 90 sec. After the 3 washes, the islets were resuspended by pipetting up and down. 7-10 ml each were put on 60 mm sterile culture dishes for hand picking.

Hand picking of islet cells was performed using a 100 îl sterile pipette tip, under a microscope. Each islet was picked individually, and care was taken to avoid all other tissue. Only those islets between 50 and 225 îm in diameter exhibiting a smooth and round or oval shape were picked.

Example II. Carbon Monoxide Suppresses the Rejection of Mouse-to-Rat Cardiac Transplants

Animals

BALB/c mouse hearts were used as donor organs for transplantation into inbred adult male Lewis rats (Harlan Sprague-Dawley, Indianapolis, IN). Animals were housed in accordance with guidelines from the American Association for Laboratory Animal Care, and research protocols were approved by the Institutional Animal Care and Use Committees of the Beth Israel Deaconess Medical Center.

Surgical model

Animals were anesthetized by a combination of methoxyflurane (Pitman-Moore, Mundelain, IL) inhalation and pentobarbital (Abbott, North Chicago, IL) at a dose of 30–50 mg/kg i.p. during all procedures. Heterotopic cardiac transplants were performed as described previously (Berk *et al.*, Physiol Rev. 8:999-1030, 2001; Petkova *et al.*, J Biol. Chem. 276:7932-7936, 2001). Graft survival was assessed daily by palpation. Rejection was diagnosed by cessation of ventricular contractions and confirmed by histologic examination.

Experimental reagents

Cobra venom factor (CVF; which blocks complement activation) (Quidel, San Diego, CA) was administered i.p. on day -1 (60 U/kg) and on day 0 (20 U/kg) with respect to the day of transplantation (day 0). Cyclosporin A (CsA; Novartis, Basel, Switzerland), which blocks T cell activation, was administered i.m. (15 mg/kg) starting at day 0 and daily thereafter until the end of each experiment. Tin protoporphyrin (SnPPIX), cobalt protoporphyrin (CoP-PIX), and iron protoporphyrin (FePPIX; Porphyrin Products, Logan, UT) were diluted in 100 mM NaOH to a stock solution of 50 mM and kept at -70°C until used. Light exposure was limited as much as possible. Both SnPPIX and FePPIX were administered i.p. (30 μM/kg) in PBS. FePPIX and SnPPIX were administered to the donor at days -2 and -1 (30 μM/kg) and to the recipient at the time of transplantation (day 0) and daily thereafter (30 μM/kg).

CO exposure

Briefly, CO at a concentration of 1% (10,000 parts per million; ppm) in compressed air was mixed with balanced air (21% oxygen) in a stainless steel mixing cylinder before entering the exposure chamber. CO concentrations were controlled by varying the flow rates of CO in a

mixing cylinder before delivery to the chamber. Because the flow rate is primarily determined by the O_2 flow, only the CO flow was changed to deliver the final concentration to the exposure chamber. A CO analyzer (Interscan Corporation, Chatsworth, CA) was used to measure CO levels continuously in the chamber. Graft donors were placed in the CO exposure chamber 2 days before transplantation. Graft recipients were placed in the exposure chamber immediately following transplantation and were kept in the exposure chamber for 14 *(n* = 3) or 16 *(n* = 3) days. CO concentration was maintained between 250 and 400 ppm at all times. Animals were removed daily from the chamber to assess graft survival and to administer CsA, SnPPIX, or FePPIX, as described above.

HO enzymatic activity

HO enzymatic activity was measured by bilirubin generation in heart and liver microsomes. Animals were sacrificed, and the liver and hearts were flushed with ice-cold PBS and frozen at -70°C until used. Organs were homogenized in four volumes of sucrose (250 mM) Tris-HCl (10 mM/L) buffer (pH 7.4) on ice and centrifuged (28,000 RPM 3X, 20 min, 4°C). The supernatant was centrifuged (105,000 RPM 3X, 60 min, 4°C), and the microsomal pellet was resuspended in $MgCl_2$ (2 mM)-potassium phosphate (100 mM) buffer (pH 7.4) and sonicated on ice. The samples (1 mg of protein) were added to the reaction mixture (400 îl) containing rat liver cytosol (2 mg of protein), hemin (50 îM), glucose-6-phosphate (2 mM), glucose-6-phosphate dehydrogenase (0.25 U), and NADPH (0.8 mM) for 60 min at 37°C in the dark. The formed bilirubin was extracted with chloroform and , OD was measured at 464–530 nm (extinction coefficient, 40 mM/cm for bilirubin). Enzyme activity is expressed as picomoles of bilirubin formed per milligram of protein per 60 min (pmol/mg/h). The protein concentration was determined by the bicinchoninic acid protein assay (Pierce, Georgetown). The background was ~5 pmol/mg/h. All reagents used in this assay were purchased from Sigma (St. Louis, MO), unless otherwise indicated. Carboxyhemoglobin was measured 2 days after transplantation by using a Corning 865 blood gas analyzer (Clinical Chemistry, Massachusetts General Hospital, Boston, MA).

Histomorphometric analysis

Grafts were harvested 3 days after transplantation, embedded in paraffin, fixed in formalin, and serially sectioned (5 îm) in toto from the apex to the base. Ten sections were placed per slide in a total of about 20–25 slides. Every fifth slide was stained with hematoxylin and eosin (H&E) for histomorphometric analysis. Two images per slide were captured by using a Nikon Eclipse E600Ŏ microscope (Nikon, Melville, NY) connected to a Hitachi 3-CCD Color Camera (model HV-C20; Hitachi, Tokyo, Japan) and to a Power MacintoshŎ 7300/200 computer (Apple Computer, Cupertino, CA) equipped with IPLab Spectrum digital imaging software (Signal Analytics Corporation, Vienna, VA). About 50 images were captured from each transplanted heart from two to three animals per group. Images were analyzed by manual segmentation, tracing the infarcted and noninfarcted areas from the right and left ventricles in each section. Areas corresponding to infarcted and noninfarcted tissue were calculated by digital imaging software as number of pixels corresponding to those areas. Infarcted and noninfarcted areas were then calculated as percentage of total area. Pooled data for each group, expressed as area in pixels or as percentage of infarction, was analyzed by using ANOVA. Results obtained in this manner were similar whether using either pixels or percentage of infarction and only the results obtained using percentage of infarction are shown (see Table II). Results are expressed as mean = SD.

Immunohistology

Grafts were harvested 3 days after transplantation, snap-frozen in liquid nitrogen, and stored at -80°C. Cryostat sections were fixed and stained as described previously (Soares *et al*, Nature Med. 4:1073, 1998). Rat leukocyte populations were analyzed by using anti-rat leukocyte common Ag (LCA, CD45; OX-1), Éé TCR (TCRÉé-chains; R73), B cell (CD45RB; OX-33), NK cell (NKR-P1; 3.2.3), and MΦ (CD68; ED-1), mAbs (Serotec, Harlan Bioproducts for Science, Indianapolis, IN). Detection of fibrin/fibrinogen was conducted by using a rabbit anti-human fibrin/fibrinogen polyclonal Ab (Dako, Carpinteria, CA). Intragraft complement activation was detected by using an anti-rat C1q (The Binding Site, Birmigham, U. K.), C3 (ED11; Serotec), or C5b-9 mAb (Dako). Rat IgM was detected by using the mouse anti-rat IgM mAb MARM-4 (a kind gift of Dr. H. Bazin, University of Louvain, Brussels, Belgium). Isotype-

matched mAbs or purified Ig, as well as a control for residual endogenous peroxidase activity, were included in each experiment. Detection of apoptosis was carried out by using ApopTagð *in situ* apoptosis detection kit (Oncor, Gaithersburg, MD) according to the manufacturer's instructions.

Complement hemolytic assay (CH50)

CH50 units were defined as the dilution of rat serum required to produce 50% maximal lysis of Ab-sensitized sheep erythrocytes. Briefly, Ab-sensitized sheep erythrocytes (1×10^8 cells/ml; Sigma) were incubated (30 min, 37°C) with rat serum in gelatin Veronal buffer (GVB^{++}; Sigma). Cells were centrifuged and hemoglobin release was measured (1 Î = 550 nm). Background was measured in the absence of sheep erythrocytes or in the absence of serum and subtracted from all samples.

Cellular ELISA

Serum levels of rat anti-mouse Abs were measured by cellular-based indirect ELISA. The mouse 2F-2B endothelial cell line (CRL-2168; American Type Culture Collection (ATCC), Manassas, VA) was used as an antigenic target. Briefly, 2F-2B cells were cultured in DMEM (Life Technologies, Rockville, MD), 10% FCS, 100 U/ml penicillin, and 100 îg/ml streptomycin (Life Technologies). Glutaraldehyde-fixed 2F-2B cells were incubated (1 h, 37°C) in the presence of rat serum serially diluted in PBS 0.05%Tween 20 (Sigma) and rat anti-mouse Abs were detected by using mouse anti-rat IgM (MARM-4), IgG1 (MARG1-2), IgG2a (Marg2a-1), IgG2b (MARGb-8), or IgG2c (MARG2c-5) (kind gifts from Prof. H. Bazin, University of Louvain, Brussels, Belgium). Mouse anti-rat Abs were detected by using HRP-labeled goat anti-mouse Fab' depleted of anti-rat Ig cross reactivity (0.1 îg/ml, 1 h, room temperature; Pierce, Rockford, IL). HRP was revealed by using *ortho*-phenyldiamine (Sigma) and H_2O_2 (0.03%) in citrate buffer (pH 4.9). Absorbance was measured at Î= 490 nm. The relative amount of circulating anti-graft Abs in the serum was expressed as OD (Î= 490) taken from one serial dilution in the linear range of the assay (1: 32 - 1: 1024).

Binding of rat C3 to mouse endothelial cells was measured by a modified cellular ELISA with mouse 2F-2B endothelial cells as antigenic targets (Miyatake *et al*, J. Immunol. 160:4114, 1998). Briefly, nonfixed 2F-2B endothelial cells were incubated in the presence of rat serum

serially diluted in GVB $^{++}$ buffer (1 h, 37°C). Cells were fixed in PBS, 0.05% glutaraldehyde, and rat C3 deposition was detected by using a mouse anti-rat C3 mAb (Serotec).

Platelet aggregation assay

Mouse 2F-2B endothelial cells were cultured on 0.2% gelatin (Sigma) coated six-well plates in 88% DMEM (Life Technologies), 10% FCS (FCS), 100 U/ml penicillin, and 100 îg/ml streptomycin (Life Technologies). Confluent endothelial cells either were left untreated or were treated with the HO-inducing agent CoPPIX (50 îM; 18 h), the HO inhibitor SnPPIX (50 îM, 18 h), or both CoPPIX (50 îM, 15 h) and SnPPIX (50 îM, 3 h). Platelet-rich plasma was obtained by centrifugation (290 – *g*, 12 min, 19°C) of normal rat plasma in 3.8% sodium citrate. Rat platelets (3 – 10^8 cells ml) were resuspended in HT buffer (8.9 mM $NaHCO_3$, 0.8 mM KH_2PO, 5.6 mM dextrose, 2.8 mM KCl solution, 0.8 mM $MgCl_2$, 129 mM NaCl, 10 mM HEPES). Platelets were overlaid (5 min; 37°C) on mouse endothelial cells, and platelet aggregation assays were conducted as described before (Kaczmarek *et al*, J. Biol. Chem. 271:33116, 1996) by using an aggregometer (Chrono-Log, Harestown, PA) and ADP (0.5 - 4 μM) as an agonist.

Cell extracts and Western blot analysis

Endothelial cells were washed in PBS (pH 7.2), harvested by scraping, and lysed in Laemmli buffer. Electrophoresis was conducted under denaturing conditions with 10% polyacrylamide gels. Proteins were transferred onto a polyvinyldifluoridine membrane (Immobilon P; Millipore, Bedford, MA) by electroblotting and detected with rabbit polyclonal Abs directed against human HO-1 or HO-2 (StressGen, Victoria, Canada) or é-tubulin (Boehringer Mannheim, Mannheim, Germany). Proteins were visualized by using HRP-conjugated donkey anti-rabbit IgG or goat anti-mouse IgG (Pierce) and the ECL assay (Amersham Life Science, Arlington Heights, IL) according to manufacturer's instructions.

Transient transfections and apoptosis assay

The murine 2F-2B endothelial cell line (ATCC) was transiently transfected as described elsewhere (Soares *et al.*, Nature Med. 4:1073, 1998; Brouard *et al.*, J. Exp. Med. 192:1015, 2000). All experiments were conducted 24 - 48 h after transfection. é-galactosidase-transfected cells were detected as described elsewhere (Soares *et al.*, Nature Med. 4:1073, 1998; Brouard *et*

al., J. Exp. Med. 192:1015, 2000). Percentage of viable cells was assessed by evaluating the number of é-galactosidase-expressing cells that retained normal morphology as described elsewhere (Soares *et al.*, Nature Med. 4:1073, 1998; Brouard *et al.*, J. Exp. Med. 192:1015, 2000). The number of random fields counted was determined to have a minimum of 200 viable transfected cells per control well. The percentage of viable cells was normalized for each DNA preparation to the number of transfected cells counted in the absence of the apoptosis-inducing agent (100% viability). All experiments were performed at least three times in duplicate. Actinomycin D (Act. D; Sigma) was dissolved in PBS and added to the culture medium (10 îg/ml) 24 h after transfection. SnPPIX (Porphyrin Products) was dissolved (10 îM) in 100 mM NaOH and conserved at -20°C until used. SnPPIX was added to the culture medium (50 îM) 6 h after transfection. Human recombinant TNF-α (R&D Systems, Minneapolis, MN) was dissolved in PBS, 1% BSA, and added to the culture medium (10 - 100 ng/ml) 24 h after transfection.

Exposure of cultured endothelial cells to CO

Cells were exposed to compressed air or varying concentration of CO (250 and 10,000 ppm), as described elsewhere (Otterbein *et al.*, Nature Med. 6:422, 2000; and Brouard *et al.*, J. Exp. Med. 192:1015, 2000).

Aortic transplant model

Aortic transplantation was carried out done as described elsewhere (Plissonnier *et al.*, Transplantation 60:414-424, 1995). Briefly, the aorta and the inferior vena cava were cut to be bled after heparinization. After additional left thoracotomy, three or four pairs of the inter-costal arteries were ligated using 7-0 nylon suture (Keisei Medical Industrial Co., LTD, Tokyo, Japan), and 2 cm of the descending aorta was harvested. The graft was inserted between the renal arteries and the aortic bifurcation by standard microsurgery technique using 9-0 Nylon sutures (Ethilon™, Ethicon, Inc, Somerville, New Jersey). The native abdominal aorta was left after both edges were ligated.

CO at a concentration of 1% (10,000 parts per million; ppm) in compressed air was mixed with balanced air (21% oxygen) as described previously (Otterbein *et al.*, Am J Physiol 276(4 Pt 1):L688-L694, 1999). For the transplant model, graft donors were placed in the CO chamber two days before transplantation. Recipients were placed in the chamber immediately

following transplantation and kept there 56 days. CO concentration was maintained at 250 ppm at all times.

Adult male (250-350g) Brown Norway rats (RT1 were used as aortic graft donors and adult male (250-350g) Lewis rats (RT1) as recipients (Charles River Lab. Wilmington, MA). Male C57BL/6, $p21^{-/-}$ and $p53^{-/-}$ null mice were purchased from Jackson Laboratory (Bar Harbor, ME). The $MKK3^{(-/-)}$ null mice were generated as previously described (Lu *et al.*, EMBO. J. 18:1845-1857, 1999). Mice were allowed to acclimate for one week with rodent chow and water *ad libitum*.

RT-PCR

RT-PCR was conducted after RNA isolation from the transplanted hearts by using an RNA extracting kit, according to the manufacturer's instructions (Qiagen, Chatsworth, CA). Primers used for mouse β-actin were: sense (5'-3'), CCTGACCGAGCGTGGCTACAGC (SEQ ID NO:1); antisense (3'-5'), AGCCTCCAGGGCATCGGAC (SEQ ID NO:2); and for mouse HO-1: sense (5'-3'), TCCCAGACACCGCTCCTCCAG (SEQ ID NO:3); antisense (3'-5'), GGATTTGGGGCTGCTGGTTTC (SEQ ID NO:4).

Enzymatic activity is critical to suppress acute vascular rejection

Mouse hearts transplanted into untreated rats underwent acute vascular rejection 2-3 days after transplantation, an observation consistent with previous reports (Soares *et al.*, Nature Med. 4:1073, 1998; and Koyamada *et al.*, Transplantation 65:1210, 1998). Under cobra venom factor (CVF) plus cyclosporin A (CsA) treatment, mouse cardiac grafts survived long term (see Table II, below), a finding also consistent with previous reports. Under CVF plus CsA treatment, graft survival was associated with up-regulation of HO-1 expression by graft endothelial and smooth muscle cells as well as by cardiac myocytes (Fig. 7). Expression of HO-1 mRNA was detected by RT-PCR 12 - 24 h after transplantation and HO-1 protein 24-72 h after transplantation (Fig. 7). Long-term graft survival did not occur when the HO inhibitor SnPPIX was administered to the donor and then to the recipient, despite treatment with CVF plus CsA. Under these conditions, all grafts were rejected in 3-7 days (Table II). Control treatment with FePPIX, a protoporphyrin that does not inhibit HO activity, did not lead to graft rejection (Table II).

Table II

Inhibition of HO-1 activity by SnPPIX precipitates graft rejection.

Treatment	Survival Time
CVF + CsA	>50 (n=8)
CVF + CsA + FePPIX	>50 (n=4)
CVF + CsA + SnPPIX	3, 4, 5 (n=2); 6 (n=4); 7 (n=2)

To generate the data in Table II, mouse hearts were transplanted into CVF plus CsA-treated rats. Graft recipients were treated with FePPIX or SnPPIX. Treatment with SnPPIX induced graft rejection 3–7 days after transplantation ($p < 0.0001$ as compared to rats treated with CVF plus CsA alone or with CVF plus CsA plus FePPIX). Statistical analyses were carried out using Fisher's exact test.

To demonstrate that SnPPIX, but not FePPIX, blocked HO-1 function in vivo, total HO enzymatic activity was quantified in transplanted and recipient hearts 2 days after transplantation (Fig. 8). Naive mouse hearts produced 35.5 ± 4 picomols of bilirubin per milligram of total protein per hour (pmol/mg/h; Fig. 8). HO activity was significantly increased in mouse hearts transplanted into untreated (98 ± 7.21 pmol/mg/h; $p = 0.001$), CVF plus CsA-treated (98.3 ± 7.23 pmol/mg/h), or CVF plus CsA plus FePPIX-treated (77.3 ± 5.51 pmol/mg/h; $p = 0.0009$) rats, as compared with naive hearts (Fig. 8). HO activity was inhibited to basal levels, as present in naive hearts, in mouse hearts transplanted into rats treated with CVF plus CsA plus SnPPIX (32.37 ± 7.23 pmol/ mg/h). This represented a highly significant inhibition as compared with mouse hearts transplanted into untreated ($p = 0.0009$), CVF plus CsA-treated ($p = 0.0009$), or CVF plus CsA plus FePPIX-treated rats ($p = 0.0018$; Fig. 8). HO activity in the recipient's livers was also up-regulated after transplantation in a manner that mimicked that of the transplanted hearts (data not shown). However, this was not the case for the recipient's own heart, in which HO activity was not up-regulated following transplantation (Fig. 8). In grafts transplanted into SnPPIX-treated rats, there was progressive myocardial infarction, which became apparent as early as 2 days after transplantation (data not shown). This was not observed in grafts transplanted into control rats treated with FePPIX (data not shown).

It has previously been shown that rats that receive a mouse cardiac graft under CVF plus CsA treatment generate anti-mouse Abs that are exclusively of the IgM isotype (Koyamada *et al.*, Transplantation 65:1210, 1998). Additional treatment with SnPPIX or FePPIX did not

influence this Ab response (Fig. 9). Generation of antigraft Abs was correlated with complement activation, as demonstrated by C3 deposition on mouse endothelial cells (Fig. 9). Neither SnPPIX or FePPIX treatment influenced C3 deposition on mouse endothelial cells (Fig. 9).

Exogenous CO fully substitutes for HO-1 enzymatic activity in suppressing acute vascular rejection

All mouse hearts transplanted into rats treated with SnPPIX and exposed to CO (400 ppm; 0.04%) survived long term (see Table III, below). The dose of CO used (400-500 ppm) corresponds to approximately one-twentieth of the lethal dose (data not shown). Rats and mice exposed to CO did not exhibit untoward reactions. CO exposure was discontinued 14 ($n = 3$) or 16 ($n = 3$) days after transplantation without influencing graft survival, i.e., grafts continued to function for >50 days (Table III).

Table III

Exogenous CO fully substitutes for HO-1 in suppressing graft rejection

Treatment	Survival Time (days)
CVF + CsA + SnPPIX	3, 4, 5, (n = 2); 6 (n = 4); 7 (n = 2)
CVF + CsA + SnPPIX + CO	> 50 (n = 6)

To generate the data in Table III, mouse hearts were transplanted into CVF plus CsA-treated rats. When indicated, graft recipients were treated with SnPPIX with or without exposure to CO. Graft rejection observed in SnPPIX-treated rats was suppressed under exposure to exogenous CO ($p < 0.0001$ as compared to recipients
treated with CVF plus CsA plus SnPPIX). Statistical analyses were carried out using Fisher's exact test.

To determine whether exogenous CO interfered with inhibition of HO-1 enzymatic activity by SnPPIX, which could account for the ability of CO to suppress graft rejection, it was investigated whether CO affected HO enzymatic activity in hearts transplanted into SnPPIX-treated rats. As shown in Fig. 10, this was not the case. Total HO enzymatic activity in hearts transplanted under SnPPIX treatment (32.37 ± 7.23 pmol/mg/h) was not significantly different from that of hearts transplanted into rats treated with SnPPIX and exposed to CO (43.6 ± 7.57 pmol/mg/h; $p = 0.1095$; Fig. 10). Similar results were obtained in the recipient's livers and

hearts (Fig. 10).

Exogenous CO may substitute for HO-1 activity in preventing graft rejection. This might work by a mechanism that involves "loading" of exogenous CO by inhalation into RBC and then delivery through the circulation into the graft at an adequate concentration. According to this theory, when endogenous HO-1 activity is being inhibited by SnPPIX, exogenous CO would mimic the effect of endogenous CO that is produced when HO-1 enzymatic activity is not impaired. Exposure of the transplant recipient to 400 ppm of exogenous CO increased carboxyl hemoglobin from 0.5 ± 1.5% to 32.1 ± 6.9% (Fig. 10). The fact that the transplanted hearts survived in animals exposed to CO, even under these suppressive effects of SnPPIX, may indicate that this level of CO was sufficient to adequately "charge" RBC, deliver CO into the graft, and suppress graft rejection (Fig. 10). Alternatively, carbon monoxide may be delivered to the graft, and all tissues of the body, dissolved in plasma.

Whether exogenous CO suppressed the development of myocardial infarction that characterizes graft rejection in SnPPIX-treated rats was investigated. Grafts were harvested 3 days after transplantation and quantified for the percentage of infarcted area. Hearts transplanted into untreated rats showed nearly complete transmural infarction of the right ventricle (87.1 ± 4.9% of the right ventricle area) with extensive endomyocardial and transmural infarction of the left ventricle (32.0 ± 6.7% of the left ventricle area; data not shown). Infarctions showed nonviable eosinophic myocardium lacking nuclei with interstitial hemorrhage, edema, and neutrophils. Left ventricle infarctions were always endomyocardial with transmural extension depending on the degree of infarction, and those in the right ventricle were more diffuse in origin. The percentage of infarcted area in both ventricles generally increased from the apex to the base of the heart. Hearts transplanted into CVF plus CsA-treated rats showed only small, diffuse, nontransmural areas of infarction in the right (4.5 ± 4.9%) but not in the left (0.7 ± 2.1%) ventricle (see Table IV, below). Hearts transplanted into CVF plus CsA plus FePPIX-treated rats showed small diffuse areas of infarction in the right (12.2 ± 9.5%) but not in the left (0.7 ± 1.3%) ventricle (Table IV). These hearts were indistinguishable from those transplanted into CVF plus CsA treated rats without FePPIX treatment (data not shown). Hearts transplanted into CVF plus CsA plus SnPPIX-treated rats showed significant transmural right ventricular infarctions (26.1 ± 12.7%) with extensive endomyocardial and transmural left ventricular infarctions (37.6 ± 15.5%) (Table IV) in a pattern that was indistinguishable from that

of hearts transplanted into untreated rats (data not shown). These lesions were specific to the transplanted heart. The recipients' native hearts did not develop any infarction. The percentage of infarcted area in hearts transplanted into SnPPIX-treated rats was significantly higher ($p < 0.001$) as compared with that of hearts transplanted into rats treated with CVF plus CsA with or without FePPIX treatment (Table IV). Hearts transplanted into SnPPIX treated rats that received exogenous CO showed very little infarction of the right (8.4 ± 5.3%) and left (1.8 ± 3.4%) ventricles (Table IV), with patterns that were similar to those of hearts transplanted into CVF plus CsA-treated rats with or without FePPIX treatment (data not shown). The percentage of infarcted area in hearts transplanted into SnPPIX-treated rats that received exogenous CO was not significantly different from that of hearts transplanted into CVF plus CsA-treated rats with or without FePPIX treatment. However, the percentage of infarcted area in these hearts was significantly different ($p < 0.001$) from that of hearts transplanted under the same treatment but that did not receive exogenous CO.

Table IV
Morphometric analysis

Treatment	Right Ventricle	Left Ventricle
CVF + CsA	4.5 ± 4.9	0.7 ± 2.1
CVF + CsA + FePPIX	12.2 ± 9.5	0.7 ± 1.3
CVF + CsA + SnPPIX	26.1 ± 12.7*	37.6 ± 15.5*
CVF + CsA + SnPPIX + CO	8.4 ± 5.3	1.8 ± 3.4

To generate the data in Table IV, mouse hearts were transplanted into ($n = 3$ per group) CVF plus CsA-treated rats. When indicated, graft recipients were treated with FePPIX or SnPPIX and exposed to CO. Results are shown as percentage of infarcted area. Statistical analyses were carried out using ANOVA test. An asterisk indicates significant difference as compared to all other treatments.

Exogenous CO suppresses vascular thrombosis and monocyte/ macrophage infiltration that characterize acute vascular rejection

Mouse hearts were transplanted into CVF plus CsA-treated rats. SnPPIX or FePPIX was administered and graft recipients were exposed to CO (250 –400 ppm). Grafts were harvested 3 days after transplantation ($n = 3$ per group) and stained for rat IgM, rat and mouse complement

C1q, rat and mouse P-selectin, rat and mouse fibrin/fibrinogen, and rat CD45 expressing leukocytes. Mouse hearts transplanted into CVF plus CsA-treated rats with or without FePPIX treatment showed extensive intravascular deposition of rat IgM and C1q (data not shown) but no detectable IgG, C3, or C5b-9 (data not shown). HO-2, HO-1, and ferritin were detected in graft endothelial and smooth muscle cells as well as in cardiac myocytes (data not shown). There was only minimal vascular thrombosis or infiltration by host leukocytes usually associated with focal areas of infarction (data not shown). There was low but detectable P-selectin expression on the vascular endothelium (data not shown). Hearts transplanted into CVF plus CsA-treated rats, under inhibition of HO-1 activity by SnPPIX, showed similar levels of intravascular deposition of IgM and C1q as compared with control FePPIX-treated rats and no detectable IgG, C3, or C5b-9 (data not shown). There was widespread vascular thrombosis of large coronary vessels associated with P-selectin-expressing platelet aggregates and intravascular fibrin. Thrombi were consistently observed in large coronary vessels at the base of the heart. There were no detectable P-selectin-expressing platelet aggregates in the microvasculature (data not shown). There was extensive graft infiltration by host neutrophils as well as by $CD45^{++}$ leukocytes expressing the monocyte/MΦ marker CD68/ ED-1 and MHC class II Ags (data not shown). Infiltrating monocyte/ MΦ were found near arterioles and scattered throughout the myocardium, associated with areas of infarction.

Hearts transplanted into SnPPIX-treated rats that were exposed to CO were essentially indistinguishable from those transplanted into rats treated with CVF plus CsA with or without FePPIX (data not shown). These hearts showed similar level of IgM and C1q vascular deposition as compared with hearts transplanted into recipients treated with SnPPIX but not exposed to CO (data not shown). Under CO exposure, there were no signs of vascular thrombosis as revealed by the lack of detectable P-selectin-expressing platelet aggregates or intravascular fibrin. P-selectin was detected on the graft vascular endothelium. There was some level of monocyte/ MΦ infiltration associated with small focal areas of infarction (data not shown).

Up-regulation of HO-1 in endothelial cells inhibits platelet aggregation

Given the absence of platelet aggregation in grafts transplanted into rats exposed to CO, whether expression of HO-1 in endothelial cells would inhibit platelet aggregation *in vitro* was

investigated. Mouse endothelial cells were exposed to CoPPIX or SnPPIX to induce or suppress HO activity in these cells, respectively. Platelets were overlaid on the endothelial cells and tested for their ability to aggregate on stimulation by ADP (2 μM). Platelets overlaid on untreated endothelial cells aggregated normally when stimulated with ADP (Fig. 11). When platelets were exposed to endothelial cells pretreated with SnPPIX, platelet aggregation was enhanced as compared with platelets exposed to untreated endothelial cells (Fig. 11). This observation indicates that untreated endothelial cells have a basal level of HO activity presumably attributable to constitutive expression of HO-2 in these cells (Fig. 11). When platelets were exposed to endothelial cells pretreated with CoPPIX, platelet aggregation was significantly inhibited as compared with platelets exposed to untreated or SnPPIX-treated endothelial cells (Fig. 11). This inhibitory effect was suppressed when platelets were exposed to endothelial cells treated with both CoPPIX and SnPPIX (Fig. 11). Both CoPPIX and SnPPIX up-regulated the expression of HO-1 in cultured endothelial cells (data not shown). The differential effects of these protoporphyrins should be attributed to the ability of SnPPIX to act as a potent inhibitor of HO-1 enzymatic activity.

HO-1 generates CO that suppresses endothelial cell apoptosis

One of the main features that characterizes the rejection of mouse hearts transplanted into rats treated with SnPPIX is the widespread apoptosis of endothelial cells and cardiac myocytes (Fig. 12). Apoptosis did not occur in mouse hearts transplanted into rats treated with FePPIX (Fig. 12). Given the ability of HO-1 to suppress endothelial cell apoptosis *in vitro* (Soares *et al.*, Nature Med. 4,1073-1077, 1998; and Brouard *et al.*, J. Exp. Med. 192:1015, 2000), whether this cytoprotective effect was mediated via the generation of CO was investigated. Apoptosis did not occur in mouse hearts transplanted into rats treated with SnPPIX and exposed to CO, suggesting that this was the case (Fig. 12). It was investigated *in vitro* whether under inhibition of HO-1 activity by SnPPIX, exogenous CO would prevent endothelial cells from undergoing TNF-É-mediated apoptosis. The data illustrated in Fig. 6 suggest that this is the case. Overexpression of HO-1 suppressed TNF-α-mediated endothelial cell apoptosis, such as it occurs in the presence of actinomycin D (Fig. 12). The antiapoptotic effect of HO-1 is mediated through its enzymatic activity because exposure of endothelial cells to SnPPIX blocked the antiapoptotic effect of

HO-1 (Fig. 12). Under inhibition of HO-1 activity by SnPPIX, exogenous CO (10,000 ppm) suppressed TNF-É-mediated apoptosis, suggesting that HO-1 suppresses endothelial cell apoptosis via the generation of CO (Fig. 12).

Carbon monoxide suppresses the development of transplant-associated arteriosclerosis

Brown Norway aortas were transplanted into Brown Norway rats (syngeneic), untreated Lewis rats (allogeneic), or Lewis rats exposed to carbon monoxide (250 ppm; allogeneic with carbon monoxide). Samples were harvested 56 days after transplantation and stained by a modified elastic tissue-masson trichrome, or by eosin hematoxylin. Brown Norway aortic segments transplanted into Lewis rats developed arteriosclerotic lesions that are consistent with those associated with chronic graft rejection (data not shown). These lesions became apparent 20-30 days after transplantation and were significantly more pronounced by 50-60 days (data not shown). For this reason, all analyses were carried out 56 days following transplantation. These lesions were characterized by intimal hyperplasia, loss of medial smooth muscle cells (SMC) and accumulation of leukocytes in the adventitia, and were not observed in aortas of the transplant recipient (data not shown). No signs of these lesions were observed when rat aortic segments were transplanted into syngeneic recipients. To test whether CO would suppress the development of these lesions, aortic grafts were transplanted into allogeneic recipients that were then exposed to CO (250 ppm) immediately following transplantation and for the subsequent 56 days. Intimal hyperplasia was inhibited in aortic grafts transplanted into recipients exposed to CO, as compared to those transplanted into recipients exposed to air, as was the accumulation of leukocytes into the adventitia (data not shown). CO had no significant effect on loss of medial SMC as compared to grafts transplanted into untreated recipients (data not shown).

Example III. Protocols for the Treatment of Organs and Tissues, a Donor, and a Recipient During Transplantation Procedures.

The following example illustrates protocols for use in treating a donor, and organ, and a recipient with carbon monoxide during a transplantation procedure. Any one, or more of the following procedures may be used in a given transplantation procedure.

Treatment of a Donor

Prior to harvesting an organ or tissue, the donor can be treated with inhaled carbon monoxide (250 ppm) for one hour. Treatment can be administered at doses varying from 10 ppm to 1000 ppm for times varying from one hour to six hours, or for the entire period from the moment when it becomes possible to treat a brain-dead (cadaver) donor to the time the organ is removed. Treatment should start as soon as possible following the declaration that brain death is present. In some applications, it may be desirable to begin treatment before brain death.

For non-human animals (e.g., pigs) to be used as xenotransplantation donors, the live animal can be treated with relatively high levels of inhaled carbon monoxide, as desired, so long as the carboxyhemoglobin so produced does not compromise the viability and function of the organ to be transplanted. For example, one could use levels greater than 500 ppm (e.g., 1000 ppm or higher, and up to 10,000 ppm, particularly for brief times).

Treatment of the organ *in situ*

Before an organ is harvested from a donor, it can be flushed with a solution, e.g., a buffer or medium, without red blood cells while it is still in the donor. The intent is to flush the organ with a solution saturated with carbon monoxide and maintained in a carbon monoxide atmosphere so that the carbon monoxide content remains at saturation. Flushing can take place for a time period of at least 10 minutes, e.g., 1 hour, several hours, or longer. The solution should ideally deliver the highest concentration of carbon monoxide possible to the cells of the organ.

Treatment of an Organ or Tissue

The organ or tissue can be preserved in a medium that includes carbon monoxide from the time it is removed from the donor to the time it is transplanted to the recipient. This can be performed by maintaining the organ or tissue in the medium comprising CO, or by perfusing it with such a medium. Since this occurs *ex vivo* rather than in an animal, very high concentrations of CO gas can be used (e.g., 10,000 ppm to keep the medium saturated with CO).

Treatment of a Recipient

The recipient can be treated with carbon monoxide. Treatment can begin on the day of transplantation at least 30 minutes before surgery begins. Alternatively, it could begin at least 30 minutes before re-perfusion of the organ in the recipient. It can be continued for at least 30 minutes, e.g., 1 hour. Carbon monoxide doses between 10 ppm and 3000 ppm can be delivered for varying times, e.g., minutes or hours, and can be administered on the day of and on days following transplantation. For example, a recipient can inhale a concentration of carbon monoxide, e.g., 3000 ppm, for three consecutive 10 second breath holds. Alternatively, the recipient can inhale, say, 200 ppm for an extended time, such as 20 days. Carboxyhemoglobin concentrations can be utilized as a guide for appropriate administration of carbon monoxide to a patient. Usually, treatments for recipients should not raise carboxyhemoglobin levels above those considered to pose an acceptable risk for a patient in need of a transplant.

Other Embodiments

It is to be understood that, while the invention has been described in conjunction with the detailed description thereof, the foregoing description is intended to illustrate and not limit the scope of the invention, which is defined by the scope of the appended claims. Other aspects, advantages, and modifications are within the scope of the following claims.

WHAT IS CLAIMED IS:

1. A method of transplanting an organ, the method comprising:

(a) administering to a donor a pharmaceutical composition comprising carbon monoxide;

(b) obtaining from the donor an organ selected from the group consisting of: kidney, liver, heart, skin, small intestine, and pancreas; and

(c) transplanting the organ into a recipient, wherein an amount of carbon monoxide administered to the donor is sufficient to enhance survival or function of the organ after transplantation into the recipient.

2. The method of claim 1, wherein the pharmaceutical composition is administered to a live donor.

3. The method of claim 1, wherein the pharmaceutical composition is administered to a brain-dead donor.

4. The method of claim 1, wherein the pharmaceutical composition comprising carbon monoxide is administered to the donor prior to and following brain death.

5. The method of claim 1, wherein the pharmaceutical composition is a first pharmaceutical composition and further comprising treating the organ *in situ* in the donor with a second pharmaceutical composition comprising carbon monoxide.

6. The method of claim 1, further comprising treating the organ *ex vivo,* prior to the transplantation step, with a second pharmaceutical composition comprising carbon monoxide.

7. The method of claim 1, wherein the pharmaceutical composition is a first pharmaceutical composition and further comprising the step of administering to the recipient a second pharmaceutical composition comprising carbon monoxide before, during, or after step (c).

8. The method of claim 7, wherein the second pharmaceutical composition is administered to the recipient before (c).

9. The method of claim 7, wherein the pharmaceutical composition comprising carbon monoxide is administered to the recipient during (c).

10. The method of claim 7, wherein the pharmaceutical composition comprising carbon monoxide is administered to the recipient after (c).

11. The method of claim 7, wherein the pharmaceutical composition comprising carbon monoxide is administered to the recipient before and during (c).

12. The method of claim 7, wherein the pharmaceutical composition comprising carbon monoxide is administered to the recipient before and after (c).

13. The method of claim 7, wherein the pharmaceutical composition comprising carbon monoxide is administered to the recipient before, during, and after (c).

14. The method of claim 1, wherein the organ is a liver.

15. The method of claim 1, wherein the organ is a kidney.

16. The method of claim 1, wherein the organ is a heart.

17. The method of claim 1, wherein the organ is a pancreas.

18. The method of claim 1, wherein the organ is a small intestine.

19. The method of claim 1, wherein the organ is skin.

20. The method of claim 1, wherein the donor is of a species different from that of the recipient.

21. The method of claim 1, wherein the donor and the recipient are of the same species.

22. The method of claim 1, wherein both the donor and the recipient are non-human animals.

23. The method of claim 1, wherein both the donor and the recipient are humans.

24. The method of claim 1, wherein the donor is a non-human animal and the recipient is a human.

25. A method of transplanting an organ, the method comprising:

(a) providing an organ of a donor;

(b) administering a pharmaceutical composition comprising carbon monoxide to the organ; and

(c) transplanting the organ into a recipient, wherein the amount of carbon monoxide administered to the organ in step (b) is sufficient to enhance survival or function of the organ after transplantation of the organ to the recipient.

26. The method of claim 25, wherein step (b) is carried out by perfusing the organ *in situ* while the organ is in the donor.

27. The method of claim 25, wherein step (b) is carried out *ex vivo*.

28. The method of claim 27, further comprising the steps of, prior to step (b), administering to the donor a second pharmaceutical composition comprising carbon monoxide; and removing the organ from the donor.

29. The method of claim 28, wherein the second pharmaceutical composition is administered to a live donor.

30. The method of claim 28, wherein the second pharmaceutical composition is administered to a brain-dead donor.

31. The method of claim 28, wherein the second pharmaceutical composition is administered to the donor prior to and following brain death.

32. The method of claim 25, further comprising the step of administering to the recipient a second pharmaceutical composition comprising carbon monoxide before, during, or after step (c).

33. The method of claim 32, wherein the second pharmaceutical composition is administered to the recipient before step (c).

34. The method of claim 32, wherein the second pharmaceutical composition is administered to the recipient during step (c).

35. The method of claim 32, wherein the second pharmaceutical composition is administered to the recipient after step (c).

36. The method of claim 32, wherein the second pharmaceutical composition is administered to the recipient before and during step (c).

37. The method of claim 32, wherein the second pharmaceutical composition is administered to the recipient before and after step (c).

38. The method of claim 32, wherein the second pharmaceutical composition is administered to the recipient before, during, and after step (c).

39. The method of claim 25, wherein the organ is a liver.

40. The method of claim 25, wherein the organ is a kidney.

41. The method of claim 25, wherein the organ is a heart.

42. The method of claim 25, wherein the organ is a pancreas.

43. The method of claim 25, wherein the organ is a lung.

44. The method of claim 25, wherein the organ is a small intestine.

45. The method of claim 25, wherein the organ is skin.

46. The method of claim 25, wherein the donor is of a species different from that of the recipient.

47. The method of claim 25 wherein the donor and the recipient are of the same species.

48. A method of transplanting an organ, the method comprising:

(a) providing an organ from a donor;

(b) transplanting the organ into a recipient; and

(c) before, during, or after (b), administering to the recipient a pharmaceutical composition comprising carbon monoxide in an amount sufficient to enhance survival of the transplanted organ in the recipient.

49. The method of claim 48, wherein the pharmaceutical composition comprising carbon monoxide is administered to the recipient before (b).

50. The method of claim 48, wherein the pharmaceutical composition comprising carbon monoxide is administered to the recipient during (b).

51. The method of claim 48, wherein the pharmaceutical composition comprising carbon monoxide is administered to the recipient after (b).

52. The method of claim 48, wherein the pharmaceutical composition comprising carbon monoxide is administered to the recipient before and during (b).

53. The method of claim 48, wherein the pharmaceutical composition comprising carbon monoxide is administered to the recipient before and after (b).

54. The method of claim 48, wherein the pharmaceutical composition comprising carbon monoxide is administered to the recipient before, during, and after (b).

55. The method of claim 48, wherein the pharmaceutical composition is administered to the recipient within 1 to 20 days after (b).

56. The method of claim 48, wherein the pharmaceutical composition is administered to the recipient at least once within the period beginning 21 days after (b).

57. The method of claim 48, wherein the pharmaceutical composition is administered to the recipient multiple times or continuously during the period beginning 21 days after (b).

58. The method of claim 48, wherein the pharmaceutical composition is administered to the recipient upon determination that the transplanted organ is undergoing or about to undergo chronic rejection.

59. The method of claim 48, wherein the pharmaceutical composition is administered to the recipient upon determination that the transplanted organ is undergoing or about to undergo acute rejection.

60. The method of claim 48, further comprising the step of, prior to obtaining the organ from the donor, administering to the donor a second pharmaceutical composition comprising carbon monoxide.

61. The method of 60, wherein the second pharmaceutical composition is administered to a live donor.

62. The method of claim 60, wherein the second pharmaceutical composition is administered to a brain-dead donor.

63. The method of claim 48, further comprising the step of, prior to (b), administering to the organ a second pharmaceutical composition comprising carbon monoxide.

64. The method of claim 63, wherein the second pharmaceutical composition is administered to the organ *in situ* in the donor.

65. The method of claim 63, wherein the second pharmaceutical composition is administered to the organ *ex vivo*.

66. The method of claim 48, wherein the organ is a liver.

67. The method of claim 48, wherein the organ is a kidney.

68. The method of claim 48, wherein the organ is a heart.

69. The method of claim 48, wherein the organ is a pancreas.

70. The method of claim 48, wherein the organ is a lung.

71. The method of claim 48, wherein the organ is a small intestine.

72. The method of claim 48, wherein the organ is skin.

73. The method of claim 48, wherein the donor is of a species different from that of the recipient.

74. The method of claim 48, wherein the donor and the recipient are of the same species.

75. A method of enhancing the function of a donor organ, comprising:

(a) providing an organ of marginal donor; and

(b) exposing the organ to an amount of a pharmaceutical composition comprising carbon monoxide, sufficient to enhance the function of the donor organ.

76. A method of maintaining an animal cell *in vitro*, the method comprising:

(a) providing a vessel containing a pressurized gas comprising carbon monoxide gas;

(b) providing an isolated cell *in vitro*, wherein the cell is a primary cell or stem cell;

(c) releasing the pressurized gas from the vessel, to form an atmosphere comprising carbon monoxide gas; and

(d) maintaining the animal cell *in vitro* in the presence of the atmosphere comprising carbon monoxide gas.

77. A method of maintaining an animal cell *in vitro*, the method comprising :

(a) providing a culture medium comprising at least 0.0001 g CO/100 g medium; and

(b) maintaining an isolated cell in the medium.

78. A method of transplanting a cell, the method comprising:

(a) maintaining an animal cell in accordance with the method of claim 77; and

(b) transplanting the animal cell into a recipient.

79. The method of claim 78, wherein the animal cell is obtained from a donor that is not the recipient.

80. The method of claim 78, wherein the animal cell is obtained from the recipient.

81. The method of claim 78, further comprising administering a carbon monoxide composition to the recipient prior to, during, or after transplanting.

82. The method of claim 81, wherein the carbon monoxide composition is administered to the recipient prior to transplanting.

83. The method of claim 81, wherein the carbon monoxide composition is administered to the recipient during transplanting.

84. The method of claim 81, wherein the carbon monoxide composition is administered to the recipient following transplanting.

85. The method of claim 81, wherein the carbon monoxide composition is administered to the recipient prior to and following transplanting.

86. The method of claim 81, wherein the carbon monoxide composition is administered to the recipient prior to, during, and following tranplanting.

87. The method of claim 78, wherein the animal cell is obtained from a donor by a method comprising:

(i) administering a composition comprising carbon monoxide to the donor; and

(ii) obtaining the cell from a tissue of the donor.

88. The method of claim 76, wherein the animal cell is part of a pancreatic islet.

89. The method of claim 76, wherein the animal cell is a liver cell.

90. The method of claim 76, wherein the animal cell is a pancreatic β-cell.

91. The method of claim 76, wherein the animal cell is a fibroblast.

92. The method of claim 76, wherein the animal cell is a bone marrow cell.

93. The method of claim 76, wherein the animal cell is a neuronal cell.

94. The method of claim 76, wherein the animal cell is a myocyte cell.

95. The method of claim 76, wherein the animal cell is a stem cell.

96. A method of enhancing survival of an animal cell after removal from a donor, the method comprising:

(a) administering to a live or brain-dead donor a pharmaceutical composition comprising carbon monoxide; and

(b) obtaining an isolated cell from the donor, wherein the amount of carbon monoxide administered to the donor is sufficient to enhance survival of the cell after removal from the donor.

97. The method of claim 96, wherein the pharmaceutical composition is a pressurized gas.

98. The method of claim 96, further comprising: (c) maintaining the cell *in vitro* in the presence of a second pharmaceutical composition comprising carbon monoxide.

99. The method of claim 98, wherein the cell of (c) is disposed within a liquid medium.

100. The method of claim 99, wherein step (c) is performed by providing a source of pressurized carbon monoxide gas and contacting the liquid medium with carbon monoxide gas released from the source of pressurized carbon monoxide gas.

101. The method of claim 99, wherein the liquid medium comprises carbon monoxide.

102. The method of claim 96, wherein the cell is part of a pancreatic islet.

103. The method of claim 96, wherein the cell is a liver cell.

104. The method of claim 96, wherein the cell is a pancreatic β-cell.

105. The method of claim 96, wherein the cell is a fibroblast.

106. The method of claim 96, wherein the cell is a bone marrow cell.

107. The method of claim 96, wherein the cell is a neuronal cell.

108. The method of claim 96, wherein the cell is a myocyte cell.

109. The method of claim 96, wherein the cell is a stem cell.

110. A method of transplanting an animal cell, the method comprising:

(a) administering to a live or brain-dead donor a pharmaceutical composition comprising carbon monoxide;

(b) obtaining an isolated cell from the donor; and

(c) transplanting the cell into a recipient, wherein the amount of carbon monoxide administered to the donor is sufficient to enhance survival of the cell after removal from the donor.

111. The method of claim 110, wherein the donor is not the recipient.

112. The method of claim 110, wherein the donor and the recipient are the same animal.

113. The method of claim 110, further comprising the step of administering a second pharmaceutical composition comprising carbon monoxide to the recipient.

114. The method of claim 113, wherein the second pharmaceutical composition is administered to the recipient prior to the transplantation step.

115. The method of claim 113, wherein the second pharmaceutical composition is administered to the recipient during the transplantation step.

116. The method of claim 113, wherein the second pharmaceutical composition is administered to the recipient following the transplantation step.

117. The method of claim 113, wherein the second pharmaceutical composition is administered to the recipient prior to and following the transplantation step.

118. The method of claim 113, wherein the second pharmaceutical composition is administered to the recipient prior to, during, and following the transplantation step.

119. The method of claim 110, wherein the cell is part of a pancreatic islet.

120. The method of claim 110, wherein the cell is a liver cell.

121. The method of claim 110, wherein the cell is a pancreatic β-cell.

122. The method of claim 110, wherein the cell is a fibroblast.

123. The method of claim 110, wherein the cell is a bone marrow cell.

124. The method of claim 110, wherein the cell is a neuronal cell.

125. The method of claim 110, wherein the cell is a myocyte cell.

126. The method of claim 110, wherein the cell is a stem cell.

127. A method of enhancing survival or function of an animal cell transplanted into a recipient, the method comprising:

(a) transplanting an animal cell into a recipient; and

(b) before, during, or after the transplanting step, causing the recipient to inhale an amount of carbon monoxide gas sufficient to enhance survival or function of the transplanted cell in the recipient.

128. The method of claim 127, wherein the carbon monoxide gas is supplied in the form of a vessel containing pressurized gas comprising carbon monoxide.

129. The method of claim 127, further comprising the step of exposing the cell to a carbon monoxide composition *ex vivo*, prior to the transplanting step.

130. The method of claim 127, wherein prior to the transplanting step, the animal cell is maintained in a liquid medium that comprises at least at least 0.0001 g carbon monoxide/100 g medium.

131. The method of claim 127, wherein prior to the transplanting step, the cell is maintained *in vitro* in an atmosphere comprising carbon monoxide.

132. The method of claim 127, wherein the carbon monoxide gas is administered to the recipient during the transplanting step.

133. The method of claim 127, wherein the carbon monoxide composition is administered to the recipient following the transplanting step.

134. The method of claim 127, wherein the carbon monoxide composition is administered to the recipient before the transplanting step.

135. The method of claim 127, wherein the cell is obtained from a donor that is not the recipient.

136. The method of claim 127, wherein the cell is obtained from the recipient.

137. The method of claim 127, wherein the cell is removed from a donor prior to being transplanted into the recipient; and

a pharmaceutical composition comprising carbon monoxide is administered to the donor prior to removal of the cell from the donor.

138. The method of claim 127, wherein the cell is part of a pancreatic islet.

139. The method of claim 127, wherein the cell is a liver cell.

140. The method of claim 127, wherein the cell is a pancreatic β-cell.

141. The method of claim 127, wherein the cell is a fibroblast cell.

142. The method of claim 127, wherein the cell is a bone marrow cell.

143. The method of claim 127, wherein the cell is a neuronal cell.

144. The method of claim 127, wherein the cell is a myocyte cell.

145. The method of claim 127, wherein the cell is a stem cell.

146. A method of improving survival of a transplanted cell in a recipient, comprising administering to the recipient, before, during, or after transplantation of the cell into the recipient, an effective amount of a pharmaceutical composition comprising carbon monoxide gas, to thereby improve survival of the cell following transplantation.

147. An article of manufacture that includes a vessel containing pressurized gas comprising least 0.001ppm carbon monoxide and a label describing use of the gas to enhance survival of isolated animal cells before, during or after transplantation of the cells into a patient.

148. A sterile cell medium comprising: (a) nutrients suitable for maintaining an animal cell in culture and (b) at least about 0.0001 g carbon monoxide/100 g medium.

149. A method of maintaining an animal cell *in vitro*, the method comprising:

(a) providing a vessel containing pressurized gas comprising carbon monoxide gas;

(b) providing an isolated animal cell *in vitro,* wherein the cell is disposed in a medium comprising dissolved carbon monoxide;

(c) releasing the pressurized gas from the vessel, to form an atmosphere comprising carbon monoxide gas; and

(d) maintaining the cell in the presence of the atmosphere; and

(e) transplanting the cell into a recipient.