Abstract:

The present invention relates to an extracorporeal blood treatment system, comprising a gas exchange module operatively associated with a gas supply unit and an optional pump for removing CO2 from blood. The gas exchange module includes a plurality of short conduits that are uniquely configured and arranged in a gas exchange mat to facilitate efficient CO2 diffusion under conditions of low blood flow.
CARBON DIOXIDE REMOVAL SYSTEM

[0001] This application claims benefit of priority to United States Provisional Patent Application No. 61/802,335, filed March 15, 2013, and European Patent Application No. 13168103.3, filed May 16, 2013. The disclosures of these applications are herein incorporated by reference in their entirety.

BACKGROUND OF THE INVENTION

Field of the Invention

[0002] The present invention is directed to a carbon dioxide removal system and methods for use thereof. In particular, the invention may be useful for treating diseases, syndromes, injuries, defects or other conditions affecting lung function, including chronic obstructive pulmonary disease (COPD), chronic and acute hypercapnia, respiratory acidosis, acute lung injury (ALI), and acute respiratory distress syndrome (ARDS).

Description of the Related Technology

[0003] The primary functions of the lung are oxygenation and elimination of carbon dioxide (CO$_2$) from blood. Currently, treatments for respiratory problems are primarily focused on addressing and enhancing oxygenation. Ventilation, for example, is the standard of care for COPD, which inhibits expiration of CO$_2$, and persistently elevated levels of CO$_2$ caused by hypercapnia. Mechanical ventilation, however, is an invasive therapy, the associated applied pressures of which induce shear stress, over distention, cyclic stretching, lesions of the alveolar-capillary membrane and other forms of tissue damage. These physiological injuries along with the increased intrathoracic pressure associated with mechanical ventilation further impair alveolar-capillary permeability, decrease cardiac output and impede organ perfusion. Furthermore, mechanical ventilation increases the risk of complications, such as ventilator associated pneumonia (VAP), can require sedation of the patient.

[0004] Alternative protective ventilation therapies, such as extracorporeal membrane oxygenation (ECMO), has fewer negative side-effects than mechanical ventilation. High blood flow is necessary to drive the low tidal oxygenation and of ECMO therapy. This large blood flow, however, increases patient risk in the event of blood leakage and requires the use of large, invasive cannulas and needles causing patient trauma.
Furthermore, ECMO has thus far only been proven safe and effective for treating select respiratory diseases.

[0005] Another type of protective ventilation therapy is provided by a combination oxygenator and CO₂ removal device. This device is designed for low blood flow resistance and therefore does not require a pump for arterial venous use. Additionally, the device utilizes long gas exchange fibers that are adapted for large mass transfer of gas, which is in efficient for CO₂ removal.

[0006] In light of the above, there exists a need to develop an improved respiratory treatment system and therapy that is safe, relatively non-invasive and that effectively removes CO₂ from the blood.

**SUMMARY OF THE INVENTION**

[0007] An extracorporeal blood treatment system according to an example embodiment of the present invention comprises a gas exchange module configured to provide a passageway for blood and to remove carbon dioxide from the blood as the blood passes through the gas exchange module. The gas exchange module comprises a plurality of conduits, wherein each conduit comprises an exterior surface and an interior luminal surface and wherein the interior luminal surface defines a passageway. At least some of the conduits comprise pores, wherein upon exposure of the blood to the exterior surface all of the conduits comprising pores have a first length that allows for diffusion of carbon dioxide from the blood to the passageway.

[0008] An extracorporeal blood treatment system according to an example embodiment of the present invention comprises a gas exchange module configured to provide a passageway for blood and to remove carbon dioxide from the blood as the blood passes through the gas exchange module. The gas exchange module comprises a plurality of conduits at least partially contained in the gas exchange module, wherein each conduit comprises an interior luminal surface defining a passageway and an exterior surface. At least some of the conduits comprise pores, and all of the conduits that comprise pores have a first length along the conduits allowing for the diffusion of carbon dioxide from the blood contained outside the conduits but inside the gas exchange module, to the passageway upon exposure of the blood to the exterior surface of the
conduits. The first length of at least one of the conduits that comprise pores is about 5.8 cm or less.

[0001] An extracorporeal blood treatment system according to an example embodiment of the present invention comprises a gas exchange module configured to provide a passageway for blood and to remove carbon dioxide from the blood as it passes through the gas exchange module. The gas exchange module comprises a plurality of conduits at least partially contained in the gas exchange module, wherein at least one conduit is configured to provide a passageway for gas and to allow for diffusion of carbon dioxide from the blood through a wall of the at least one conduit and to the passageway upon exposure of the blood to an exterior surface of the at least one conduit and wherein the at least one conduit has a first length available for carbon dioxide diffusion of about 5.8 centimeters or less. The extracorporeal blood treatment system does not have a heat exchanger adapted for regulating the temperature of the blood.

[0002] An extracorporeal blood treatment system according to an example embodiment of the present invention comprises a gas exchange module configured to provide a passageway for blood and remove carbon dioxide from the blood as the blood passes through the gas exchange module. The gas exchange module comprises a plurality of conduits at least partially contained in the gas exchange module, wherein at least one conduit is configured to provide a passageway for gas and to allow for diffusion of carbon dioxide from the blood contained outside the conduits but inside the gas exchange module to the passageway upon exposure of the blood to an exterior surface of the at least one conduit and wherein the at least one conduit has a surface area available for carbon dioxide diffusion of about 5.42 X 10^-5 m² to about 7.85 X 10^-5 m². The extracorporeal blood treatment system does not have a heat exchange mechanism.

[0003] An extracorporeal blood treatment system according to an example embodiment of the present invention comprises a gas exchange module configured to provide a passageway for blood and remove carbon dioxide from the blood as it passes through the gas exchange module. The gas exchange module comprises a plurality of conduits at least partially contained in the gas exchange module and arranged to form a gas exchange mat, wherein at least one conduit is configured to provide a passageway for gas and to allow for diffusion of carbon dioxide from the blood upon exposure of the blood to an exterior surface of the at least one conduit and wherein a ratio of a first length
of the at least one conduit to a total thickness of the gas exchange mat is about 1:1 or less. The extracorporeal blood treatment system does not have a heat transfer mechanism.

[0004] An extracorporeal blood treatment system according to an example embodiment of the present invention comprises a gas exchange module configured to provide a passageway for blood and remove carbon dioxide from the blood as it passes through the gas exchange module. The gas exchange module includes a plurality of conduits forming one or more gas exchange mats, wherein at least one conduit is configured to provide a passageway for gas and to allow along a first length of the at least one conduit diffusion of carbon dioxide from the blood upon exposure of the blood to an exterior surface of the at least one conduit. A ratio of the first length to a total thickness of the gas exchange mats is about 3:1 or less, about 2:1 or less and about 1:1 or less.

[0009] According to an example embodiment, a collective average of the first lengths of the conduits that comprise pores is about 5.8 cm or less.

[0010] According to an example embodiment, at least one of the plurality of conduits has an outer diameter of about 350 μm to about 410 μm.

[0011] According to an example embodiment, all of the conduits that comprise pores have an average outer diameter of about 350 μm to about 410 μm.

[0012] According to an example embodiment, a first length of at least one of the conduits that comprise pores is about 76.3% or less than a full length of the at least one of the conduits that comprise pores.

[0013] According to an example embodiment, an average of the first length of all of the conduits that comprise pores is about 76.3% or less than an average of the full length of all of the conduits that comprise pores.

[0014] According to an example embodiment, an exposed surface area of the at least one conduit is about 5.71 X 10^{-5} m² to about 7.47 X 10^{-5} m².

[0015] According to an example embodiment, the pores of the conduits that comprise pores are about 0.2 microns or less.

[0016] According to an example embodiment, the at least one conduit is constructed from polymethylpentene.

[0017] According to an example embodiment, all of the conduits that comprise pores are constructed from polymethylpentene.
According to an example embodiment, the at least one conduit has a microporous microstructure covered by a thick and impervious diffusion layer membrane.

According to an example embodiment, the conduits that comprise pores are arranged in a crisscrossing pattern.

According to an example embodiment, the conduits that comprise pores are arranged to form conduit layers located between a blood inlet and a blood outlet of the gas exchange module, the blood inlet faces the conduit layers such that the blood flows towards the conduit layers in a direction substantially orthogonal to the conduit layers.

According to an example embodiment, each conduit layer is comprised of two or more of the conduits that comprise pores arranged substantially parallel to one another.

According to an example embodiment, the two or more of the conduits that comprise pores and are arranged substantially parallel to one another are knitted or woven together by a separate thread or thread-like structure.

According to an example embodiment, the conduits of adjacent conduit layers are oriented substantially perpendicular to one another.

According to an example embodiment, the gas exchange module comprises at least about 10,000 conduits that comprise pores, at least about 12,000 conduits that comprise pores, at least about 13,000 conduits that comprise pores, or at least about 13,119 conduits that comprise pores.

According to an example embodiment, a combined surface area available for carbon dioxide diffusion of all conduits that comprise pores is about 0.98 m² or more.

According to an example embodiment, a combined surface area available for carbon dioxide diffusion of all conduits that comprise pores is about 0.92 m² or more, about 0.95 m² or more, about 0.98 m² or more.

According to an example embodiment, the system further comprises a pump operatively associated with the gas exchange module for directing and regulating a flow of the blood to the gas exchange module, wherein the pump is adapted to deliver the blood to the gas exchange module at rate of about 1 L/min or less.

According to an example embodiment, the system further comprises a pump operatively associated with the gas exchange module for directing and regulating a flow
of the blood to the gas exchange module, wherein the pump is adapted to deliver the blood to the gas exchange module at rate between about 0.2 L/min to about 0.8 L/min.

[0029] According to an example embodiment, the gas exchange module comprises a pressure sensor positioned adjacent to the blood outlet and in direct contact with the blood exposed to the conduits that comprise pores for measuring blood pressure as the blood exits the gas exchange module.

[0030] According to an example embodiment, the gas exchange module further comprises a gas inlet and gas outlet, wherein all of the conduits of the gas exchange module that comprise pores are in fluid communication with the gas inlet.

[0031] According to an example embodiment, the system does not include a heat exchange mechanism.

[0032] According to an example embodiment, the system does not regulate the temperature of any fluid entering or leaving the gas exchange module.

[0033] According to an example embodiment, the system further comprises a cannula operatively associated with the gas exchange module, wherein the cannula has a size of about 2.1 French (7 mm) or less, about 19 French (6.33 mm) or less, about 16 French (5.33 mm) or less, or about 13 French (4.33 mm) or less.

[0034] According to an example embodiment, the cannula is a double-lumen cannula.

[0035] According to an example embodiment, a combined volume of the conduits of the gas exchange module that comprise pores is about 0.085 liters to about 0.100 liters.

[0036] According to an example embodiment, the plurality of conduits form one or more gas exchange mats, and the ratio of the first length of the at least one conduit to a total thickness of the gas exchange mat is about 3.0 or less.

[0037] According to an example embodiment, the system is configured for carbon dioxide removal from the blood with at most only nominal diffusion of oxygen to the blood.

[0038] A method for removing carbon dioxide from blood according to an example embodiment of the present invention uses a blood treatment system comprising a gas exchange module configured to provide a passageway for blood and remove carbon dioxide from the blood as it passes through the gas exchange module. The gas exchange module comprises a plurality of conduits at least partially contained in the gas exchange
module, wherein at least one conduit is configured to provide a passageway for gas and to allow for diffusion of carbon dioxide from the blood to pass to the passageway upon exposure of the blood to an exterior surface of the at least one conduit and wherein at least one conduit has a first length available for carbon dioxide diffusion of about 5.8 cm or less. The method for using the blood treatment system comprises: selecting a gas exchange module to treat a human including an adult human; flowing the blood into the gas exchange module at a rate of 1 liter per minute or less; and exposing the blood to a plurality of conduits that comprise pores to remove carbon dioxide from the blood.

[0039] According to an example embodiment, the method involves flowing blood into the gas exchange module at a rate of about 0.51 liters per minute or less or between about 0.4 liters per minute to about 0.51 liters per minute.

[0040] According to an example embodiment, the method involves flowing gas through the conduits at a rate of 0.2 liters per minute to 15 liters per minute.

[0041] According to an example embodiment, the method involves flowing gas through the conduits at a rate of more than about 15 liters per minute.

[0042] According to an example embodiment, the method involves selecting a gas that has a partial pressure of carbon dioxide that is zero or at least lower than a partial pressure of carbon dioxide of the blood flowing into the gas exchange module.

[0043] According to an example embodiment, the method involves treating the blood without regulating blood temperature.

[0044] According to an example embodiment, wherein throughout the length of the at least one conduit, there exists a carbon dioxide gradient between a gas flowing through the at least one conduit and the blood exposed to the exterior surface of the at least one conduit.

[0045] According to an example embodiment, wherein the carbon dioxide gradient is substantially constant along the length of the at least one conduit.

[0046] According to an example embodiment, the method involves after said step of exposing, measuring blood pressure using a sensor of the gas exchange module in direct contact with the blood exposed to the conduits after exposing the blood to the plurality of conduits.
According to an example embodiment, the method involves measuring the amount of carbon dioxide removed from the blood using a sensor of the gas exchange module.

According to an example embodiment, the conduits are arranged in layers and are located between a blood inlet and a blood outlet of the gas exchange module, and wherein the blood flows towards the conduits in a direction substantially orthogonal to the length of the conduits.

According to an example embodiment, the method involves obtaining from a venous blood source the blood delivered to the gas exchange module and treating the blood such that a partial pressure of carbon dioxide in the blood after exposure to the conduits is about 50 mm Hg to about 70 mm Hg.

According to an example embodiment, the method involves obtaining from a venous blood source the blood delivered to the gas exchange module and treating the blood such that a pH value of the blood exposed to the conduits is about 7.25 to about 7.35.

According to an example embodiment, the method involves extracting from a venous circulatory system the blood delivered to the gas exchange module and returning the blood treated by the gas exchange module to the venous circulatory system.

According to an example embodiment, the blood is treated by the gas exchange module for a period of about 6 hours to about 30 days.

According to an example embodiment, the method involves using the blood treatment system to remediate a respiratory condition in the adult human selected from the group consisting of chronic obstructive pulmonary disease, acute lung injury, acute respiratory distress syndrome and hypercapnia.

According to an example embodiment, the method involves treating the blood by removing carbon dioxide from the blood with no or at most only nominal diffusion of oxygen.

According to an example embodiment, the method for removing carbon dioxide is performed using any of the above described example blood treatment system embodiments.

An extracorporeal blood treatment system according to an example embodiment of the present invention comprises a gas exchange module configured to
provide a passageway for blood and remove carbon dioxide from the blood as it passes through the gas exchange module. The gas exchange module comprises a plurality of conduits at least partially contained in the gas exchange module, wherein at least one conduit is configured to provide a passageway for gas and to allow for diffusion of carbon dioxide from the blood upon exposure of the blood to an exterior surface of the at least one conduit and wherein the at least one conduit has a length available for carbon dioxide diffusion of about 5.8 centimeters or less. The blood treatment system further includes a gas inlet and gas outlet, wherein all of the conduits of the gas exchange module are operatively associated with the gas inlet to permit fluid communication of the gas though the gas exchange module.

**BRIEF DESCRIPTION OF THE DRAWINGS**

[0057] Figure 1 is a diagram showing an exemplary blood treatment system attached to a patient's jugular vein using a dual lumen catheter and including a gas exchange module.

[0058] Figure 2 is a diagram showing an exemplary blood treatment system attached to a patient's jugular vein using a dual lumen catheter and including a gas exchange module operatively associated with a gas supply unit and a pump.

[0059] Figure 3(a) is a perspective view of an exemplary gas exchange module of the blood treatment system.

[0060] Figure 3(b) is a perspective view showing the internal housing components of the gas exchange module of Figure 3(a), including a single blood treatment chamber without the gas exchange conduits.

[0061] Figure 3(c) is a perspective view of another embodiment of the gas exchange module of Figure 3(b) showing a frame dividing the blood treatment chamber into two compartments, each adapted for receiving a gas exchange mat.

[0062] Figure 3(d) is a front view of the gas exchange module of Figure 3(a).

[0063] Figure 3(e) is a cross-sectional view of the gas exchange module of Figure 3(d) taken at line A-A, showing a single, empty blood treatment chamber.

[0064] Figure 3(f) is a cross-sectional view of the gas exchange module of Figure 3(d) taken at line A-A, showing a blood treatment chamber with a gas exchange mat.
situated within the blood treatment chamber and illustrating the flow of gas through the
gas exchange module.

[0065] Figure 3(g) is a cross-sectional view of another embodiment of the gas
exchange module of Figure 3(e) corresponding to the embodiment of Figure 3(c),
showing a frame dividing the blood treatment chamber into two compartments that fluidly
communicate with one another as best shown in Figure 3(c), each compartment
containing a gas exchange mat.

[0066] Figure 3(h) is an overhead view of the blood treatment system of Figure 3(a).

[0067] Figure 3(i) is a cross-sectional view of the gas exchange module of Figure
3(h) at line B-B illustrating the flow of gas through the gas exchange module.

[0068] Figure 3(j) is a cross-sectional view of the gas exchange module of Figure
3(i) at line D-D.

[0069] Figure 3(k) is a two dimensional schematic diagram of two adjoining conduit
layers of the gas exchange mat showing the perpendicular orientation of the conduit
layers.

[0070] Figure 3(l) is a three dimensional diagram of a portion of a conduit layer
showing a plurality of parallel conduits.

[0071] Figure 3(m) is a two dimensional schematic diagram of two adjoining conduit
layers of the gas exchange mat showing the relative perpendicular orientation of the
conduit layers.

[0072] Figure 3(n) is a cross-sectional view of the gas exchange module of Figure
3(h) at line C-C.

[0073] Figure 4 shows an exemplary blood treatment system attached to a patient's
jugular and femoral veins using two small single lumen catheters and including a gas
exchange module and integral pump operatively associated with a gas supply unit.

[0074] Figure 5 shows a flow chart of describing an exemplary blood treatment
method of the present invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0075] For illustrative purposes, the principles of the present invention are described
by referencing various exemplary embodiments. Although certain embodiments of the
invention are specifically described herein, one of ordinary skill in the art will readily
recognize that the same principles are equally applicable to, and can be employed in other systems and methods. Before explaining the disclosed embodiments of the present invention in detail, it is to be understood that the invention is not limited in its application to the details of any particular embodiment shown. Additionally, the terminology used herein is for the purpose of description and not of limitation. Furthermore, although certain methods are described with reference to steps that are presented herein in a certain order, in many instances, these steps may be performed in any order as may be appreciated by one skilled in the art; the novel method is therefore not limited to the particular arrangement of steps disclosed herein.

[0076] It must be noted that as used herein and in the appended claims, the singular forms "a", "an", and "the" include plural references unless the context clearly dictates otherwise. Thus, for example, reference to "a conduit" may include a plurality of conduits and equivalents thereof known to those skilled in the art, and so forth. As well, the terms "a" (or "an"), "one or more" and "at least one" can be used interchangeably herein. It is also to be noted that the terms "comprising," "including," "composed of," and "having" can be used interchangeably.

[0077] For purposes of the present invention, the "active length" or "active portion" of a conduit refers to the collective lengths or portions of a conduit having a surface area that allows for passage of gas through the conduit, particularly CO₂ diffusion. For example, the active length or active portion may be the total lengths or portions of a conduit membrane having pores that are at least substantially unimpeded and allow for gas exchange through the conduit via the pores.

[0078] As used herein the "inactive length" or "inactive portion" of a conduit refers to the collective lengths or portions of the conduit incapable of passage of gas through the conduit, particularly incapable of CO₂ diffusion. For example, the inactive length or inactive portion may be the total lengths or portions of a conduit potted within a matrix such that any pores of the potted length or portion are blocked or otherwise prevented from the transfer of gas through the conduit wall.

[0079] As used herein, "non-physiological values" of the partial pressure of CO₂ in blood or of blood pH refers to values of CO₂ partial pressure or blood pH that are not within the standard accepted physiological range. For example, for blood taken from the arterial system, normal physiological values of PCO₂ of the blood typically may be about
32-46 mm Hg and normal value of pH may be about 7.45; for blood taken from the
venous system, normal physiological values of pCO₂ of the blood typically may be about
38-54 mm Hg and normal values of pH may be about 7.35.

As used herein, "property of blood" refers to a physiological characteristic or
component of blood. Exemplary properties include temperature, composition and partial
pressure or CO₂ content.

Furthermore, "treating" as used herein refers to improving, alleviating or
remedying a disease, syndrome, injury and defect, other condition, or an associated
symptom thereof.

The present invention is directed to a novel extracorporeal blood treatment
system and therapeutic method for efficiently, effectively and safely removing CO₂ from
a patient's blood stream in a minimally invasive manner. In an exemplary embodiment,
the invention is adapted to directly access a patient's vascular system, the extracorporeal
blood treatment system is specifically designed to remove substantially all the CO₂ from a
flow of a patient's blood passing through a gas exchange module of the system at a low
flow rate in a single pass. The invention may be used for various applications, including
treating respiratory conditions, such as COPD, chronic and acute hypercapnia, respiratory
acidosis, acute lung injury, acute respiratory distress syndrome and hypercapnia, by
substantially eliminating CO₂ from blood circulating in a patient.

**Blood Treatment System**

Figures 1-2 illustrate exemplary embodiments of the extracorporeal blood
treatment system 1 of the present invention, which include a gas exchange module 10
having a plurality of conduits 30, at least some or all of which are configured to alter a
property of blood flowing through gas exchange module 10. In particular, gas exchange
module 10 includes a plurality of short conduits 30 each having a gas permeable
membrane, wherein conduits 30 are uniquely configured and arranged in one or more gas
exchange mats 34 for efficient gas diffusion, such as efficient CO₂ diffusion. In an
exemplary embodiment, gas exchange module 10 is configured as a gas transfer device
having a plurality of gas permeable conduits 30 specifically designed and adapted for
CO₂ diffusion. Blood treatment system 1 may optionally further include a gas supply unit
50 that delivers a stream of gas through the lumens of conduits 30 while blood passes
through gas exchange module 10 contacting and flowing past an exterior surface of conduits 30 at a low flow rate. Gas diffusion, specifically CO₂ diffusion, from the blood and through the gas permeable membrane of conduits 30 is driven by the difference in gas partial pressure, e.g. CO₂ partial pressure, between the gas flowing through conduits 30 and the gas partial pressure, e.g. CO₂ partial pressure, of the patient's blood exposed to and flowing around conduits 30. Gas supply unit 50 supplies gas at a high velocity gas flow rate through conduits 30 to maximize and maintain the driving force of gas diffusion, e.g. CO₂ diffusion, along the length active length of conduit 30. Blood treatment system 1 may optionally further include a pump 60 and an integral or otherwise operatively associated control unit 62 for regulating the flow of blood through gas exchange module 10. In an exemplary embodiment, extracorporeal blood treatment system 1 is not designed to oxygenate the patient's blood and/or does not include a heat exchanger for heating or cooling blood delivered to, flowing through or exiting from the gas exchange module 10 or otherwise seek to change or regulate blood temperature.

Figures 2(a)-2(m) show an exemplary gas exchange module 10 having a housing 12 defining an internal cavity 13 through which blood is flowed and for at least partially containing a plurality of conduits 30 adapted for gas diffusion, in particular CO₂ diffusion. As shown in Figures 3(a)-3(b) and 3(d)-3(f), gas exchange module 10 includes a blood inlet port 14 and blood outlet port 16 spaced apart from one another and located on opposing faces of housing 12. A plurality of gas exchange conduits 30 are arranged between blood inlet and outlet ports 14, 16 such that blood entering blood inlet port 14 flows towards conduits 30 in a direction substantially orthogonal to the length of one or more, or all of conduits 30. The opening and length of elongated blood inlet and/or outlet ports 14, 16 may also be oriented substantially orthogonal to the length of one or more conduits 30. Gas exchange module 10 further includes a gas inlet port 18 and gas outlet port 20 for delivering gas to and from the plurality of conduits 30. Gas inlet and outlet ports 18, 20 are spaced apart from one another and may be aligned in the same plane as conduits 30 and oriented substantially orthogonal to blood inlet and outlet ports 14, 16 such that gas flowing through gas exchange module 10 is substantially orthogonal to blood flow through gas exchange module 10.

Conduits 30 may be configured as hollow, thin fibers or other tubules with a central lumen for gas passage, best shown in Figures 3(k)-3(m). These lumens provide a
passageway through which gas is transported to induce CO₂ diffusion from blood contacting an exterior surface of conduit 30, through the conduit walls and into the conduit lumens. Conduits 30 may be configured to have a gas permeable membrane, such as a porous membrane including a plurality of pores adapted for gas diffusion, particularly CO₂ diffusion. In one embodiment, conduits 30 may have a microporous membrane, such as the microporous polypropylene hollow fiber manufactured by Polypore and marketed under the trade name OXYPAHAN having a maximum 2 micron pore size, or alternatively a diffusive membrane, such as the diffusive polymethylpentene hollow fiber membrane having a 55% porosity manufactured by Polypore and marketed under the trade name OXYPLUS. Conduits 30 may have the same or different degree of porosity and/or pore size. In one embodiment, the gas permeable membrane of conduit 30 may have a pore size or diameter of about 0.2 microns or smaller. In one embodiment, the gas permeable membrane of conduits 30 may be configured to only permit gas passage, specifically CO₂ diffusion, inhibiting diffusion of liquids or solids. The gas permeable membrane may also be configured to inhibit blood plasma leakage. In one embodiment, conduits 30 may be configured to allow for CO₂ diffusion while preventing blood plasma leakage for up to at least 30 days under normal operating pressures and flow rates. Conduits 30 may be constructed from any gas permeable material that optionally also inhibits blood plasma leakage. In an exemplary embodiment, polymethylpentene may be used to construct conduits 30.

[0086] While gas exchange module 10 may include other types of conduits different than gas exchange conduits 30, such as conduits which do not affect a property of blood, non-porous conduits which affect the property of blood, gas impermeable conduits which affect the property of blood, and/or porous conduits which allow for diffusion of gases other than CO₂, in one embodiment all the conduits of gas exchange module 10, inclusive of all the gas exchange conduits 30, are adapted for gas diffusion, such as CO₂ diffusion. In another embodiment, all the conduits of gas exchange module 10 that are configured to alter a property of blood, inclusive of gas exchange conduits 30, may be gas permeable and/or have a microporous membrane with pores adapted for gas diffusion, such as CO₂ diffusion.

[0087] Efficient removal of CO₂ using gas exchange module 10 under low blood flow rate conditions is achieved by the uniquely configured conduits 30 and/or the
arrangement of a plurality of these conduits 30 to form one or more gas exchange mats 34 having a sufficient collective thickness to effectively diffuse CO2 from blood. In an exemplary embodiment, gas exchange conduits 30 may have a short length that allows for decreased fluidic resistance of the gas, such as a high velocity stream of gas, flowing through the lumen, and therefore minimizes any pressure drop within and across conduit 30. Consequently, the low back pressure conditions within conduit 30 inhibits formation of potentially dangerous microbubbles on the exterior blood contacting surface of conduit 30 thereby preventing formation of an emboli in the blood. In one embodiment, conduit 30 may have a sufficiently short length that substantially prevents formation of microbubbles on an exterior of conduit 30 and/or a drop in gas flow pressures within and along the length of conduit 30 as gas is flowed through the conduit lumen at a predetermined, constant gas flow rate. In an exemplary embodiment, conduits 30 have a full length, illustrated as dimension X in Figures 3(i) and 3(j), of about 71 cm to about 81, about 71 to about 76, or about 76 to about 81.

[0088] Each conduit 30 has an elongated body including a proximal end 36 and distal end 38. As will be described in further detail below, when conduits 30, are positioned within, potted in, affixed to, attached to or otherwise disposed within a blood treatment chamber 24 located in the internal cavity 13 of housing 12, portions of conduit 30, particularly proximal and distal ends 36, 38, may be rendered incapable of gas transfer by virtue of the manner in which conduit 30 is attached to blood treatment chamber walls 26. This inactive portion or inactive length of a conduit 30, shown in Figure 3(i) by the collective dimensions W of the total length X of one conduit 30, have pores that may be blocked and otherwise prevented from allowing localized gas diffusion, specifically CO2 diffusion. In the illustrated embodiment, the inactive length of a conduit 30 is the sum of the two W dimensions of a total length X of one conduit 30. The remaining active portion or active length of conduit 30, shown in Figure 3(i) as dimension Y, may allow for gas diffusion, in particular CO2 diffusion. In the illustrated embodiment, one Y reference denotes the active length of the conduits 30 of a first conduit layer 32a (labeled as 32), and the other Y reference denotes the active length of the conduits 30 of an adjoining perpendicularly oriented second conduit layer 32b (not labeled) beneath conduit layer 32a. In an exemplary embodiment, the active length of the conduit 30 available for CO2 diffusion may be about 5 cm to about 6 cm, about 5.2 cm to about 5.8
cm, about 5.2 cm to about 5.5 cm, or about 5.5 cm to about 5.8 cm. The percent of the active length of conduit 30 to the overall length of conduit 30 may be about 76.3% or less, about 40% to about 76.3%, about 68.4% to about 76.3%, or about 68.4% to about 72.4%. In another embodiment, the ratio of conduit active length to the total length of conduit 30 is about 0.724:1 ± 5%, about 0.79:1 or less, about 0.77:1 or less. The ratio of conduit active length to conduit inactive length may be about 2.12:1 to about 3.22:1, about 2.12:1 to about 2.62:1, or about 2.62:1 to about 3.22:1. The available active surface area for CO₂ diffusion of a single conduit 30 may be 5.42 X 10⁻³ m², about 5.42 X 10⁻³ m² to about 7.85 X 10⁻³ m², about 5.60 X 10⁻³ m² to about 7.85 X 10⁻³ m², about 5.71 X 10⁻³ m² to about 7.47 X 10⁻³ m², or about 5.71 X 10⁻³ m² to about 7.01 X 10⁻³ m². In an exemplary embodiment, the active surface area of a single conduit 30 may be about 5.71 X 10⁻³ m² ± 5% to about 7.47 X 10⁻³ m² ± 5%. The outer diameter of conduit 30 may be about 350 µm to about 410 µm. Additionally, the volume of conduit 30 may be about 0.085 L to about 0.100 L.

As best shown in Figures 3(k)-3(m), conduits 30 are arranged in a set and positioned substantially parallel to one another, wherein conduits 30 are bound to, attached to or otherwise connected to one another in order to form a thin conduit layer 32. Conduit layer 32 may be constructed from conduits 30 of the same or different configuration and/or dimensions, such as length and diameter. Conduits 30 and conduit layer 32 form a plurality of passages for gas to pass from one side of the gas exchange module 10 to an opposite side of gas exchange module 10. Additionally, conduit layer 32 is configured to allow for blood to pass between and around adjacent conduits 30. In one embodiment, the conduits 30 within a conduit layer 32 are knitted together with a filament, such as thread, yarn or other suitable material, so as not to substantially or at most only minimally impede and interfere with gas diffusion. This is best illustrated in Figure 3(i), wherein conduits 30 are arranged in a conduit layer 32 and fixed to one another by intermittently knitting one or more filaments along the length of conduit layer 32 to connect adjoining conduits 30.

In an exemplary embodiment, a plurality of conduit layers 32 are stacked on top of one another and oriented parallel to one another in order to form a gas exchange mat 34, as shown in Figures 3(k) and 3(m). Gas exchange mat 34 may be constructed from conduit layers 32 of the same or different dimensions and/or configuration.
length of conduits 30 of two adjoining conduit layers 32 are oriented in the same plane and offset from one another. In one embodiment, the two adjoining conduit layers 32 are oriented substantially perpendicular to one another such that the conduit length of and direction of gas passing through a first conduit layer 32a is substantially perpendicular to the conduit length of and direction of gas passing through an adjoining second conduit layer 32b. In one embodiment, the conduits 30 of two adjoining conduit layers 32a, 32b are oriented substantially about 45° to about 135°, about 65° to about 115°, about 75° to about 105°, or about 85° to about 95° out of phase with and relative to one another. By way of example, there may be about 120 to about 160, about 130 to about 155, about 135 to about 153, or about 140 to about 148 conduits layers 32 in gas exchange mat 34. In another embodiment, there may be about 95 to about 115, about 100 to about 108, or about 102 to about 106 conduits layers 32 in gas exchange mat 34. In one embodiment, there may be about 131.19 to about 11,712 conduits 30 in gas exchange mat 34. The resultant gas exchange mat 34 can have any configuration fitted to and/or positionable within blood treatment chamber 24, such as a cuboid or cylinder. This layered arrangement of conduit layers 32 creates a dense network of gas exchange conduits 30 designed to maximize the available surface area for gas transfer and thereby enhance CO₂ diffusion efficiency, while still allowing for sufficient flow of blood between the blood inlet and outlet ports 14,16.

[0091] Gas exchange module 10 may include one or more gas exchange mats 34. In one embodiment, gas exchange module 10 may have a single gas exchange mat 34. In another embodiment, as best shown in Figure 3(g), two adjacent gas exchange mats 34a, 34b, each composed of a plurality of stacked conduit layers 32, may be potted within blood treatment component 24. These gas exchange mats 34a, 34b may adjoin and be positioned in a stacked orientation such that blood passing through blood treatment chamber 24 flows in a direction substantially orthogonal to both gas exchange mats 34. As illustrated in the exemplary embodiment of Figures 3(c) and 3(g), first and second gas exchange mats 34a, 34b may be spaced apart from one another by a frame 28 having a plurality of openings to allow blood to pass from first gas exchange mat 34a to second gas exchange mat 34b with no to minimal impedance.

[0092] To further improve CO₂ diffusion efficiency, the collective thickness of one or more gas exchange mats 34 is may be sufficient to effectively remove in a single pass
through the one or more gas exchange mat 34 and/or in a single pass through gas
exchange module 10 substantially all the CO2 from the patient's blood that is passed therethrough. A suitable total thickness of the adjoining one or more gas exchange mats 34, identified in the exemplary embodiment of Figure 3(j) as dimension Z, may be described in terms of the length of conduits 30. In one embodiment, the ratio of the active length of conduit 30 to the total thickness of one or more gas exchange mats 34 of gas exchange module 10 may be about 3:1 to about 0.5:1, about 2:1 to about 0.8:1, about 2:1 to about 0.9:1, or about 1:1 to about 0.9:1. In another embodiment, the ratio of the active length of conduit 30 to the thickness of gas exchange mat 34 is about 3:1 or less, about 2:1 or less, or about 1:1 or less. In one embodiment, a ratio of about 1:1 suggests that the blood flow path and gas flow path are designed to allow for maximum exposure, processing and filtration of the blood by conduits 30 and to facilitate CO2 diffusion by reducing the relative differences in blood flow and gas flow resistance. In another embodiment, the aforementioned ratio values may also represent the ratio of the active length of conduits 30 to the shortest path of blood flow through the blood treatment chamber. In an exemplary embodiment, the total thickness of the one or more gas exchange mat 34 may have a thickness of about 54.7 mm. In one embodiment, the overall available gas exchange surface area of the gas exchange mat 34 is about 0.5 m² to about 1.3 m², 0.5 m² to about 1.2 m², about 0.5 m² to 0.98 m², or 0.98 m² to 1.3 m². The gas exchange mat 34 may include at least about 10,000, at least about 12,000 conduits, at least about 13,000 conduits, at least about 13,19 conduits, or at least about 13,300 conduits. Alternatively or additionally, the gas exchange mat 34 may have at least 13,300 conduits per square meter of gas exchange surface area.

As shown in Figures 3(f) and 3(i)-3(j), gas exchange mats 34 are potted within, disposed within, affixed to or otherwise attached to one or more blood treatment chamber 24 positioned within housing internal cavity 13. Blood treatment chamber 24, which is in fluid communication with and connects blood inlet port 14 and blood outlet port 16, is designed to process the blood so as to filter CO2 from the blood circulated through blood treatment chamber 24 by exposure to the gas exchange surface area of one or more gas exchange mats 34, e.g. unpotted surface area of gas exchange mats 34 capable of CO2 diffusion. One or more gas exchange mats 34 may be potted using any suitable material, such as an epoxy resin, within blood treatment chamber 24 so that
opposing proximal and distal ends of each conduit layer 32 and the proximal and distal ends 36, 38 of their respective conduits 30 extend across blood treatment chamber 24 and through the walls 26 of blood treatment chamber 24, such that the blood treatment chamber walls 26 form a liquid impermeable and sealed perimeter of the blood treatment chamber 24. The proximal and distal ends 36, 38 of conduits 30 in each conduit layer 32 of gas exchange mat 34 extend outwardly beyond the potted portions of gas exchange mats 34 and blood treatment chamber 24, so as to be in fluid communication with and open to a space exterior to blood treatment chamber 24, namely gas passageways 41a, 41b. The lumens of conduits 30 are therefore in fluid communication with gas passageways 41a, 41b as well as gas inlet and outlet ports 18, 20 as described in further detail below.

[0094] Figures 3(e)-3(f) and 3(i) show a plurality of gas passageways 41a, 41b, each having two interconnected first and second sections 42a, 42b and 42c, 42d, respectively. As shown, gas passageways 41a, 41b may be configured as channels positioned within the housing internal cavity 13 around and along the perimeter of blood treatment chamber 24. As previously described, gas passageways 41a, 41b are in fluid communication with conduits 30 for delivering gas to and receiving gas from conduits 30. In the embodiment illustrated in Figure 3(i), each section 42a, 42b, 42c, 42d, configured as compartments of gas passageways 41a, 41b, is defined by a corresponding housing sidewall 22a, 22b, 22c, 22d of housing 12 and a corresponding opposing blood treatment chamber wall 26a, 26b, 26c, 26d spaced apart relative to one another to form the gas passageways 41a, 41b. The length of each section 42a, 42b, 42c, 42d is oriented in the same plane as and is substantially perpendicular to a length of conduits 30 in fluid communication with the respective sections 42a, 42b, 42c, 42d. In one embodiment, all of conduits 30 are in fluid communication with gas inlet port 18 and/or gas outlet port 20 via a gas passageway 41a, 41b. Gas inlet port 18 may be positioned between and connected to first and second interconnected sections 42a, 42b of gas passageway 41a and is defined by respective adjoining housing sidewalls 22a, 22b and blood treatment chamber walls 26a, 26b, forming a forked gas passage. Upon entering gas inlet port 18, gas travels through one of the two diverging sections 42a, 42b of gas passageway 41a and through the proximal ends 36 of conduits 30 of alternating conduit layers 32. For example, gas flowing through section 42a passes through a plurality of the alternating conduit layers (i.e. conduit layer
32a) in a first direction while gas flowing through section 42b passes through adjoining intervening conduit layers (i.e. conduit layer 32b) in a second direction perpendicular to the first direction, as illustrated in Figures 3(f) and 3(i). CO2 diffusion occurs upon exposure of and contact between the blood and conduits 30, flowing blood over, around and between the porous membranes of conduits 30 while a gas, such as a gas substantially free of CO2, is flowed through conduits 30. Blood may flow through the interstices of one or more gas exchange mats 34 over, between and around conduits 30 in a direction that is substantially orthogonal to the direction of the gas flow within conduits 30 and substantially orthogonal to a length of conduits 30. Gas exiting a distal end 38 of conduits 30 flow into first and second sections 42c, 42d of gas passageway 41b which converge and deliver the gas to gas outlet port 20. Gas outlet port 20 may be located between and connected to first and second sections 42c, 42d of gas passageway 41b, defined by adjoining housing sidewalls 22c, 22d and blood treatment chamber walls 26c, 26d.

In an exemplary embodiment, gas exchange module 10 may optionally further include one or more sensors 44 for detecting a physiological parameter of blood or gas flowing through gas exchange module 10. For example, sensor 44 may be in direct contact with blood entering or exiting gas exchange module 10 and is adapted for detecting and measuring blood pressure, blood flow rate, CO2 content, or O2 content. In the exemplary embodiment shown in Figure 3(h), at least one sensor 44 is located within or otherwise disposed at blood outlet port 16, adjacent to the passageway through which blood flows through blood outlet port 16. A second sensor 44 may also or alternatively be attached to and extend from an internal surface of blood inlet port 14. Optionally, one or more sensors 44 may be in direct contact with gas flowing through gas exchange module 10. For example, sensor 44 may be attached to and/or extend from an internal surface of gas inlet port 18 and/or gas outlet port 20. Each of the above described sensors 44 may be operatively associated with control unit 62 and used to confirm blood flow, blood pressure or CO2 partial pressure within gas exchange module 10; detect the presence of gas or blood leakage through gas exchange module 10; and/or provide information based on which the user may set, change and/or modify the blood and gas flow rates through gas exchange module 10 may be adjusted to achieve efficient or otherwise the desired degree or rate of CO2 diffusion.
Blood treatment system 1 may optionally further include a gas supply unit 50 operatively associated with gas exchange module 10 to provide a continuous stream of gas at a controlled, high velocity flow rate to gas inlet port 18. As shown in Figures 1-2, gas supply unit 50 delivers gas directly to gas inlet port 18 of gas exchange module 10 through one or more tubing. In an exemplary embodiment, gas supply unit 50 may be adapted to controls gas flow through conduits 30 such that the gas flow rate through the lumens of conduits 30 is about 0.2 L/min to about 15 L/min, about 1 L/min to about 15 L/min, about 2 L/min to about 15 L/min, or about 5 L/min to about 15 L/min. Gas supply unit 50 may also be used to control the gas pressure within conduits 30. In one embodiment, there is substantially no change in gas pressure across conduit 30.

The gas delivered to conduits 30 may be non-toxic, biocompatible and substantially free from CO₂ and may be administered in toxicological safe amounts. In one embodiment, the partial pressure of CO₂ in the gas is either negligible or there is no CO₂ in the gas. In an exemplary embodiment, the gas may be oxygen, mixtures of oxygen with air, nitrogen or any suitable noble gas. Optionally, gas supply unit 50 may further include one or more gas blending functionalities for mixing or otherwise preparing the gas to be delivered to gas exchange module 10.

Optionally, blood treatment system 1 may further include a blood pump 60 and/or control unit 62 that are operatively associated with gas exchange module 10 for regulating the flow rate of blood through blood treatment chamber 24. In the embodiments shown in Figures 2 and 4, blood pump 60 is fluidly connected to a venous access point and gas exchange module through one or more tubing. In one embodiment, pump 60 may be an occlusive (i.e. peristaltic) pump or centrifugal pump, such as the centrifugal pump manufactured by Maquet Cardiopulmonary of Rastatt, Germany and marketed under the trade name ROTASSIST, or a roller pump. A control unit 62 may be integrated in or otherwise operatively associated with pump 60 to regulate blood flow through pump 60 and through blood treatment chamber 24. Pump 60, as instructed by control unit 62, may control and regulate blood flow through gas exchange module 10, specifically through blood treatment chamber 24, at a rate of about 1.2 L/min or less, about 1 L/min or less, about 0.8 L/min or less, about 0.51 L/min or less, about 0.5 L/min or less, or about 0.4 L/min to about 0.51 L/min. A user may, as desired, interface with control unit 62 to change the rate of blood flow within a designated low blood flow range.
In an exemplary embodiment, blood treatment system 1 does not have a heat exchanger. In such embodiments, gas exchange module 10 does not have any substantially water impermeable fibers adapted for passing a thermally managed flow of water to heat or cool blood within gas exchange module 10. Additionally, in these embodiments blood treatment system 1 is not designed to provide oxygenation and therefore regulation of blood temperature is not required. Blood treatment system 1 may therefore be configured as a dedicated CO\textsubscript{2} removal system adapted specifically and/or only for CO\textsubscript{2} diffusion.

Blood treatment system 1 may optionally further includes a catheter providing vascular access to the patient. Since blood treatment system 1 can be operated under conditions of low blood flow, it is possible to work with small-lumen cannulas or dual-lumen cannulas which provide for less invasive vascular access and improved safety, and thus requires fewer monitoring controls and potential complications. In one embodiment, the size of a single lumen cannula may be about 2\,1 French (7 mm) or less, about 13 French (4.33 mm) or less. In another embodiment, the size of a double lumen cannula may be about 24 French (8 mm) or less or about 19 French (6.33 mm) or less.

In an exemplary embodiment, the blood contacting lumens (e.g. cannula and tubing lumens), chambers (e.g. blood treatment chamber), components and portions of extracorporeal blood treatment system 1, including those lumens, chambers, compartments and surfaces of gas exchange module 10, optional pump 60, access catheters as well as all connective tubings of system 1 may be coated with a material that improves the biocompatibility of the extracorporeal circulation system and may also be thromboresistant.

While the above described embodiments of blood treatment system 1 describe in particular a CO\textsubscript{2} removal system, one skilled in the art would appreciate that blood treatment system 1, gas exchange module 10, particularly conduits 30, and all other described system components may be designed, adapted and configured for the removal, diffusion, extraction or exchange of other gases, in addition to or in place of CO\textsubscript{2}. In particularly, the gas permeable membrane of conduit 30 and selection of gas to be flowed through conduits 30 may be designed and selected for the transfer of these other gases.

The unique configuration of blood treatment system 1 of the present invention provides numerous operational and therapeutic advantages. Designed to
accommodate a low rate of blood flow through gas exchange module 10, the blood
treatment system 1 enables the use of minimally invasive small-lumen or dual-lumen
cannulas to provide minimally traumatic vascular access. The low blood flow rate also
results in low blood pressure conditions within the lumen of conduit 30, which reduces
the potential for blood leakage from blood treatment system 1 as well as reduces the
severity of the risk associated with blood leakage. Consequently, blood treatment system
1 need not require any or a plurality of highly sensitive, highly restrictive blood pressure
and/or blood flow monitors for accessing the possibility of leakages, thereby simplifying
the overall system.

[00104]  Another advantageous feature of the exemplary embodiments of the
invention is the configuration and arrangement of gas exchange conduits 30. The
relatively short length of conduits 30 decreases fluidic resistance of the gas flowing
through conduit 30, which consequently reduces fluidic back-pressure for gases passing
through the lumen of conduit 30. The short length of conduit 30 thereby inhibits the
formation of microbubbles on an exterior blood contacting surface of the conduit 30
membrane, which can obstruct blood flow in capillaries, cause tissue ischemia and form
blood embolisms leading to further vascular and tissue damage. By contrast, oxygenators
are designed with long fibers that are few in number in order to achieve mass transfer of
gas.

[00105]  By including a large number of conduits 30 in gas exchange mat 30, no
efficiency in the gas exchange module is lost by virtue of the short length of conduits 30.
To the contrary, due to the relatively short length of conduits 30 and high gas flow rate
therein, the difference in the partial pressure of CO₂ of the gas and of the patient's
blood is greater at the distal end (i.e. gas exiting end) of conduit 30 than a distal end (i.e.
gas exiting end) of a longer conduit. Consequently, CO₂ diffusion driving force and
efficiency is greater as a result of using a plurality of shorter conduits 30.

[00106]  Additionally, exemplary embodiments of the invention further enhances CO₂
removal efficiency by arranging the plurality of parallel conduits 30 in layers 32 to form
one or more gas exchange mats 34, such that the conduits 30 of adjoining layers 32 are
oriented substantially perpendicular to one another, thereby providing a maximum surface
area available for CO₂ diffusion. The efficiency of CO₂ diffusion is further improved by
dictating that the combined thickness of the one or more gas exchange mat 34 is such that
the ratio of the active length of a conduit 30 to the total thickness of the one or more gas exchange mats 34 is about 3:1 to about 0.5:1, thereby enabling efficient removal of CO2 from blood flowed through gas exchange module 10 at a low blood low flow rate. In an exemplary embodiment, the thickness of the gas exchange mat may be about 2.6 cm to about 5.4 cm.

Furthermore, an exemplary embodiment of blood treatment system 1 and all its components, including gas exchange module 10 may be compact, light-weight and portable, enabling a patient to remain mobile while being treated. In one embodiment, the various components of system 1 may be integrated into a single device that is either hand-held or otherwise portable, as shown in Figures 1-2 and 4. In one embodiment, all the components of system 1 may be removably positioned on, hung on or otherwise attached to a wheeled cart or stand, enabling a patient to easily roll system 1 to a desired location with minimal hindrance, thereby allowing system 1 to move with the patient.

**Blood Treatment Method**

The present invention is further directed to a novel method for removing CO2 from blood circulated through extracorporeal blood treatment system 1. In one embodiment, the method involves accessing a patient's circulatory system, directing blood through a circuit of the extracorporeal blood treatment system so as to remove substantially all the CO2 from the blood upon passage through gas exchange module 10 and returning the substantially CO2-free blood to the patient's circulatory system. This therapeutic method may be used to treat a variety of respiratory conditions associated with impaired lung functionality, particularly health problems associated with excess CO2 concentration in the blood or inhibited ability to remove CO2 from the blood. Exemplary conditions that may be treated with the present method include diseases, syndromes, injuries or defects affecting lung function including but not limited to COPD, chronic and acute hypercapnia, respiratory acidosis, ALI and ARDS.

In the exemplary embodiment set forth in Figure 5, the method involves diagnosing a patient with or otherwise accessing/determining the likelihood that a patient has a respiratory condition and applying the blood treatment system 1 to the patient for the purpose of decreasing CO2 concentration in a patient's blood or otherwise treating the respiratory condition. In particular, a physician may select and apply any one of the
aforementioned embodiments of blood treatment system 1, including any gas exchange
module 10, optional gas supply unit 50, optional pump 60, or combinations thereof that is
adapted for treating a patient, in particular for treating an adult human. The physician may
also select the gas flow, blood flow and/or the gas to be delivered to the conduits in order
to optimize CO2 diffusion. In one embodiment, the parameters set by the physician for
gas flow, blood flow and/or gas selection are not optimized for transfer of O2 for patient
oxygenation.

[00110] Vascular access is achieved by percutaneous cannulation of the jugular vein,
subclavian vein, femoral vein or any combinations thereof using two small single lumen
catheters or a double lumen catheter. The tip of the catheter or a separate needle
positioned within a cannula of the catheter may be used to create a small vascular
puncture site, connecting the catheter to the patient's circulatory system. When using a
needle, upon puncture, the needle may be retracted and/or the catheter may be advanced
to secure the catheter to the vein. In an exemplary embodiment, only a single puncture
site is necessary to provide vascular access, such as venous-venous access using a small
double lumen catheter.

[00111] A tubing attached to a proximal port of the catheter may be used to transport
blood from the vascular access site to and from gas exchange module 10 at a low flow
rate. In exemplary embodiments of blood treatment system 1 that include optional pump
60, blood is transported to pump 60 which directs and delivers the blood to blood
treatment chamber 24 of gas exchange module 10 at a controlled rate. Control unit 62,
operatively associated with pump 60, instructs pump 60 to regulate blood flow through
blood treatment chamber 24 at a predetermined low flow rate. If desired, the user may
instruct controller 62 and/or pump 60 to change the rate of blood flow through gas
exchange module 10 within a designated low flow rate range. In one embodiment, blood
is delivered to blood inlet port 14 and through blood treatment chamber 24 at a low flow
rate of about 0.5 L/min or less.

[00112] As blood is delivered to gas exchange module 10, optional gas supply unit 50
supplies a continuous stream of gas substantially free of CO2 to gas inlet port 18 of gas
exchange module 10. Best shown in Figures 3(f) and 3(i), gas flows through gas inlet port
18 and diverges into one of two compartments or sections 42a, 42b of gas passageway
41a which are in fluid communication with open conduit ends of the conduits 30 of
alternating conduit layers 32 that form gas exchange mat 34. The gas then flows through the conduits 30 of respective conduit layers 32 in a direction substantially perpendicular to the length of the corresponding sections 42a, 42b, as illustrated by the arrows in Figure 3(i). In one embodiment, gas supply unit 50 controls and regulates the flow rate of gas such that the gas flow rate through conduits 30 is maintained at a high velocity of about 15 L/min. Additionally, the gas pressure within conduits 30 may be kept low and regulated so that it does not exceed a level at which conditions would induce microbubble formation, i.e. bubble point.

When blood enters blood inlet port 14 and flows into blood treatment chamber 24, the flow of blood is oriented in a direction substantially orthogonal to the one or more gas exchange mats 34, conduit layers 32 and the respective lengths of conduits 30. Blood passes through the interstices of and contacts the one or more gas exchange mats 34 so as to pass over, around and between the exterior surface of individual conduits 30 forming conduit layers 32 and one or more gas exchange mats 34. Upon contact with and exposing the flow of blood to the porous membrane of conduits 30, through which a constant supply of gas substantially free of CO₂ is flowed, CO₂ diffuses from the blood, through the porous membrane of conduit 30 and is swept along and through the lumen of conduit 30 by the high velocity gas flowing through conduit 30. The difference in the partial pressure of CO₂ in the patient's blood introduced into gas exchange module 10 and any partial pressure of CO₂ in the gas circulated through conduits 30 drives the diffusion of CO₂ from the blood and into the lumen of conduit 30. In an exemplary embodiment, this difference in the partial pressure of CO₂ may be about 45 mm Hg to about 70 mm Hg, about 45 mm Hg to about 50 mm Hg, or about 40 mm Hg to about 50 mm Hg. By providing a high velocity stream of gas through conduit 30, the exposure and contact time between the blood and gas flowing through conduits 30 is relatively short. Consequently, the partial pressure of CO₂ in the blood and the partial pressure of CO₂ in the gas, or lack thereof, is prevented from equilibrating, thereby maintaining a continuous driving force of CO₂ diffusion created by the blood and gas CO₂ partial pressure differential. The gradient of the high pCO₂ concentration in blood in comparison to the low PCO₂ gradient in the gas is therefore maintained by the high velocity of gas flowing through conduits 30; gas carrying diffused CO₂ from blood is quickly purged and replaced with new gas having substantially no CO₂. The gradient is
further maintained as only small amounts of pCC^ are diffused from the blood and into each conduit lumens. As discussed above, near complete removal of pCC^ from the blood, however, may be accomplished by including a plurality of such short conduits 30 within gas exchange mat 34.

[00114] In an exemplary embodiment, substantially all the CO₂ may be removed from the blood introduced into gas exchange module 10 upon a single pass of the blood through gas exchange module 10, specifically through blood treatment chamber 24 and gas exchange mats 34. In one embodiment, the percent of CO₂ removed from blood after a single pass through gas exchange module 10 may be about 10% to about 95%, about 20% to about 90%, about 40% to about 90%, and 60% to about 90%. The partial pressure of CO₂ in the blood after a single pass through the gas exchange module 10 may be about 60 mm Hg to about 5 mm Hg, about 40 mm Hg or less, about 30 mm Hg to about 10 mm Hg, or about 25 mm Hg to about 5 mm Hg. In an exemplary embodiment, the pH of blood after a single pass through gas exchange module 10 may be about 7.45 or more, about 7.6 or more, about 7.8 or more, about 7.5 to about 8.2, about 7.6 to about 8.2, or about 7.7 to about 8.2.

[00115] A fresh supply of gas may be constantly streamed through gas exchange module 10, and the patient's blood may be recirculated through extracorporeal blood treatment system 1 as desired until all or substantially all the CO₂ is removed. In an exemplary embodiment, the method of the present invention allows for the complete or substantially complete depletion of all CO₂ from the treated blood.

[00116] The gas containing CO₂ leaving conduits 30 is collected in first and second sections 42c, 42d of gas passageway 41b and pushed out through gas outlet port 20 of gas exchange module 10 by the high velocity flow of gas in gas passageways 41a, 41b and conduits 30. This gas may be subsequently vented to atmosphere or collected in a reservoir. In one embodiment, gas outlet port 20 may optionally connected to a vacuum source to further control the rate of gas flow through conduits 30.

[00117] The overall duration of the therapy may be up to about 30 days, about 6 hours to about 30 days. In another embodiment, the therapy may last for a period of time up to about 5 days or about 6 hours to about 5 days. Additionally, the therapy may be continuously or intermittently administered as needed to achieve the desired degree of CO₂ removal.
[00118] The same or similar method of use of other embodiments blood treatment system 1 may be used to remove, extract, transfer or exchange other gases from the blood. Again, blood treatment system 1, inclusive of gas exchange module 10, particularly conduits 30 and the selection of gas to be flowed through conduits 30, as well as all other described system components may be designed, adapted and configured for the removal, diffusion, extraction or exchange of other gases in addition to or in place of CO₂.

[00119] The CO₂ removal method of the present invention has a number of therapeutic advantages. For example, low blood flow makes it possible to decrease the invasiveness of the procedure by reducing the size of the vascular access point, permitting usage of a small-lumen or small dual-lumen cannulas which causes less stress and trauma to the vessels during cannulation. Moreover, the veno-venous cannulation, low blood flow and corresponding low blood pressure reduces the risk of death or consequences associated with the patient bleeding out due to blood leakage from blood treatment system 1.

[00120] Additionally, the high velocity stream of gas through conduits 30 maintains a stable and maximized driving force of CO₂ diffusion created by the difference in the CO₂ partial pressure of the patient's blood and in the gas. Microbubble formation on the blood contacting outer surface of the conduit 30 membrane is also inhibited by maintaining a low gas pressure in conduits 30.

[00121] Furthermore, in one embodiment, the method enables efficient CO₂ diffusion by endeavoring to substantially remove all CO₂ from blood in a single pass through gas exchange module 10 and seeking to achieve non-physiological values of the partial pressure of CO₂ in blood and non-physiological values of blood pH. For example, the PCO₂ of the treated arterial blood may be about 32 mm Hg or less, about 25 mm Hg or less, about 15 mm Hg or less, and the pH of treated arterial blood may be about 7.45 or more, about 7.6 or more, or about 7.8 or more, representative of respiratory alkalosis. In one embodiment, the PCO₂ value of the treated arterial blood may be about 10 to about 15 mm Hg and the pH value may be about 7.8. In these embodiments, the method may involve targeting and managing therapy conditions to these atypical values that are not within standard acceptable physiological ranges. In contrast, oxygenators are optimized to maintain normal physiological partial pressures of gas, inclusive of CO₂; mass transfer of gas is thus only achievable by requiring a high blood flow through the oxygenator and
complete elimination of CO₂ would not be possible. Surprisingly, the blood treatment system 1 of the present invention is as or more effective than large gas exchange modules that require high blood flow and whose gas exchange conduits have greater gas exchange surface areas.

Examples

Example 1

[00122] In one embodiment, gas exchange module 10 of the present invention has the same configuration as shown in Figures 3(a)-3(b), 3(d)-3(f) and 3(h)-3(m). Gas exchange module 10 included a gas exchange mat 34 constructed from 13,834 or more microporous gas permeable conduits 30 adapted for carbon dioxide diffusion. Conduits 30 were positioned parallel to one another to form conduit layers 32. The conduit layers 32 were stacked on top of one another to form gas exchange mat 34, each layer oriented perpendicular to an adjoining layer. All of the conduits 30 had an active length of about 5.5 cm and a total conduit length of about 7.6 cm. The active length percentage of conduit 30 capable of gas transfer was at most about 72.4%. Gas exchange mat 34 had a total gas exchange surface area of about 0.98 m² and a conduit density of about 14,116 conduits per m². The ratio of a maximum conduit active length to the 5.4 cm thickness of the gas exchange mat 34 (which can also be expressed here as the minimum distance of the blood flow passageway through blood treatment chamber 24) is about 1.02:1. The blood and gas flow paths through gas exchange mat 34 and blood treatment chamber 24 were designed to expose the blood to conduits 30 and ensure comprehensive treatment and processing of the blood passing therethrough. This configuration also facilitate CO₂ diffusion by virtue of the relative blood flow resistance and gas flow resistance.

Example 2

[00123] In one embodiment, gas exchange module 10 of the present invention has the same configuration as shown in Figures 3(a)-3(b), 3(d)-3(f) and 3(h)-3(m). Gas exchange module 10 included a gas exchange mat 34 constructed from 13,119 or more microporous gas permeable conduits 30 adapted for carbon dioxide diffusion. Conduits 30 were positioned parallel to one another to form conduit layers 32. The conduit layers 32 were stacked on top of one another to form gas exchange mat 34, each layer oriented
perpendicular to an adjoining layer. All of the conduits 30 had an active length of about 5.8 cm and a total conduit length of about 7.6 cm. The active length percentage of conduit 30 capable of gas transfer was at most about 76.3%. Gas exchange mat 34 had a total gas exchange surface area of about 0.98 m² and a conduit density of about 13,300 conduits per m². The ratio of a maximum conduit active length to the 5.4 cm thickness of the gas exchange mat 34 (which can also be expressed here as the minimum distance of the blood flow passageway through blood treatment chamber 24) is about 1.07:1. The blood and gas flow paths through gas exchange mat 34 and blood treatment chamber 24 were designed to expose the blood to conduits 30 and ensure comprehensive treatment and processing of the blood passing therethrough. This configuration also facilitate CO₂ diffusion by virtue of the relative blood flow resistance and gas flow resistance.

Example 3

[00124] In one embodiment, gas exchange module 10 of the present invention has the same configuration as shown in Figures 3(a)-3(b), 3(d)-3(f) and 3(h)-3(m). Gas exchange module 10 included a gas exchange mat 34 constructed from 17,148 or more microporous gas permeable conduits 30 having an outer diameter of about 0.35 mm and is adapted for carbon dioxide diffusion. Conduits 30 were positioned parallel to one another to form conduit layers 32. The conduit layers 32 were stacked on top of one another to form gas exchange mat 34, each layer oriented perpendicular to an adjoining layer. All of the conduits 30 had an active length of about 5.2 cm and a total conduit length of about 7.6 cm. The active length percentage of conduit 30 capable of gas transfer was at most about 68.4%. Gas exchange mat 34 had a total gas exchange surface area of about 0.98 m² and a conduit density of about 17,497 conduits per m². The ratio of a maximum conduit active length to the 5.4 cm thickness of the gas exchange mat 34 (which can also be expressed here as the minimum distance of the blood flow passageway through blood treatment chamber 24) is about 0.963:1. The blood and gas flow paths through gas exchange mat 34 and blood treatment chamber 24 were designed to expose the blood to conduits 30 and ensure comprehensive treatment and processing of the blood passing therethrough. This configuration also facilitate CO₂ diffusion by virtue of the relative blood flow resistance and gas flow resistance.
The foregoing description of the invention has been presented for the purpose of illustration and description only and is not to be construed as limiting the scope of the invention in any way. The scope of the invention is to be determined from the claims appended hereto.
CLAIMS

1. An extracorporeal blood treatment system comprising:
   a gas exchange module configured to provide a passageway for blood and to
   remove carbon dioxide from the blood as the blood passes through the gas exchange
   module;
   wherein the gas exchange module comprises a plurality of conduits, each
   conduit comprises an exterior surface and an interior luminal surface, the interior luminal
   surface defining a passageway;
   wherein at least some of the conduits comprise pores and wherein upon
   exposure of the blood to the exterior surface, all of the conduits comprising pores have a
   first length that allows for diffusion of carbon dioxide from the blood to the passageway;
   and
   wherein the first length of at least one of the conduits that comprise pores is
   about 5.8 cm or less.

2. An extracorporeal blood treatment system comprising:
   a gas exchange module configured to provide a passageway for blood and
   remove carbon dioxide from the blood as it passes through the gas exchange module,
   wherein the gas exchange module comprises:
   a plurality of conduits, at least one conduit is configured to provide
   a passageway for gas and to allow for diffusion of carbon dioxide from the blood
   upon exposure of the blood to an exterior surface of the at least one conduit,
   wherein the at least one conduit has a first length available for carbon dioxide
   diffusion of about 5.8 centimeters or less; and
   a gas inlet and gas outlet,
   wherein all of the conduits of the gas exchange module are
   operatively associated with the gas inlet to permit fluid communication of the gas
   though the gas exchange module.

3. An extracorporeal blood treatment system comprising:
   a gas exchange module configured to provide a passageway for blood and to
   remove carbon dioxide from the blood as it passes through the gas exchange module,
wherein the gas exchange module comprises a plurality of conduits, at least one conduit is configured to provide a passageway for gas and to allow for diffusion of carbon dioxide from the blood through a wall of the at least one conduit and to the passageway upon exposure of the blood to an exterior surface of the at least one conduit, wherein the at least one conduit has a first length available for carbon dioxide diffusion of about 5.8 centimeters or less; and

wherein the extracorporeal blood treatment system does not have a heat exchanger adapted for regulating the temperature of the blood.

4. An extracorporeal blood treatment system comprising:

   a gas exchange module configured to provide a passageway for blood and remove carbon dioxide from the blood as the blood passes through the gas exchange module,

   wherein the gas exchange module comprises a plurality of conduits, at least one conduit is configured to provide a passageway for gas and to allow for diffusion of carbon dioxide from the blood contained outside the conduits but inside the gas exchange module to the passageway upon exposure of the blood to an exterior surface of the at least one conduit, wherein the at least one conduit has a surface area available for carbon dioxide diffusion of about 5.42 X 10^-5 m^2 to about 7.85 X 10^-5 m^2; and

   wherein the extracorporeal blood treatment system does not have a heat exchange mechanism.

5. An extracorporeal blood treatment system comprising:

   a gas exchange module configured to provide a passageway for blood and remove carbon dioxide from the blood as it passes through the gas exchange module, wherein the gas exchange module comprises a plurality of conduits forming one or more gas exchange mats, wherein at least one conduit is configured to provide a passageway for gas and to allow along a first length of the at least one conduit diffusion of carbon dioxide from the blood upon exposure of the blood to an exterior surface of the at least one conduit, wherein a ratio of the first length to a total thickness of the gas exchange mats is about 1:1 or less; and
wherein the extracorporeal blood treatment system does not have a heat exchange mechanism.

6. The system of any of claims 1-5, wherein a collective average of the first lengths of all of the conduits that comprise pores is about 5.8 cm or less.

7. The system of any one of claims 1-6, wherein at least one of the plurality of conduits has an outer diameter of about 350 µm to about 410 µm.

8. The system of any of claims 1-6, wherein all conduits that comprise pores have an average outer diameter of about 350 µm to about 410 µm.

9. The system of any one of claims 1-8, wherein the first length of at least one of the conduits is about 76.3% or less than a full length of the at least one of the conduits.

10. The system of any one of claims 1-8, wherein an average of the first length of all conduits that comprise pores is about 76.3% or less than an average of the full length of all of the conduits that comprise pores.

11. The system of any one of claims 1-4 or 5-10, wherein an exposed surface area of the at least one conduit is about $5.71 \times 10^{-3}$ m$^2$ to about $7.47 \times 10^{-3}$ m$^2$.

12. The system of any one of claims 1-11, wherein pores of all conduits that comprise pores are about 0.2 microns or less.

13. The system of any one of claims 1-12 wherein the at least one conduit is constructed from polymethylnpentene.

14. The system of any one of claims 1-12 wherein all of the conduits that comprise pores are constructed from polymethylnpentene.
15. The system of any one of claims 1-14 wherein the at least one conduit has a microporous microstructure covered by a thick and impervious diffusion layer membrane.

16. The system of any one of claims 1-158 wherein the conduits are arranged in a crisscrossing pattern.

17. The system of any one of claims 1-16 wherein the conduits are arranged to form conduit layers and positioned between a blood inlet and a blood outlet of the gas exchange module, the blood inlet faces the conduit layers such that the blood flows towards the conduit layers in a direction substantially orthogonal to the conduit layers.

18. The system of claim 17, wherein conduits of each conduit layer are oriented substantially parallel to one another.

19. The system of claim 18, wherein the conduits of each conduit layer are knitted or woven together.

20. The system of any one of 17-19, wherein the conduits of adjacent conduit layers are oriented substantially perpendicular to one another.

21. The system of any one of claims 1-20, wherein the gas exchange module comprises at least 10,000 conduits adapted for transferring carbon dioxide.

22. The system of any one of claims 1-21, wherein a combined surface area for carbon dioxide diffusion of all the conduits is about 0.98 m² or more.

23. The system of any one of claims 1-22, wherein the system further comprises a pump operatively associated with the gas exchange module for directing and regulating a flow of the blood to the gas exchange module, wherein the pump is adapted to deliver the blood to the gas exchange module at rate of about 1 L/min or less.
24. The system of any one of claims 1-23, wherein the gas exchange module further comprises a pressure sensor positioned adjacent to the blood outlet and in direct contact with the blood exposed to the conduits for measuring blood pressure as the blood exits the gas exchange module.

25. The system of any one of claims 1 and 3-24, wherein the gas exchange module further comprises a gas inlet and gas outlet, wherein all of the conduits of the gas exchange module adapted for carbon dioxide diffusion are in fluid communication with the gas inlet.

26. The system of any one of claims 1-2 and 6-25, wherein the system does not include a heat exchange mechanism.

27. The system of any one of claims 1-2 and 6-25, wherein the system does not regulate the temperature of any fluid entering or leaving the gas exchange module.

28. The system of any one of claims 1-27, wherein the system further comprises a single lumen cannula operatively associated with the gas exchange module and having a cannula has a size of about (4.7 mm) or less.

29. The system of any one of claims 1-26, wherein the system further comprises a double-lumen cannula operatively associated with the gas exchange module and having a cannula has a size of about 6.0 mm or less.

30. The system of any one of claims 1-29, wherein a combined volume of the conduits of the gas exchange module that comprise pores is about 0.085 liters to about 0.100 liters.

31. The system of any one of claims 1-4 and 6-30, wherein the plurality of conduits form one or more gas exchange mats, and the ratio of the first length of the at least one conduit to a total thickness of the gas exchange mat is about 3.0 or less.
32. The system of any one of claims 1-31, wherein the system is configured for carbon dioxide removal from the blood with at most only nominal diffusion of oxygen.

33. A method for using an extracorporeal blood treatment system to remove carbon dioxide from blood, wherein the blood treatment system comprises:
   a gas exchange module configured to provide a passageway for blood and remove carbon dioxide from the blood as it passes through the gas exchange module,
   wherein the gas exchange module comprises a plurality of conduits, wherein at least one conduit is configured diffusion of carbon dioxide from blood to an internal lumen of the at least one conduit upon exposure of the blood to an exterior surface of the at least one conduit, wherein at least one conduit has a first length for carbon dioxide diffusion of about 5.8 cm or less; and
   wherein the method for using the blood treatment system comprises:
   selecting the gas exchange module to treat an adult human;
   flowing blood into the gas exchange module at a rate of 1 liter per minute or less; and
   exposing the blood to a plurality of conduits to remove carbon dioxide from the blood.

34. The method of claim 33, wherein the blood flows into the gas exchange module at a rate of about 0.51 liters per minute or less.

35. The method of any one of claims 33-34, wherein a gas is flowed through the conduits at a rate of about 0.2 liters per minute to about 15 liters per minute.

36. The method of any one of claims 33-35, wherein a gas is flowed through the conduits at a rate of more than about 15 liters per minute.

37. The method of any one of claims 33-36, wherein a gas delivered to the conduits has a partial pressure of carbon dioxide that is zero or at least lower than a partial pressure of carbon dioxide of the blood flowing into the gas exchange module.
38. The method of any one of claims 33-37, further comprising treating the blood without regulating blood temperature.

39. The method of any one of claims 33-38, wherein throughout the length of the at least one conduit, there exists a carbon dioxide gradient between a gas flowing through the at least one conduit and the blood exposed to the exterior surface of the at least one conduit.

40. The method of any one of claim 39, wherein the carbon dioxide gradient is substantially constant along the length of the at least one conduit.

41. The method of any one of claims 33-40, further comprising measuring blood pressure using a sensor of the gas exchange module in direct contact with the blood exposed to the conduits after exposing the blood to the plurality of conduits.

42. The method of any one of claims 33-41, further comprising measuring an amount of carbon dioxide removed from the blood using a sensor of the gas exchange module.

43. The method of any one of claims 33-42, wherein the conduits are arranged in layers and are located between a blood inlet and a blood outlet of the gas exchange module, and wherein the blood flows towards the conduits in a direction substantially orthogonal to the length of the conduits.

44. The method of any one of claims 33-43, further comprising obtaining the blood delivered to the gas exchange module from a venous blood source and treating the blood such that a partial pressure of carbon dioxide in the blood after exposure to the conduits is about 50 mm Hg to about 70 mm Hg.

45. The method of any one of claims 33-44, further comprising obtaining the blood delivered to the gas exchange module from a venous blood source and treating the blood such that a pH value of the blood after exposure to the conduits is about 7.25 to about 7.35.
46. The method of any one of claims of 33-45, further comprising obtaining the blood delivered to the gas exchange module from a venous circulatory system and returning the blood treated by the gas exchange module to the venous circulatory system.

47. The method of any one of the claims of 33-45, further comprising circulating the blood through the gas exchange module for a period of about 6 hours to about 30 days.

48. The method of any one of the claims of 33-47, further comprising: remediate a respiratory condition in the adult human selected from the group consisting of: chronic obstructive pulmonary disease, acute lung injury, acute respiratory distress syndrome and hypercapnia.

49. The system of any one of claims 33-48, further comprising treating the blood by removing carbon dioxide from the blood with no or at most only nominal diffusion of oxygen.

50. The method of any one of claims 33-49, wherein the blood treatment system used to perform the method is any one of the blood treatment systems of claims 1-32.
Assessing, determining or diagnosing a respiratory condition of a patient

Directly accessing the patient's blood vessel and circulating blood through the extracorporeal blood treatment system

Regulating blood flow through the blood treatment compartment of the gas exchange module at a low flow rate

Regulating gas flow through the conduit of the gas exchange module at a high flow rate

Removing carbon dioxide from the blood flowed through the gas exchange module

Returning the treated blood to the patient

FIGURE 5