AN APPARATUS FOR TRANSFERRING A GAS BETWEEN TWO LIQUIDS

Inventor: Guenter H. Marx, Engadiner Str. 4, Munich, Germany

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Abstract

An artificial lung which has a plurality of flexible and resilient small diameter tubes constructed of a gas pervious material and extending in a generally upright direction through a surrounding housing. An oxygen transferring medium is in the housing for the transfer of oxygen to the blood and withdrawal of carbon dioxide from the blood. Blood entering the housing is cooled to facilitate the oxygen absorption and is warmed to body temperature before exiting the housing. The pressure of the fluid in the housing is pulsed and appropriate check valve means are inserted in the blood stream at the blood intake and outlet to induce a cyclical, heart-like blood flow through the compression and expansion of the flexible tubes.

22 Claims, 5 Drawing Figures
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BACKGROUND OF THE INVENTION

This invention relates to an artificial lung having a multiplicity of small diameter, flexible tubes disposed in a housing through which oxygen or an oxygen-gas mixture flows. At one end of the tubes an intake for low oxygen blood is provided for connection to a body vein while an outlet at the other end of the tubes is for the discharge of high oxygen content blood and for connection to a suitable body artery. A heat exchanger brings the blood temperature to the body temperature.

Generally, such artificial lungs are known and are constructed so that the flexible tubes extend substantially horizontally through the housing. Oxygen or an oxygen-gas mixture flows in a vertical, usually downward direction through the housing. The heat exchanger is positioned downstream of the housing. This arrangement requires a relatively large blood volume for filling the artificial lung and its heat exchanger. Additionally, relatively large pressure drops are experienced which make the use of booster pumps normally positioned downstream of the artificial lung necessary. The booster pump further increases the required blood volume. Moreover, such pumps are relatively expensive and can easily damage blood particles.

Prior art artificial lungs in which the flexible blood transporting tubes are horizontally arranged and terminate at upstream and downstream distribution headers have the further disadvantage that the blood flow through the various tubes is unequal. It has been determined that the flow is concentrated and highest in the tubes at the center of the tube bundle while peripherally positioned tubes have a substantially lower flow rate. Such artificial lungs are, therefore, relatively inefficient since the maximum possible oxygen transfer through the gas pervious tube walls cannot be exploited, or, alternatively, since insufficient oxygen reaches the blood flowing through the center tubes at relatively high rates.

SUMMARY OF THE INVENTION

The present invention provides an artificial lung pump that can be operated as an artificial heart-lung combination which overcomes the shortcomings and disadvantages found in prior art artificial lungs. The artificial lung of the present invention comprises a housing and a plurality of relatively small diameter gas pervious, flexible and resilient tubes disposed within the housing and terminating in a main intake and main outlet communicating the interior of the tubes with the housing exterior. A fluid including oxygen is disposed in the housing for transfer of the oxygen through walls of the tubes to the blood. The tubes are maintained in a generally upright position to assure an even blood flow through them.

Normally, there will be a multiplicity of small diameter blood transporting tubes and the housing is so constructed as to position the tubes extend in an upright, preferably vertical direction. A heating coil is placed interiorly of the housing adjacent the outlet from the blood transporting tubes and a cooling coil is preferably positioned adjacent the tube inlet to temporarily lower the blood temperature and thereby increase the oxygen absorption rate of the blood.

The present invention provides simple, relatively inexpensive means for the heart-paced pumping of the blood from the artificial lung to overcome any pressure drops caused by the artificial lung. This pumping action is obtained by placing suitable check valves upstream and downstream of the tube bundle in the blood flow and providing a cyclically opened and closed valve for cyclically venting the housing interior to the exterior. This valve can be manually or mechanically operated.

The check valves are so designed that when the pressure in the housing interior exceeds the ambient pressure on the housing exterior backflow of blood from the tubes is prevented. The relatively high pressure acting on the tube bundle compresses the tubes and forces blood downstream out of the housing. When the valve vents the housing and the pressure in the housing interior equals the ambient exterior pressure the upstream blood pressure together with the force or vacuum obtained interiorly of the tubes from the previously flattened tubes' resilient tendency to return to their normal, round or cylindrical shape draws upstream, low oxygen content blood into the tubes. A downstream check valve is closed and prevents a blood backflow from the downstream side of the housing. A cyclical, heart-like pumping action is thereby obtained.

To increase the pump capacity, it is preferred that upstream and downstream distribution headers between the inlet and outlet and the tube bundle are also constructed of a resiliently deformable material so that they are compressed and inflated during the pumping action in the same manner as the resilient tubes.

The upright or vertically oriented tube bundle results in a substantially uniform blood flow through all tubes of the bundle irrespective of their relative positions. Thus, with a given oxygen transfer rate through the gas pervious tube material, the oxygen content of all blood irrespective of the tube through which it passes the artificial lung is equally increased. An oxygenized blood of substantially higher quality than blood oxygenized in prior art artificial lungs is thereby obtained.

The incorporation of the heart pump within the housing of the artificial lung eliminates undesirable pressure drops across the artificial lung and/or the need for an independent booster pump that requires additional blood as was the case with prior art artificial lungs. When the artificial lung of the present invention is also operated as a heart-pump, its pulses can be synchronized with the patient's heart pulses. Most importantly, however, it requires no additional blood volume for its pumping operation over that required by the artificial lung. It works gently and eliminates blood damage encountered with some prior art pumps.

The cyclical compression of the gas pervious, flexible and resilient tubes causes an intermittent flattening of such tubes. In addition to the forward flow of the blood in the tubes in a downstream direction, the blood stream is subjected to intermittent lateral flows. This results in a better mixture of the blood, assures that more blood is contacted with the interior of the tube walls and thus provides for a better oxygenation of the blood as it passes through the artificial lung.

The artificial lung of the present invention is of a much simpler construction than prior art artificial lungs. It can be manufactured at substantially lower cost. Thus, an artificial lung having substantially enhanced operating characteristics as compared to prior art artificial lungs is provided without the often en-
countered greater increased costs that are so characteristic for advances in today's medical instrumentation and that is a major factor in today's high medical costs.

The artificial lung of the present invention not only operates for oxygenizing oxygen-poor blood but it can equally well be employed for reducing the oxygen content of oxygen-rich blood where such reduction is desired. In such applications, nitrogen instead of oxygen is admixed with the fluid in the housing surrounding the tube bundle through which the blood flows.

The apparatus of the present invention can be used for transferring a gas between a first and second fluid, including fluids. liquids.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a cross sectional elevation of an artificial lung constructed in accordance with the present invention;

FIG. 2 is a cross sectional elevation similar to FIG. 1 and further illustrates blood pumping means in a suction mode and constructed in accordance with the present invention;

FIG. 3 is a view similar to FIG. 2 but illustrate the blood pumping means in a pressure mode;

FIG. 4 is an enlarged, cross sectional view in an axial direction through a blood carrying tube employed in the artificial lung of the invention; and

FIG. 5 shows the blood carrying tube in a flattened compressed state during pressure cycle of the blood pumping means.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

Referring to FIG. 1, an artificial lung 8 constructed in accordance with the invention broadly comprises an upright, preferably vertically extending cylindrical and fluid tight housing 10 and a bundle 12 of a multiplicity of small diameter, elongate blood flow tubes 14 extending in an upright, preferably vertical direction axially through the housing from an inlet 16 in a housing bottom 18 to an outlet 20 in a housing top 22. A fluid 24 such as silicone oil or a fluorocarbon fluid is disposed in the housing, surrounds the exterior of tube bundle 12 and is continuously enriched with oxygen introduced into the fluid through an oxygen intake 26 in housing bottom 18. The oxygen is partially dissolved in the fluid and partially forms small bubbles 28. Tubes 14 are constructed of a gas, and particularly oxygen, pervious material such as silicone rubber so that oxygen disposed in solution with the fluid and/or in the form of small oxygen bubbles transfers through walls 30 of tubes 14 and is dissolved in blood flowing in the tubes to enrich the oxygen content of such blood.

Silicone rubber is the presently preferred material for the construction of tubes 14 since it is inert to human and animal blood, and has good oxygen transfer characteristics and since it is readily deformable, flexible and resilient, characteristics which are important as more fully set forth below. Typical tubes have inner diameters of 0.52 millimeters, wall thickness of 0.09 millimeters and lengths of 230 millimeters, or about 9 inches. Silicone rubber of 0.09 millimeters wall thickness has an oxygen exchange rate of up to about 200 cubic centimeters of oxygen per square meter per minute. Thus, an artificial lung for use on an average human body under average conditions requires about 780 square centimeters of oxygen exchange area on tubes 14, or about 200 tubes of the above outlined dimensions to make up tube bundle 12 and provide a sufficient oxygen transfer area.

The ends of the tubes are placed side by side and bonded together with a suitable bonding agent 32 that extends over a relatively short length of the tubes to form fluid tight bundle ends. The bundle ends are inserted in flared tubular headers 34 and are bonded thereto at 36. The headers taper or curve down into a cylindrical portion 38 for connection to suitable conduits or hoses (not shown) that communicate with the patient's circulatory system in a conventional manner. The cylindrical portion of the header at each end of tube bundle 12 extends through the housing bottom 18 or housing top 22 and respectively defines inlet 16 and outlet 20.

In use, blood is flowed from the lower one of headers 34 through tube bundle 12 into the upper one of headers and hence out of the housing while blood oxygenation takes place as the blood flows through the tube bundle. Simultaneously with the blood oxygenation carbon dioxide is removed from the blood, transferred through tube walls 30 and discharged into fluid 24 where it rises to fluid level 40 and into an upper gas chamber or trap 42 of the housing. The carbon dioxide together with oxygen that flows from oxygen intake 26 through fluid 24 and collects in gas trap 42 is withdrawn from the housing through a vent 44.

To assure that the blood discharged from artificial lung 8 and recirculated to the patient is of body temperature, a heating coil 46 is placed about the upper end of tube bundle 12 and is located adjacent outlet 20. A heated fluid medium such as warm water is passed through the heating coil. The water temperature is so selected that blood discharged from outlet 28 is of body temperature, or slightly higher if blood cooling between the housing outlet and the patient is encountered.

The positioning of heating coil 46 adjacent outlet 20 leaves space at the lower end of tube bundle 12 for positioning a cooling coil 49 about the lower end of the tube bundle through which a cooling fluid such as cold water is passed for initially lowering the blood temperature as it passes from inlet 16 through the lower portion of the tubes. Since lower temperature blood has an increased oxygen absorption rate better blood oxygenation is thereby obtained. Thereafter, the undercooled blood is brought to the required temperature by heating coil 46. It will be observed that the cooling and heating of the blood for the above stated advantages takes place within the artificial lung and requires neither an additional length of tubes 14 nor additional blood containing conduits or a vessel for performing the heat exchange so that the total blood volume in the artificial lung and associated conduits between it and the patient is not increased. Blood drain from the patient's circulatory system or the need for additional blood, which is scarce and expensive, is thus reduced.

Referring now to FIGS. 2 through 4, at a flow rate of about 150 ml. per minute of blood through the above described 200 capillary tube bundle 12 a pressure drop of about 45 millimeter Hg is encountered. For efficient blood circulation through artificial lung 8 blood pumping means are therefore required. In accordance with the invention, such pumping means are incorporated in the artificial lung.
The pumping means comprise first and second check valves 52 and 54 located upstream and downstream, respectively, of tube bundle 12 to assure a blood flow in the flow direction and prevent a backflow of blood. Furthermore, the pump means includes a cyclically, manually or automatically opened and closed valve 56 alternatingly venting and closing the interior of housing 10 from the exterior. Oxygen containing gas under a pressure exceeding the ambient pressure on the exterior of housing 10 is introduced into the housing interior through oxygen intake 26. When valve 56 is closed, the relatively high pressure of the housing interior flattens tubes 14 as illustrated in FIG. 5. This reduces the interior volume of each tube and thereby forces blood through downstream check valve 54 towards the patient. Backflow through blood inlet 16 is prevented by upstream check valve 52 which is closed by the excess pressure on the interior of tubes 14. The flattening of the tubes further causes blood flows lateral to the tube axes to increase the contact of the blood with tube walls 30 and assure a uniform oxygen content in the blood oxygenized in artificial lung 8. The pumping action exerted by tubes 14 is reinforced by resilient headers 34 which collapse under the increased pressure on the interior of housing 10 as illustrated in FIG. 3.

Upon opening of valve 56 the pressure on the interior of the housing is reduced to ambient pressure. The natural resiliency of tubes 14 and headers 34 causes them to return to their normal position (as illustrated in FIGS. 2 and 4) thereby causing a slight vacuum on the interior of the tubes and the headers. This vacuum closes downstream check valve 54 since the pressure on the downstream side of the check valve now exceeds the pressure on the upstream side thereof. It further opens upstream check valve 52 since the pressure on the upstream side of the check valve exceeds the pressure on the downstream side thereof so that blood flows into headers 34 and tubes 14. Upon closing of valve 56 the pressure on the housing interior builds up again until the upstream check valve is closed, the downstream check valve is opened and blood is pumped out of the artificial lung. The actuation of the valve can be timed so that it coincides with the heart beat of the patient.

Although a variety of check valves can be employed a check valve comprising a disc 58 constructed of a deformable, and at least partially resilient material such as a thermoplastic material is presently preferred. The downstream side of the disc is connected to a plastic rod or member 60 that is secured, e.g., bonded to an adjacent conduit wall and biases the disc into a closed position preventing a backflow of blood. When the pressure on the upstream sides of the disc exceeds the pressure on the downstream side thereof the peripheral portion of the disc is deflected by the pressure differential and unsealed from the sealing surface 62 to permit fluid flow past the disc until the upstream pressure acting against the disc exceeds the pressure acting on the downstream side thereof whereupon the disc seats on surface 62 and prevents a fluid backflow.

I claim:

1. A heart-lung combination comprising: a housing containing a liquid which has a high solubility for oxygen and in which an oxygen containing gas is introduced, a plurality of relatively long, small diameter tubes constructed of a resilient, flexible, gas pervious material for the transfer of oxygen to blood flowing in the tubes, the tubes being disposed in the housing and in fluid communication through blood inlet and blood outlet means with the exterior of the housing for connection to a circulatory system, first valve means communicating the housing interior with the exterior, and check valve means disposed in the blood inlet and blood outlet means to control the flow of blood, means to provide pressurization of the liquid in the housing and means for selectively alternatingly opening and closing the first valve means whereby the tubes are alternatingly compressed and expanded and thereby alternatingly draw blood in a flow direction from the housing exterior into the tubes and force blood in the same direction of flow from the tubes to the housing exterior.

2. A heart-lung combination according to claim 1 including means connecting the tube ends to an upstream tube end member and a downstream tube end member, wherein said tube end members extend through the housing and communicate with the housing exterior for connection to the circulatory system, and wherein the tube end members are constructed of a deformable and resilient material.

3. A heart-lung combination according to claim 1 including first and second tube means extending through the housing, means fluidly connecting the ends of said small diameter tubes to respective first and second tube means said first tube means being connected to the upstream ends of said tubes and said second tube means being connected to the downstream ends of said tubes, and wherein the check valve means are disposed in the tube means and comprise a first disc disposed in the first tube means, means biasing the first disc in an upstream direction, and a first interface means against which the biased disc seats, and a second disc disposed in said second tube means, means biasing the second disc in an upstream direction, and a second interface means against which the biased second disc seats, so that when the pressure in the tubes exceeds the pressure of the blood on the exterior of the housing, a blood flow from the tubes past the second disc occurs and when the blood pressure in the tubes is less than the blood pressure on the exterior of the housing upstream of the tubs, a blood flow past the first disc into the tubes takes place.

4. An artificial heart-lung combination according to claim 3 wherein the discs are constructed of a flexible material and wherein the biasing means comprises means substantially rigidly securing one portion of the disc to the adjacent tube means whereby blood flow past the disc occurs through deflection of peripheral portions of the disc with respect to a center portion.

5. An apparatus for transferring a gas between a first and second liquid comprising: a housing for holding a second liquid, a multiplicity of small diameter, gas pervious, flexible tubes constructed of a resilient material permitting a flattening of the tubes when the pressure on the tube exterior exceeds the pressure on the tube interior and a substantially return of the tubes to their original shape when the pressure is reduced, means mounting the tubes to the housing interior, and providing parallel communication of the tubes with each other and forming a passage for a first liquid in a flow direction from the housing exterior through the tubes in the housing and back to the housing exterior, means for supplying the second liquid with a gas for transfer of the gas to the first liquid, means for withdrawing
waste gases from the housing interior, means for cyclically increasing and decreasing pressure in the housing whereby the tubes are cyclically flattened, so as to force the first liquid out of the tubes, and cyclically returning the tubes substantially to their original shape to draw said first liquid into said tubes and means to provide a flow of said liquid in only one direction and means disposed interorily of the housing and surrounding the tubes for heating the first liquid flowing through the housing before it exits from the housing.

6. The apparatus according to claim 5 wherein the heating means comprises a heating coil surrounding the tubes and disposed adjacent the exit for the first liquid from the housing, said apparatus further including means disposed interorily of the housing and adjacent an entrance for the first liquid into the housing for cooling entering first liquid to facilitate the gas transfer between the second liquid and the first liquid.

7. A heart-lung machine which comprises a housing in which an oxygen containing gas is introduced and which contains a multiplicity of flexible tubes which consist of gas-permeable material which are positioned to form a bundle, said bundle having at one end an inlet means for low oxygen content blood and at the other end an outlet means for oxygen-enriched blood, said inlet and outlet means extending through the housing, the housing having an opening, said housing having positioned therein a housing valve means for selectively opening and closing said housing opening, the inlet means for low oxygen content blood is provided with an inlet check valve, which is closed when said housing valve is closed, and the outlet means for oxygen enriched blood is provided with an outlet check valve which is opened when the said housing valve is closed, the alternate opening of the housing valve causing the closing of the outlet means check valve and the opening of the inlet means check valve whereby there is a blood flow which is maintained in the only one direction said housing containing a liquid which has a high solubility for oxygen and heating means whereby the blood flowing through the tube bundle is heated to a suitable temperature, and means for supplying an oxygen containing gas to said liquid within said housing.

8. An apparatus for transferring a gas between a first and second liquid, comprising tubular conduit means for the first liquid constructed of a resilient, flexible, gas pervious material which under superatmospheric pressure is at least partially reduced in volume and which when the pressure is released substantially returns to its previous size and shape, a housing containing the second liquid, the housing and second liquid surrounding said tubular conduit means, said conduit means having for said first liquid an inlet at one end thereof and an outlet at the other end thereof, the housing having an inlet means for introducing gas at a superatmospheric pressure into the second liquid in the housing and an outlet means for releasing gas from said housing, said tubular conduit means having at the inlet thereto a check valve and having at the outlet thereto a check valve whereby the first liquid in passing through said conduit means is permitted to flow in only one direction said housing outlet means including means for selectively alternately closing and opening said housing outlet means whereby the gas pressure in the housing is increased when the outlet means is closed and released when the outlet means is opened causing said first liquid to be pumped through said tubular conduit means.

9. An apparatus for transferring a gas between a first and second liquid, comprising tubular conduit means for the first liquid constructed of a gas pervious material, means for passing the first liquid through the conduit means, a housing containing the second liquid, the housing and liquid surrounding said conduit means, said conduit means having for said first liquid, an inlet at one end thereof and an outlet at the other end thereof, means disposed within said housing for cyclically increasing and decreasing the pressure in the housing including, an inlet for introducing a gas into the second liquid in the housing and an outlet for releasing gas from said housing, the inlet to the conduit means having a check valve and the outlet to the conduit means having a check valve whereby the first fluid in passing through said conduit means is permitted to flow in only one direction.

10. An apparatus for transferring a gas between a first and second liquid, comprising tubular conduit means for the first liquid constructed of a resilient, flexible, gas pervious material which under superatmospheric pressure is at least partially reduced in volume and which when the pressure is released substantially returns to its previous size and shape, a housing containing the second liquid, the housing and second liquid surrounding said tubular conduit means, said conduit means having for said first liquid an inlet at one end thereof and an outlet at the other end thereof, the housing having an inlet means for introducing gas at a superatmospheric pressure into the second liquid in the housing and an outlet means for releasing gas from said housing, said tubular conduit means having at the inlet thereto a check valve and having at the outlet thereto a check valve whereby the first liquid in passing through said conduit means is permitted to flow in only one direction said housing outlet means including means for selectively alternately closing and opening said housing outlet means whereby the gas pressure in the housing is increased when the outlet means is closed and released when the outlet means is opened causing said first liquid to be pumped through said tubular conduit means.

11. An apparatus for transferring oxygen from a liquid to blood comprising a multiplicity of resilient, flexible, gas pervious tubes disposed in a housing, said housing containing a liquid which surrounds said tubes, said tubes having an inlet means for low oxygen content blood at one end thereof and outlet means for oxygen enriched blood at the other end thereof, means disposed within said housing for cyclically increasing and decreasing the pressure in the housing including an inlet for introducing into the liquid in the housing an oxygen containing gas and said housing having an outlet for releasing gas therefrom, means for passing blood into the inlet in said tubes and out of the outlet of said tubes and said tubes having at the inlet thereto a check valve and having at the outlet thereto a check valve whereby the blood in passing through the tubes is permitted to flow in only one direction.

12. An apparatus according to claim 11 including means positioned adjacent the low oxygen content blood inlet means for cooling the blood flow to increase its oxygen absorbtue.

13. An apparatus according to claim 11 including means adjacent the oxygen-enriched blood outlet means for heating the blood to about body temperature.
14. An apparatus according to claim 11 wherein the oxygen enriched blood heating means is disposed internally of the housing.

15. An apparatus according to claim 11 wherein the inlet for introducing oxygen containing gas is disposed adjacent a lowermost portion of the housing for supplying oxygen to the liquid.

16. An apparatus according to claim 11 wherein said housing outlet is disposed adjacent an uppermost portion of the housing for the withdrawal of gas from the housing.

17. An apparatus according to claim 11 including means bonding the ends of the tubes to each other, and means bonded to the ends of the tubes and forming headers between the respective ends of said tubes and the blood inlet means and the blood outlet means.

18. A heart-lung apparatus for transferring oxygen from a liquid to blood and for pumping said blood, comprising a multiplicity of resilient, flexible, gas pervious tubes disposed in a housing, which tubes under superatmospheric pressure are at least partially reduced in volume and which when the pressure is reduced substantially return to their previous size and shape, said housing containing a liquid which surrounds said tubes, said tubes having an inlet means for low oxygen content blood at one end thereof and outlet means for oxygen enriched blood at the other end thereof, the housing having an inlet means for introducing into the liquid in the housing at superatmospheric pressure an oxygen containing gas and said housing having an outlet means for releasing gas therefrom, means for passing blood into the inlet means of said tubes and out of the outlet means of said tubes having at the inlet means thereto a check valve and having at the outlet means thereto a check valve whereby the blood in passing through the tubes is permitted to flow in only one direction, said housing outlet means including means for selectively alternatingly closing and opening said housing outlet means whereby the gas pressure in the housing is cyclically increased when the outlet means is closed and reduced when the outlet means is opened causing the tubes to be cyclically decreased in size so as to force oxygen enriched blood out of the tubes and cyclically returned to their normal size to cyclically draw low oxygen content blood into the tubes.

19. The lung-heart apparatus of claim 18 including heating means positioned adjacent the blood outlet means for heating the blood to about body temperature.

20. A heart-lung apparatus according to claim 18 wherein the liquid comprises a silicone oil.

21. A heart-lung apparatus according to claim 18 wherein the liquid comprises a fluorocarbon liquid.

22. A heart-lung apparatus according to claim 18 including means for subjecting the liquid in the housing to a pressure in excess of the pressure of the liquid in the tubes.

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