

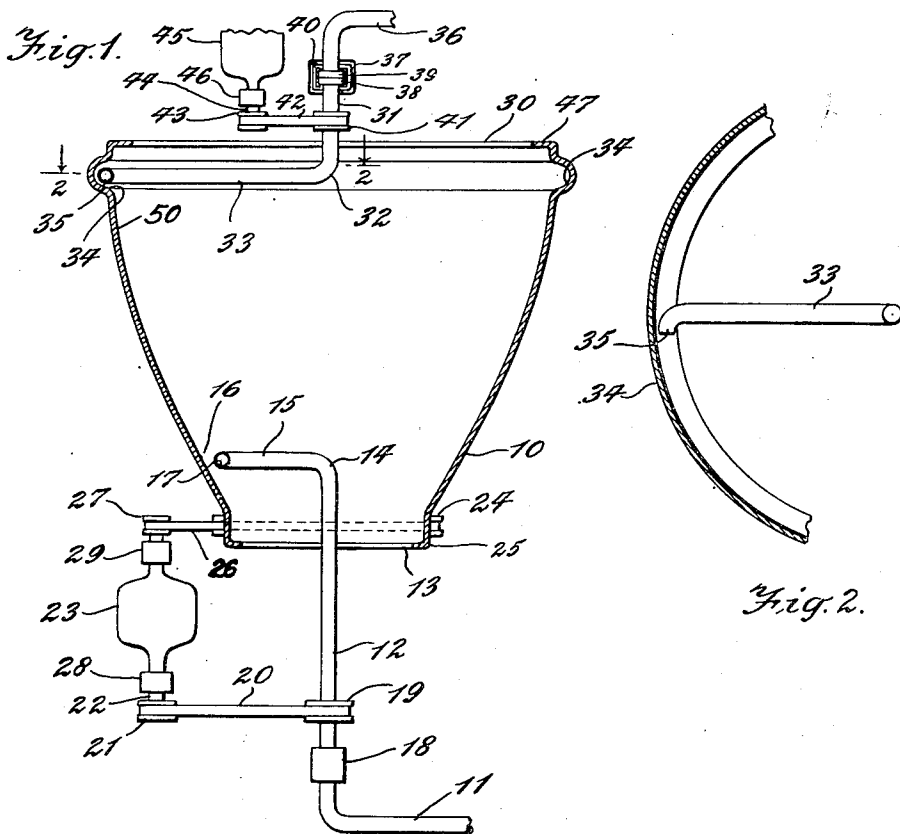
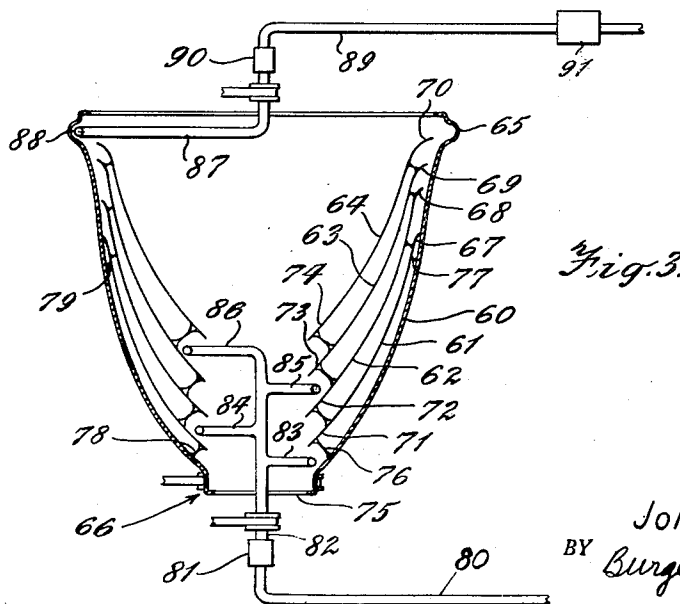
Nov. 9, 1954

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2,693,802

BLOOD OXYGENATION

Filed May 15, 1951



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2,693,802

## BLOOD OXYGENATION

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Application May 15, 1951, Serial No. 226,423

6 Claims. (Cl. 128—214)

This invention relates to a method and apparatus for oxygenating blood wherein venous blood is removed from a living animal, oxygenated, and returned to the arterial system of the animal. The apparatus may be referred to as a kind of artificial lung in which blood is spread out in a thin film, exposed to air or oxygen for a short time, and then returned to the body of the patient or experimental animal.

According to the invention, venous blood is conducted to an oxygenating zone and deposited therein, following which it is quickly moved, preferably during deposition, to form a layer. The moving layer is rapidly accelerated to spread the blood into a moving film of about 50 microns' thickness and this film of blood is quickly passed through the oxygenating zone while oxygen or air is brought into continuous contact with the same, thereby oxygenating the blood. The oxygenated blood is collected and returned to the arterial system of the animal. It is essential to maintain the film of blood at a thickness of about 50 microns in order to oxygenate the blood within a reasonable period of time. For maintaining the film at the desired thickness, the acceleration imparted to the blood should be equivalent to 2 to 7 times the acceleration of gravity. If the film is too thick, the oxygenation is slow and thus, for satisfactory oxygenation, it would be necessary to slow down the moving film; a slow moving film, in turn, is apt to clot readily, requiring the addition of an anticoagulant such as heparin or "Dicumarol." The use of anticoagulants, however, is not favored in circumstances requiring the use of an artificial lung.

According to the invention, it is preferred to oxygenate the blood while it is undergoing circular or rotary movement, it having been found that the dispersal of the blood into a film of requisite thinness, its oxygenation, and its subsequent collection, may be practically controlled by virtue of subjecting the blood to rotary movement. The blood is deposited in the oxygenating zone and quickly rotated to form an annular ring or layer, and this layer is rapidly spread into an inclined film having a slope in the range of 0.5 to 6 (as hereinafter described) and a film thickness of about 50 microns by rapidly accelerating the blood along the said slope to a rotational acceleration equivalent to 2 to 7 times the acceleration of gravity. This rotating inclined film of blood is then rapidly advanced through the zone in as short a time as possible consistent with satisfactory oxygenation. Preferably, the blood is present in the oxygenating zone for a period up to two seconds. Usually not more than 6 seconds are required, although oxygenation may be secured within a range of 0.25 to 15 seconds. The oxygenated blood is collected, and then, while still rotating, is removed from the zone and returned to the arterial system of the subject.

A form of apparatus suitable for carrying out the foregoing method is shown in Figs. 1 and 2, wherein Fig. 1 is a diagrammatic, partly sectioned view of the apparatus, and Fig. 2 is a partial view taken along the line 2—2 of Fig. 1. Fig. 3 is a view like Fig. 1 but showing a modification.

Referring to Fig. 1, the apparatus comprises an oxygenating chamber 10 having the shape of an inverted cone which may be truncated, as shown. The lower and upper ends of the chamber are open. Adjacent the lower end is a stationary inlet tube 11 above which is a rotatable inlet tube 12 which extends into the lower end 13 of the chamber. The tube is bent as at 14 to

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form a lateral portion 15 which extends to a point 16 adjacent the inner lower wall of the chamber. Tube 15 terminates in an opening 17. A liquid-tight joint 18 connects the tubes 11 and 12. Means for rotating tube 12 are provided in the form of a pulley 19 attached to the tube which is driven through a belt 20 by the pulley 21 attached to the shaft 22, the latter being connected to the shaft of motor 23. In a similar way the chamber 10 is driven by a pulley 24 attached to the downwardly extending portion 25, this pulley being driven through a belt 26 by a pulley 27 driven by motor 23. Gear reducers 28, 29 are provided for controlling the speed of pulleys 21 and 27. Extending through the upper end 30 of the chamber is a rotatable outlet tube 31 which is bent as at 32 to form a lateral extension 33 which extends into an annular pocket or groove 34. Tube 33 has an opening 35 in communication with groove 34. A stationary tube 36 is connected to the rotatable tube through a joint 37, which is similar to joint 18, and which consists of a flange 38 on the tube 31 and a flange 39 on the tube 36. These flanges have smooth abutting surfaces and are held together by clamps, as shown at 40, inside the housing 37. Tube 31 has a movable connection with flange 38 and is rotated by means of a pulley 41 driven through a belt 42 by a pulley 43 on the shaft 44 of motor 45, the latter being provided with a gear reducer 46.

Venous blood is introduced into the oxygenating chamber through the tubes 11 and 12. The chamber is first set in motion, and preferably the tube 12 is also rotated in the same direction as the chamber but at a different speed. Blood is deposited on the walls of the chamber and, due to the rotation, is rapidly spread into an inclined layer or film which moves upwardly along the walls of the rotating chamber, the area of the film being rapidly and continuously increased as the blood advances upwardly. Oxygen introduced to the chamber comes in contact with the blood and oxygenates it, this phenomenon taking place while the blood is dispersed in film form between the point of introduction of the blood and the groove 34. At groove 34 the blood is collected and removed through opening 35 in the tube 33, the tube being rotated at a speed less than that of the chamber. Opening 35 points in a direction opposite the direction of spin of the chamber, and as may be apparent, the blood passes into the opening by virtue of its own momentum. In order to decrease the upward rate of flow of the blood as it approaches the enlarged end of the chamber and so render it more easily controllable, the upper chamber wall is made more nearly vertical, as shown in Fig. 1, and the annular groove 34 is disposed in this vertical portion of the wall. This change in the slope occurs just below the groove, as at the point generally indicated at 50. The greater portion or length of the wall, however, has a slope in the range of 0.5 to 6. An annular lip or flange 47 is provided on the upper enlarged end of the chamber to prevent the blood from passing over the top of the chamber.

The inner surface of the chamber should be as smooth as practicable to facilitate the flow of blood. As one example, a chamber made of aluminum having its inner surface coated with paraffin gave satisfactory results. The chamber may be made of other materials, and non-wettable agents such as tetrafluoroethylene and silicone resins may be used to coat the inner surface of the same. A glass chamber coated with a silicone polymer, preferably in fluid form, is suitable. The flanges 38, 39 of the joint 37, particularly the abutting surfaces of the flanges, should be made of non-wettable material. If desired, these surfaces may be coated with the same type of non-wettable agent employed to coat the chamber 10. Of course, the flanges should have smooth abutting surfaces prior to application of any agent. The inlet and outlet tubes should also have non-wettable internal surfaces, and these tubes may either be fabricated of non-wettable material, such as plastic, or coated with a non-wettable agent of the kind described.

Oxygen may be admitted to the chamber in any desired way, either to the upper enlarged end or to the lower restricted end. If one end of the chamber is closed, as it may be if desired, the oxygen may enter and leave

through the open end. Pure oxygen or air is suitable. If desired, the chamber may be placed in an incubator in which an atmosphere of oxygen is constantly maintained.

The slope of the inclined film, or to say the same thing, the slope of the wall of the chamber, should be in the range of 0.5 to 6. That is to say, the wall of the chamber, when viewed in cross section as in Fig. 1, is inclined to the horizontal, and the tangent of the inclination angle is in the range of 0.5 to 6; or stated another way, the inclination angle has a rise and a run, and the rise/run ratio is in the range of 0.5 to 6. For this purpose, the wall of the chamber, as viewed in Fig. 1, is assumed to be straight, although actually it is convex in an outward direction. It will be noted that the slope is positive. For purposes of this application, the chamber wall or the film of blood on it will be referred to as having a slope in the range of 0.5 to 6. The significance of such a sloped wall is that it enables an effective dispersal of the blood to be obtained, and further it aids the blood to be moved through the chamber, i. e., it facilitates the throughput of blood. If the slope is too low, that is, below about 0.5, the dispersal and throughput of the blood can not be very well controlled, and if the slope is too high, the blood cannot be adequately dispersed.

The acceleration imparted to the blood is along the slope of the chamber wall, and as described, should be in the range of 2 to 7 times the acceleration of gravity. This acceleration is the net acceleration. That is, it is the value after subtracting from the applied acceleration the acceleration due to gravity, since in Fig. 1 the blood is moving against the action of gravity. Accelerating the blood along the walls of the chamber is important because, as in the case of the slope, the acceleration helps to disperse the blood and to move it through the chamber at a sufficient rate. If the acceleration is too low, the blood moves too slowly and may clot; also, oxygenation is not efficient because the blood film is apt to be too thick. If the acceleration is too high, damage to the blood results.

As indicated, the time during which the blood is present in the oxygenating zone is preferably about 2 seconds and usually not more than 6 seconds. In this range, rapid oxygenation may be accomplished while avoiding clotting. Oxygenation may also be carried out employing a time range of 0.25 to 15 seconds. If a lower time is used, there is apt to be no appreciable oxygenation, while if the time is too long, clotting is apt to occur.

With the slope of the film of blood in the range of 0.5 to 6, and the net acceleration in the range of 2 to 7 times the acceleration of gravity, it has been found that the blood film will have a thickness on the order of about 50 microns, and that the blood can be advanced through the oxygenating zone within a satisfactory interval of time and without damage. At a film thickness of about 50 microns the oxygenation is rapid and complete and the tendency to clot is minimized. Satisfactory oxygenation may be carried out at a film thickness as low as 20 microns, so that a preferred range of thickness is 20 to 50 microns. A blood film having a thickness up to 100 microns can be handled. If the film is too thick, i. e., more than 100 microns, the oxygenation will not be satisfactory and in addition the tendency to clotting will be greatly increased.

The acceleration may be varied by varying the speed of rotation of the chamber. It has been found that the speed of rotation need not be more than about 400 R. P. M. and may be as low as 30 R. P. M.

As will be understood, the temperature at which the oxygenation is carried out should approximate the body temperature of the patient or experimental animal.

If desired, the oxygenation of the blood may be carried out with the chamber 10 in a reversed position. That is, the end 13 may be the upper end instead of the lower. In this case, the blood will be introduced to the chamber in the same manner as described above and will be spread into an inclined layer or film on the wall of the chamber. The film in this case will move downwardly and will be collected in the groove 34 and removed from the chamber by means of tube 33. The net acceleration applied to the blood along the slope of the chamber will be the same as before, namely, 2 to 7 times the acceleration of gravity. The applied acceleration will be less than that applied in the first case since in the present instance the blood is moving downwardly

and its movement will be aided by the acceleration of gravity. The latter value is added to the applied acceleration so that the net acceleration is in the range of 2 to 7 times the acceleration of gravity. The slope of the wall of the chamber will be in the range of 0.5 to 6, but will be a negative slope.

In Fig. 3 the apparatus comprises a plurality of nested oxygenating chambers 60, 61, 62, 63, and 64, each having the shape of an inverted cone and each having walls that are convex in an outward direction and that have a slope in the range of 0.5 to 6. The outermost chamber 60 is substantially the same as that shown in Fig. 1, being provided with a groove 65 and means 66 by which it may be rotated. The upper ends 67, 68, 69, and 70 of chambers 61, 62, 63, and 64 are disposed at varying heights below groove 65, and are flared so as to feed the blood either directly to groove 65 or to the wall of chamber 60 immediately below the groove from whence the blood passes to the groove. The lower ends 71, 72, 73, and 74 of the chambers are disposed at varying heights above the lower restricted end 75 of chamber 60. Chamber 61 is spaced from and supported on the chamber 60 by means of a series of spaced upper and lower struts, several of which are shown at 76, 77, 78, and 79. These struts may have a streamlined cross section to avoid the possibility of blood being obstructed by them or depositing along their edges. In a similar way, chamber 62 is spaced from and supported on chamber 61; chamber 63 is spaced from and supported on chamber 62; and chamber 64 is spaced from and supported on chamber 63.

As in the case of Fig. 1, a stationary inlet tube 80 is provided which is connected by means of the joint 81 to a rotatable inlet tube 82, the latter having means for rotating the same of the kind described in Fig. 1. Tube 82 is provided with a number of branches 83, 84, 85, and 86, each extending to a point adjacent the inner wall of one of the chambers at the lower portion of the same. Each branch terminates in an opening for introducing blood to the chambers. At the upper end of chamber 60 a rotatable tube 87, having an inlet 88, is connected to a stationary tube 89 by a joint 90, by means of which blood may be removed from the apparatus in the manner described. A pump 91 may aid in returning the blood to its source, or may be omitted and the blood returned under the force acquired by it in the oxygenating chamber. A pump may also be employed with the apparatus of Fig. 1. Essentially the operation of the apparatus of Fig. 3 is like that of the apparatus of Fig. 1.

In the light of the foregoing description, the following is claimed:

1. Apparatus for oxygenating blood comprising an oxygenating chamber having the shape of an inverted cone, said chamber having walls that are convex in an outward direction and that have a slope in the range of about 0.5 to 6, an annular groove in said walls adjacent the enlarged end of the chamber, said groove having an opening communicating with the interior of the chamber, a stationary inlet tube adjacent the lower restricted end of the chamber, a rotatable inlet tube extending into the lower end of the chamber, a liquid-tight joint connecting said stationary and rotatable tubes, said rotatable tube extending to a point adjacent the inner wall of the chamber at the lower portion of the same and having an opening at said point, means for rotating said rotatable tube, means for rotating the chamber at a speed different from that of the rotatable tube, a rotatable outlet tube extending through the upper enlarged end of the chamber, said outlet tube extending into said annular groove and having an opening communicating with said groove, said opening being adapted to point in a direction opposite the direction of rotation of the chamber, a stationary outlet tube adjacent the rotatable outlet tube, a liquid-tight joint connecting both said outlet tubes, means for rotating the rotatable outlet tube at a speed less than that of the rotatable chamber, and means for introducing a free oxygen-containing gas to the interior of the chamber.

2. Apparatus for oxygenating blood comprising an oxygenating chamber having walls that are convex in an outward direction and that have a slope in the range of about 0.5 to 6, an annular groove in said walls adjacent the enlarged end of the chamber, said groove having an opening communicating with the interior of the chamber, an inlet tube extending into the chamber from the lower

end thereof to a point adjacent the inner wall of the chamber at the lower portion of the same, means for rotating the chamber, an outlet tube extending through the upper enlarged end of the chamber and into said annular groove, and means for introducing a free oxygen-containing gas to the interior of said chamber.

3. Apparatus for oxygenating blood comprising a plurality of nested oxygenating chambers each having the shape of an inverted cone, each chamber having walls that are convex in an outward direction and that have a slope in the range of about 0.5 to 6, an annular groove in the walls adjacent the enlarged end of the outermost chamber, said groove having an opening communicating with the interior of the outermost chamber, the upper ends of the other chambers being disposed at varying heights below said groove, the lower ends of said other chambers being disposed at varying heights above the lower restricted end of the outermost chamber, means for supporting said chambers in spaced relation to each other, a stationary inlet tube adjacent the lower end of the outer chamber, a rotatable inlet tube extending into the outer chamber from the lower end thereof, a liquid-tight joint connecting said stationary and rotatable tubes, said inlet tube having a plurality of outlets each extending to a point adjacent the inner wall of one of said chambers at the lower portion of the same, means for rotating said inlet tube, means for rotating the nested chambers as a group at a speed different from that of the inlet tube, a rotatable outlet tube extending through the upper enlarged end of the outer chamber into said annular groove, said rotatable outlet tube having an opening adapted to point in a direction opposite the direction of rotation of said chambers, a stationary outlet tube adjacent the rotatable outlet tube, a liquid-tight joint connecting both said outlet tubes, means for rotating the rotatable outlet tube at a speed less than that of the chambers, and means for introducing a free oxygen-containing gas to the interior of the chambers.

4. Apparatus for oxygenating blood comprising a plurality of nested oxygenating chambers each having walls that are convex in an outward direction and that have a slope in the range of about 0.5 to 6, an annular groove in the walls adjacent the enlarged end of the outermost chamber, said groove having an opening communicating with the interior of the outermost chamber, the upper ends of the other chambers being disposed at varying heights below said groove, the lower ends of said other chambers being disposed at varying heights above the lower restricted end of the outermost chamber with each said height increasing from the outer to the inner chamber, means for supporting said chambers in spaced relation to each other, an inlet tube extending into the outer chamber from the lower end thereof, said tube having a plurality of outlets each extending to a point adjacent the inner wall of one of said chambers at the lower portion of the same, means for rotating the chambers, an outlet tube extending through the upper enlarged end of

the outer chamber and into said annular groove, and means for introducing a free oxygen-containing gas to the interior of said chambers.

5. Apparatus for oxygenating blood comprising an oxygenating chamber having the shape of an inverted cone, said chamber having walls that are convex in an outward direction and that have a slope in the range of about 0.5 to 6, means for introducing blood to be oxygenated to the inner wall of the reduced end portion of the chamber, means for rotating the chamber, an annular groove in said walls adjacent the enlarged end of the chamber for collecting oxygenated blood, said groove having an opening communicating with the interior of the chamber, means for removing oxygenated blood from said annular groove, and means for introducing a free oxygen-containing gas to the interior of the chamber.

6. Apparatus for oxygenating blood comprising a chamber having walls that are convex in an outward direction and that have a slope in the range of about 0.5 to 6, means for introducing blood to be oxygenated to the inner wall of one end portion of the chamber, means for rotating the chamber to thereby disperse the blood and to advance the same over the chamber walls in the form of a moving inclined film, means for introducing a free oxygen-containing gas to the interior of the chamber to make contact with said moving film of blood and to oxygenate the blood, a blood collector in said chamber adjacent the other end portion thereof for collecting oxygenated blood, said collector having an opening communicating with the interior of the chamber, and means for removing oxygenated blood from said collector.

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