EXPERIMENTAL STUDIES IN EXTRACORPOREAL CIRCULATION USING THE HELIX-RESERVOIR BUBBLE OXYGENATOR

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Open heart surgery is in its infancy in South Africa and to date only a few successful open heart operations utilizing total cardio-pulmonary bypass have been performed. Since July 1958 we have been using the helix-reservoir bubble oxygenator[1] in our experimental laboratory and in this paper we present the results of our first consecutive 20 animal experiments.

Our recent experiences in this laboratory, and the experiences of one of us (C.N.B.) at the University of Minnesota Medical School, Minneapolis, during 1956-58, lead us to agree with Lillehei[2] that the helix-reservoir bubble oxygenator is a highly satisfactory oxygenator for use in open heart surgery and that the unsatisfactory results obtained by some workers[3-5] using this apparatus are due to errors in technique, or to unnecessary and undesirable modifications.[6]

In spite of a vast amount of literature on the subject, we have been unable to trace any reference which describes, in detail, certain steps in the preparation and assembly of the oxygenator which we consider to be of vital importance to its proper function. We will therefore describe our technique in detail.

DESCRIPTION OF THE OXYGENATOR

The helix-reservoir bubble oxygenator, as described by DeWall *et al.*[1, 6] has been used in all our experiments (Fig. 1). The plastic components of the oxygenator which are in contact with the blood are made of Mayon*—a pure polyvinyl plastic hose. Three short sections of latex rubber tubing (internal diameter $\frac{3}{4}$ inch) are used in the circuit through the pumps. We have used the sigmamotor pump† model TM2 in the main circuit, and model TM4 in the cardiotomy return circuit. Special highly polished stainless steel connectors‡ are used to connect the various plastic components in the circuit. These connectors are without abrupt shoulders or other obstructions and minimize potential turbulence.

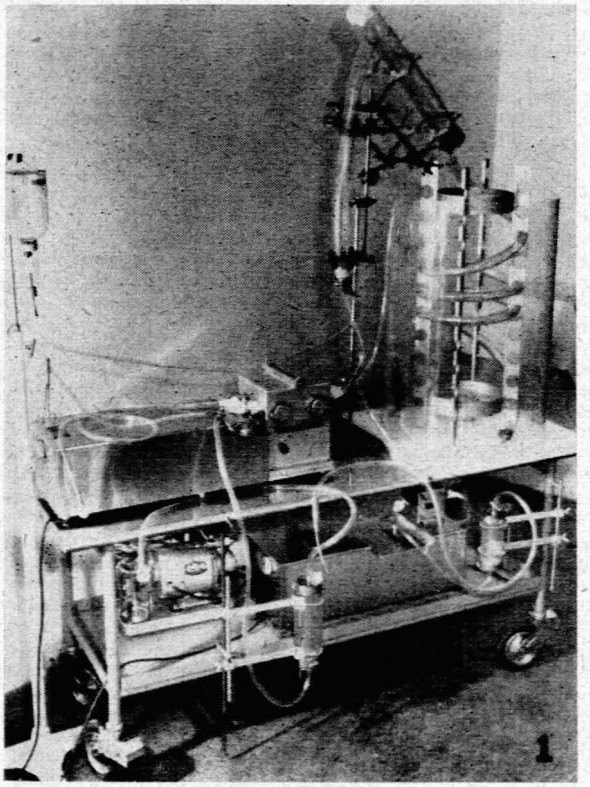

Fig. 1. The helix-reservoir bubble oxygenator.

The components of the oxygenator are connected as shown in Fig. 2. Blood is drained by gravity from both venae cavae into a venous well, which is placed close to the operating table, the bottom of the well being approximately 20 inches below the level

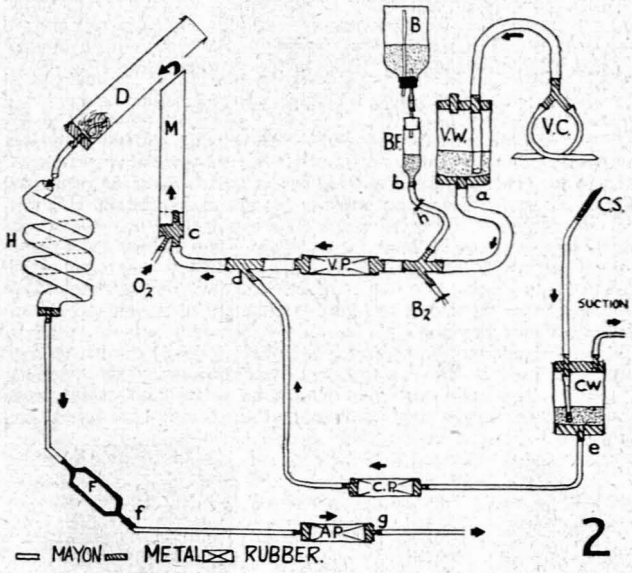

Fig. 2. Diagrammatic representation of the helix-reservoir bubble oxygenator. A.P.=Arterial pump. V.P.=Venous pump. C.P.=Cardiotomy return pump. V.W.=Venous well. C.W.=Cardiotomy return well. C.S.=Cardiotomy sucker. V.C.=Venous catheters. M.=Mixing chamber. D.=De-bubbling chamber. H.=Helix. F.=Double metal filter. B.=Blood bottle. B_2.=Lead to second blood bottle. B.F.=Blood filter.

of the right atrium. The well is adjustable and can be raised or lowered to decrease or increase the venous return respectively. We have, however, rarely had occasion to alter the level of the well during perfusion.

Blood from the venous well is pumped, *via* the venous circuit, into a vertical mixing chamber where it is mixed with 100% oxygen. The oxygen input to the mixing chamber is 3-4 times the blood-volume input, and enters through an oxygen diffuser plate[7] at the bottom of the mixing chamber. The blood-oxygen mixture, owing to the flow of venous blood entering and the flow of oxygen passing upwards, gently rises in the mixing chamber, from the top of which it empties into a de-bubbling chamber.

The de-bubbling chamber lies at an an angle of approximately 20° with the horizontal and is designed to dissipate bubbles and separate the excess O_2 and CO_2 from the arterialized blood. Its walls are coated with a potent non-toxic silicone antifoam substance.¶

* Mayon Plastics, 415 17th Avenue North, Hopkins, Minnesota.
† Sigmamotor Inc., 3 North Main Street, Middleport, N.Y.
‡ Phelan Mnfg. Co., 2029 Washington Avenue, So. Minneapolis, Minnesota.
¶ Antifoam A, Dow Corning Co., Midland, Michigan.

Blood flows by gravity through the de-bubbler and empties into a helix which is wound onto an aluminium stand and placed in a perspex waterbath, the temperature of which is thermostatically controlled between 38°C and 41°C. The helix is made of Mayon tubing with an internal diameter of 1¼ inch, and its length is such that it will accommodate a volume of blood equal to one minute's flow rate plus 400 ml.

The helix acts as a reservoir and, in addition, removes any free gas remaining in the blood. The mechanism of this action was first described by DeWall *et al.*[1] Blood containing free gas is less dense than normal blood and consequently is forced upward by hydrostatic pressure. The lighter blood containing free gas therefore laminates on the upper layer within this tube. As the flow of blood is down the inclined plane of the helix, the heavier gas-free blood descends by gravity beneath the lighter gas-containing blood, forcing it continuously upward. This lamination of the flow is present as long as blood of the two densities is present. After a short flow down the tube the lighter gas-containing blood coalesces and rises upwards, and oxygenated blood, free of excess gas, flows to the bottom of the helical coil.

From the bottom of the helix, blood passes *via* a double metal filter** and thence *via* the arterial circuit to the femoral artery of the subject.

Cardiotomy suction has been used in those experiments in which a ventriculotomy or atriotomy is performed. Blood is aspirated into the cardiotomy well (suction at −30 mm. Hg pressure) and is then pumped by a sigmamotor pump to the venous limb of the main circuit, which it joins distal to the venous pump (Fig. 2).

PREPARATION OF THE APPARATUS

The venous and cardiotomy wells, the mixing and de-bubbling chambers and the helix are assembled before autoclaving, as described by DeWall *et al.*[2] and the helix is marked off into sections with a grease pencil, each section having a volume of 100 ml. The connectors at the ends of these tubes are fixed in position by means of motor-car radiator hose clamps. The clamps are loosely applied before autoclaving and finally tightened when the oxygenator is assembled. The exposed ends of the stainless-steel connectors are each covered with cotton gauze which is held in place by elastic bands.

The upper end of the mixing chamber is covered with cotton gauze, held in place by means of autoclaving tape; this covering is applied in such a way that it can be removed without contaminating the upper end of the mixer (Fig. 3). The upper end

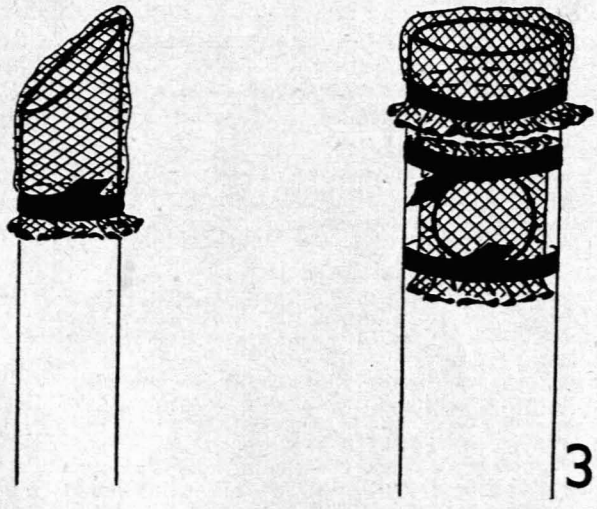

Fig. 3. Diagram illustrating method of covering mixing chamber and de-bubbling chamber with cotton-gauze and autoclave tape before autoclaving.

of the helix is similarly covered with a cap of gauze which can be removed and then replaced when filling the helix. The upper end of the de-bubbling chamber is covered with gauze in such a way that the hole into which the mixing chamber is inserted can be exposed without contamination and without uncovering the proximal end of the tube (Fig. 3). Elastic bands should not be placed around the Mayon tubing during autoclaving since this causes constriction of the tubing.

The technique of applying 'antifoam' is important to ensure adequate de-bubbling and to prevent 'bubbling over' from the proximal end of the de-bubbler and the top of the helix during perfusion. For each experiment 10 g. of 'antifoam' are used. Approximately ¾ of this is poured into the de-bubbling chamber before assembly and allowed to flow down its 'roof'. By means of a cotton-gauze plug on the end of a stout piece of wire this central stream is spread laterally so that the walls of the de-bubbler are evenly coated with a thin layer of 'antifoam'. There must be no pooling of 'antifoam' at any site. To increase the de-bubbling surface a 6-ft. length of ⅛ inch bore Mayon tubing is loosely coiled, coated with 'antifoam' and placed in the distal end of the de-bubbling chamber. The upper 20 inches of the helix, the *outer* wall of the tube leading from the de-bubbling chamber to the top of the helix, and the cardiotomy well are treated with the remaining 2½ g. of 'antifoam'—this is applied evenly to the walls of these portions of the apparatus by means of a gauze plug.

Each portion of the apparatus is then separately wrapped in a surgical towel and steam-autoclaved. It is essential for the operation of the oxygenator that the Mayon tubing be transparent. The tubing, however, tends to become 'fogged' during autoclaving and, in spite of experimenting with many different methods during the last 6 weeks, we have still not solved this problem to our entire satisfaction. This is due to the fact that a suitable autoclave is not available to us. Using the method to be described below, however, we are now able to produce transparent tubing after autoclaving, but the procedure is time-consuming and consequently we have not used a sterile technique in our experiments.

The tubing, wrapped in surgical towels, is placed in a steam autoclave at 259°F. and 20 lb. pressure per sq. inch for 30 minutes. The autoclave is then exhausted for 10 minutes at a negative pressure of −20 lb. per sq. inch. The door of the autoclave is then opened 12 inches and the tubing is allowed to cool down gradually during the ensuing 8 hours. The temperature of the autoclave we have used remains at about 150°F. during this time. The autoclave door is then opened to its full extent and the tubes are left for a further 8 hours.

The stainless-steel connectors and lengths of rubber latex tubes are boiled in a sterilizer immediately before assembling the oxygenator. The blood filters which we use are supplied sterile by the manufacturers.

Assembling the Oxygenator

The oxygenator (Fig. 2) is assembled in an ante-room by a surgeon under sterile conditions as for a surgical operation (in the laboratory, our apparatus is assembled by a technician). The various components of the venous circuit are connected as shown in Fig. 2. The ends of the tubes to the venous well (*a*), the blood-bottle filter (*b*) (or filters if 2 blood bottles are to be used simultaneously or alternately), and the mixing chamber (*c*), are covered with rubber finger stalls held in place by elastic bands. The cardiotomy circuit is then connected and joined to the venous limb (*d*), the end of the tubing from the cardiotomy well (*e*) being covered with a finger stall. The arterial circuit is then assembled, the connector (*f*) leading to the double metal filter is covered with a finger stall, and the connector (*g*), to which the arterial limb will later be attached, is covered with cotton gauze. As all the exposed ends are covered, sterile precautions are no longer necessary when handling this portion of the apparatus.

The apparatus, thus far assembled, is taken into the operating theatre for further assembly of the oxygenator. The arterial limb, leading to the patient, is kept sterile and, except for the proximal 12-inch end, which is handed to an assistant to be connected to the connector (*g*) (Fig. 2), is placed on a tray adjacent to the patient's right leg. The connections between rubber latex tubing, metal connectors, and Mayon tubing at the pump heads are tightly taped with adhesive strapping (Fig. 4). As an extra precaution, when used for operations on patients, radiator hose clamps are applied over the strapping to secure the rubber latex tubes to the stainless-steel connectors. To prevent the rubber tubing from 'milking through' the pump, several layers of adhesive tape are

** List No. 4498 Abbott Labs., North Chicago, Illinois, USA.

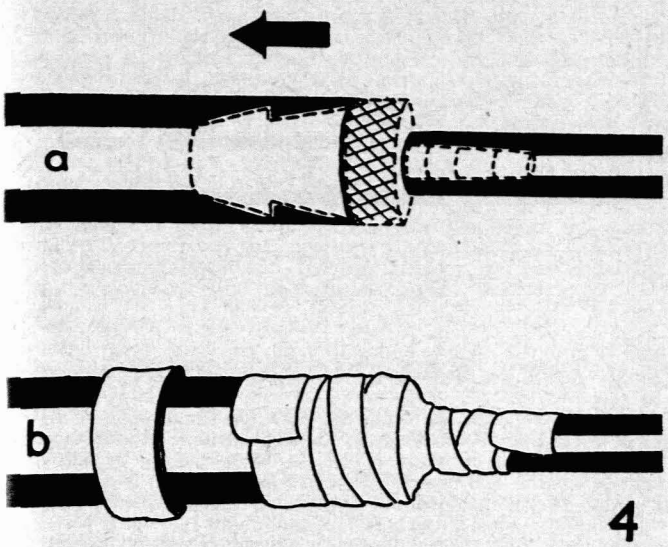

Fig. 4. Diagram illustrating connections at pump head (*a*) before and (*b*) after securing with adhesive tape. The 'shoulder' of adhesive tape is also shown, the arrow indicating the direction of flow.

wound around the tubing forming a shoulder on the inlet side of the pump head (Fig. 4).

The mixing and de-bubbling chambers are then set up on a metal stand (Fig. 1). The venous circuit is connected to the mixing chamber and the venous well, which have been previously secured in position by means of metal brackets. Rubber finger-stalls or cotton gauze coverings are removed and the Mayon tubing is slipped over the metal connectors, care being taken to avoid contamination of the ends during this process. The cardiotomy limb is similarly connected to the bottom of the cardiotomy well. The leads from the cardiotomy sucker to the cardiotomy well and from the venous catheters to the venous well are handled by the operating surgeon and connected during the course of the operation.

The connection between mixing and de-bubbling chambers is made under sterile conditions. This is done by removing the gauze covering the end of these chambers and inserting the top of the mixing chamber into the hole in the de-bubbler without contaminating these parts.

Priming the Oxygenator with Dextrose-Water Solution

The sterile helix, both ends of which are covered with gauze, is wound onto an aluminium stand in such a manner that its lower and upper 12 inches form a steep slope; the central coils of the helix slope only slightly downwards (Fig. 1). The double metal filter is then joined to the connector at the bottom of the helix and the limb distal to the filter is clamped.

The helix is then partially filled with sterile 5% dextrose-water solution. The next step is to clear approximately 500 ml. of fluid in the lower end of the helix of bubbles. This is done by trapping a large bubble at the distal end of the helix, which is then slowly allowed to ascend. As it ascends smaller bubbles coalesce and pass upwards in the helix, which is finally beaten with a patellar hammer to dislodge all bubbles. This is an essential operation in the setting up of the oxygenator—every bubble must be dislodged and this may take 20 or 30 minutes to achieve.

Once all the bubbles have been dislodged from the helix the filter must be similarly filled and cleared of bubbles. This is achieved by loosening the clamp on the arterial limb thus allowing fluid to pass slowly from the helix into the filter. The latter is then beaten with the patellar hammer to dislodge any bubbles which may have been trapped. The tubing distal to the filter is clamped and connected to the arterial circuit (*f*) which has previously been assembled. The clamp is then removed and the fluid is allowed to flow slowly through the remainder of the arterial limb, the distal end of which will be connected to the femoral artery catheter, and is handled under the sterile precautions already described. The possibility of bubbles being trapped in the opaque section of latex rubber tubing passing through the pump head must be remembered—this section is therefore also beaten to obviate this possibility. When all bubbles have been dislodged, the end of the arterial limb is clamped with a sterile clamp and the helix, on its stand, is placed in the water bath. At no stage should the volume of fluid in the helix be allowed to fall below 500 ml. thus preventing the possibility of bubbles entering the arterial circuit. The rubber latex tubing of the arterial circuit is then placed in the pump and the latter is checked for occlusion, and calibrated.

Pump Occlusion and Calibration

The sigmamotor pump is used as an occlusive pump, i.e. one finger of the pump mechanism is always compressing the tubing, thus preventing back-flow. Should the pump be incorrectly set and non-occlusive, raising the resistance against which it has to pump will decrease the output.[8]

The arterial limb of the circuit distal to the pump (still handled under sterile precautions) is elevated above the level of fluid in the helix and all clamps removed. If the pump is correctly set there should be no back-flow into the helix. The pump is rapidly turned on and off by an assistant so that a different finger of the pump comes to lie in the closed position and occlusion is again checked. This manoeuvre should be repeated 5 times. Should there by any back-flow the occlusion plates on the pump are adjusted until this no longer occurs. It is important to adjust the plates in such a manner that occlusion is not excessive thus preventing excessive haemolysis of the blood.

The pump is calibrated using arterial catheters of a size estimated to be suitable for the patient undergoing perfusion. This catheter is connected to the end of the arterial limb, the pump is turned on for 15 seconds and the volume of fluid pumped is measured. The volume flow per minute for a given size catheter at a given pump-speed-setting is then calculated. During the operation, the pump operator is therefore able to achieve a known arterial input by setting the pump speed accordingly. Once again during this procedure 5% dextrose in water is added to maintain the volume of fluid in the helix.

Priming the Oxygenator with Blood

The oxygenator is primed with compatible donor blood to which heparin (20 mg./500 ml.) has been added as an anticoagulant. The blood should be at a slightly higher temperature than the water in the waterbath surrounding the helix. If cold blood enters the helix, dissolved oxygen will come out of solution as the blood is warmed and minute bubbles will be formed. In animal experiments we have not performed compatibility tests. In operations on humans, each pint of blood is cross-matched with the patient's blood, and with every other pint.

A volume of blood equal to the calculated minute-flow for the patient is required to prime the oxygenator and priming is commenced about 20 minutes before the surgeon is due to insert the catheter into the femoral artery. When the catheter has been inserted, the priming of the oxygenator should have been completed, so that the arterial limb may immediately be connected to the femoral catheter. The vena caval catheters are inserted after this connection has been established; should they obstruct the venous return to the heart the perfusion can then be commenced with a minimum of delay.

The arterial head of the pump is opened and the helix is drained until approximately 100 ml. of 5% dextrose-water remains. The venous circuit is then placed in the pump, the arterial head is left open, the lead from the venous well is clamped, the oxygen flow is turned on (a slow flow rate of 2 litres per min. is adequate during priming), the blood is connected and the venous pump is started. Blood is thus pumped *via* the mixing chamber and de-bubbler into the helix. Once the oxygenator has been primed the oxygen flow must not be turned off completely, or the minute holes in the oxygen diffuser will become blocked.

During priming, the clamp on the lead from the venous well is temporarily released to allow blood to enter the well and to rise to a depth of about 8 cm. This provides blood to be pumped *via* the mixing chamber, until the venous flow from the venae cavae to the venous well becomes established.

The helix, which is now in the waterbath, is examined and any bubbles in the blood column are dispersed as previously described. When all bubbles have been dislodged, the clamp is removed from the end of the arterial limb by the surgeon and the 5% dextrose-water is run out to be replaced by blood. The arterial

head of the pump is closed, the level of blood in the helix is noted and marked on the outside of the perspex waterbath, and the oxygenator is then ready to be connected to the patient.

OPERATIVE TECHNIQUE

1. *Bleeding of Donors*

Dogs are anaesthetized with a volatile anaesthetic agent (or N_2O and O_2), an endotracheal tube is inserted, and intermittent-positive-pressure respiration is instituted. A femoral cut-down, with a local anaesthetic, is performed and a catheter is inserted into the femoral artery. The blood is run into glass bottles, which are gently agitated and to which heparin has been previously added. The donor blood is placed in a waterbath at 41°C, where it is kept until the oxygenator is primed.

Barbiturates should not be used to anaesthetize donor dogs; this has been shown to lower the survival rate of the dogs used for the experiments (DeWall *et al.*,[6] Milner *et al.*[9]).

Human donors are bled on the morning of the operation. Venous blood is drawn into sterile siliconized glass bottles to which heparin has been added.

2. *Anaesthesia*

The staff of the anaesthetics department, Groote Schuur Hospital, have kindly administered anaesthetics for all our experiments, and the salient points, without details of methods used are as follows:

Anaesthesia, in 13 dogs, consisted of thiopentone induction followed by N_2O with O_2 for maintenance. In 4 dogs, thiopentone induction followed by intermittent doses of thiopentone was used. In the remaining 3 animals, a technique using only volatile anaesthetic agents was employed and will be the subject of a further communication.

It appears to be important to maintain a very light plane of anaesthesia throughout. At the onset of perfusion one is faced with the problem of 2 volumes of blood, viz. (1) that in the patient's circulation and (2) that in the oxygenator, each of which may contain a different concentration of anaesthetic agents and relaxants. In practice we have found that post-operative recovery has been more rapid if no additional barbiturate or relaxant is administered during bypass. This cannot always be achieved and considerable skill and practice is necessary in clinically judging the correct state of anaesthesia before the start of perfusion, since signs of depth of anaesthesia are difficult to assess once perfusion has commenced. EEG monitoring of anaesthesia would, we feel, enable more constant conditions to be achieved. Facilities for this are unfortunately not yet available to us. Details of anaesthetic problems will be the subject of a separate communication.

3. *Cannulation*

A thoracotomy is performed through the right 4th interspace. Particular care is taken with haemostasis, all bleeding points being coagulated with diathermy. The azygos vein is ligated in continuity at its point of entrance into the superior vena cava. A tape is placed around each vena cava at its entrance into the right atrium and the two ends of each tape are drawn through 2-inch cuffs of rubber tubing. By tightening and cross-clamping these (Fig. 6*a*) once the cavae have been catheterized, the entire systemic venous return can be shunted into the venous well. The pericardial sac is then opened, and the edges of this incision are cauterized.

The left femoral artery is then exposed, the patient is heparinized (1·5 mg per kg. body weight), and the largest possible Bardic* arterial catheter is introduced through a transverse arteriotomy. In the dog the distal end of the artery is ligated to prevent bleeding back. In the patient the artery is clamped and the defect is repaired when the catheter is removed after the perfusion. The technique of anchoring the catheter firmly is shown in Fig. 5. The arterial catheter is connected to the arterial limb of the oxygenator in such a manner that no bubbles are trapped at the connection. In order to achieve this, the blood in the arterial limb must completely fill the tubing so that a meniscus bulges from the open end of the tubing. The arterial catheter is then gradually released and the connection is made as blood begins to flow from this catheter. The connection is then firmly tied with linen thread to prevent the possibility of slipping.

* Bardic No. 1055. Manufactured by C. R. Bard Inc. USA.

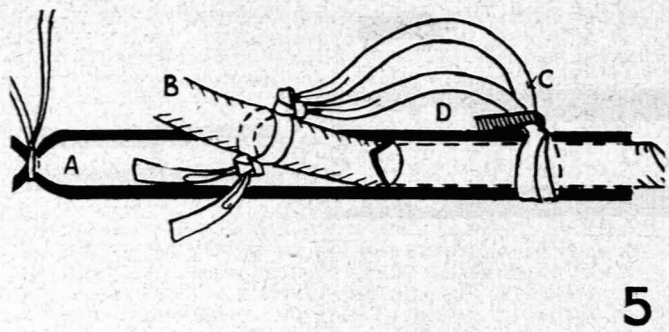

Fig. 5. Diagram illustrating method of anchoring arterial catheter *in situ*. A=Artery. B=Catheter. C= Umbilical tape. D=Artery forceps.

Large-sized Bardic catheters are used for cannulation of the venae cavae and are inserted *via* the right atrium. The distance from the point of insertion of each catheter into the auricle to each vena cava is estimated. A ring $\frac{1}{8}$ inch in width is cut from a section of rubber tubing and slipped over each catheter to mark this point. A purse-string suture of atraumatic 'O' silk is placed around the apex of the right auricular appendage and the two ends of the suture are threaded through a short cuff of $\frac{1}{8}$-inch-bore

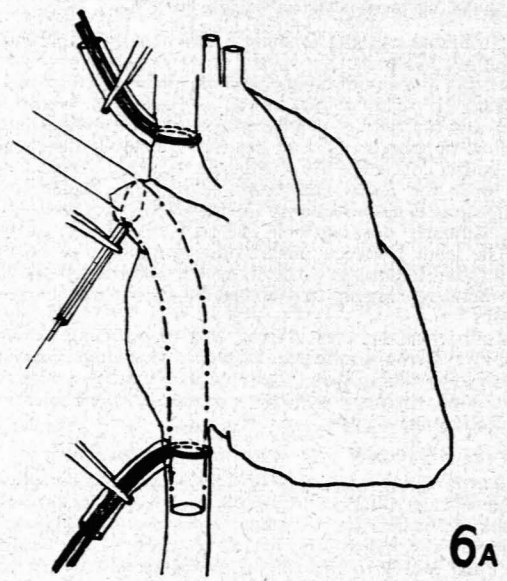

Fig. 6 (*a*). Diagrammatic representation of inferior vena caval catheter *in situ*, showing method of taping and occluding venae cavae and of anchoring catheter in the atrium.

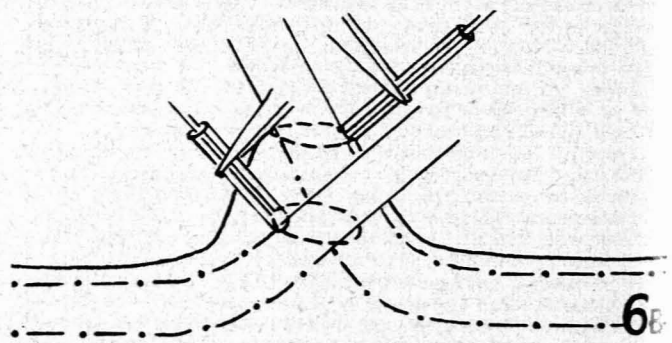

Fig. 6 (*b*). Diagrammatic representation of superior and inferior vena caval catheters *in situ*, showing insertion of superior catheter *via* the lateral wall of the right atrium, method of anchoring the catheter, and crossing of the superior and inferior catheters within the atrium.

rubber tubing. An auricular clamp is then applied below the purse-string, the apex of the auricular appendage is snipped off and any obstructing musculi pectinati are cut through. As the clamp is released, the inferior vena caval catheter is inserted until the rubber marker is flush with the purse-string, which is pulled tight and anchored by cross clamping the rubber cuff (Fig. 6*a*). A second purse-string is then inserted in the right lateral well of the right auricle (Fig. 6*b*). Traction on the two ends of the suture causes the auricular wall to 'peak' and a clamp is applied below the purse-string. A longitudinal incision is made in the auricular wall in the centre of the purse-string suture and, as the clamp is withdrawn, the superior vena caval catheter is inserted and anchored as before. The two catheters are then connected to the venous well and the perfusion can now be commenced.

4. *Perfusion*

The pump is turned on to start the bypass, the arterial flow being set at a predetermined level, calculated according to body weight. The tapes around the venae cavae are tightened, so that the total venous return leaves the body *via* the venous catheters. The only blood entering the heart at this stage is the coronary venous return. Intermittent-positive-pressure respiration is then stopped, the lungs being kept in a semi-inflated position during the perfusion. At the commencement of the perfusion, the level of blood in the helix will fall. As soon as the mixing and de-bubbling chambers become filled, the helix level will remain stable, provided that the venous return is unimpeded and that there is no blood loss from the cardiotomy. The venous pump is so regulated that there is always some blood in the venous well. This prevents air from being sucked in, which would cause unnecessary turbulence and haemolysis. The level of blood in the helix must be carefully observed and not allowed to fall below the 500 ml. mark. Should this occur a known volume of blood is allowed to enter the oxygenator by releasing the clamp (*h* in Fig. 2) on the tube from the blood bottle to the venous circuit. The cardiotomy well is intermittently emptied by turning on the cardiotomy pump. If for any reason it is desired to increase the perfusion rate, the arterial head of the pump can be adjusted accordingly.[10]

5. *Termination of Perfusion*

When it is desired to stop the perfusion, the tape around the superior vena cava is released and intermittent-positive-pressure respiration is recommenced. Some venous blood now enters the heart, which gradually begins to take over the circulation. If the beat remains steady the inferior vena caval tape is released, and after a few minutes the pump is turned off and the arterial and venous limbs of the circuit are clamped.

The venous catheters are removed one at a time, the defects in the auricle being closed by tying the purse-string sutures which are already *in situ*. One half of the calculated dose of protamine sulphate is then injected intravenously, the remaining half being administered slowly during the next half hour. The total dose of protamine sulphate which we have used is equal to twice the amount of heparin originally injected.[7, 11, 12] The arterial catheter is then removed and the proximal end of the artery ligated.

A rubber drain connected to a suction apparatus at a negative pressure of −30 mm. Hg. is placed in the pleural cavity and the thorax is closed in layers with continuous linen sutures. The drain is removed when blood loss from the thorax ceases (usually about 30 min. post-operatively) and the animal is placed in a warmed cage. No special post-operative care, other than anti-biotic therapy, has been found necessary.

RESULTS

The results of our first 20 consecutive operations on mongrel dogs are shown in Table I. The animals were perfused at a flow rate of 70 ml. per kg. of body weight per minute and

TABLE I. RESULTS OF OPERATIONS ON 20 MONGREL DOGS—PERFUSED AT A FLOW RATE OF 70 ML. PER KG. OF BODY WEIGHT PER MIN.

Dog No.	*Wt. (kg.)*	*Duration of bypass (min.)*	*Operative procedure*	*Anaesthetic*	*Art. O_2 / Ven. O_2* vols. %	*Art. CO_2 / Ven. CO_2* vols. %	*Result*
1	16	15	*nil*	Pent. O_2	—	—	Survival
2	13	26	*nil*	Pent. O_2	—	—	Survival
3	19	32	*nil*	Pent. N_2O O_2	—	—	Survival
4	16	30	*nil*	Pent. O_2	91 71	20·6 20·8	Survival
5	14	30	*nil*	Pent. N_2O O_2	101 57	35 43·5	Survival
6	13	35	*nil*	Pent. O_2	99 69	32 36	Survival
7	16	30	RV	Pent. N_2O O_2	95 75	Spoilt	Survival
8	14	32	RV	Pent. N_2O O_2	—	—	Survival
9	14	31	RV	Pent. N_2O O_2	—	—	Survival
10	13	30	RV	Pent. N_2O O_2	98 76	36 43·5	Survival
11	17	35	RV	Pent. N_2O O_2	96 61	36·5 49	Survival
12	16	32	X	Pent. N_2O O_2	—	—	Died 3 hours post-op.
13	13	28	RV	Pent. N_2O O_2	—	—	Survival
14	13	22	*nil*	Pent. N_2O O_2	—	—	Survival
15	14	22	RV	Pent. N_2O O_2	—	—	Survival
16	14	54	Y	Volatile anaesthetic agents	100 73	26 30·5	Survival
17	18	52	RV	,,	—	—	Survival
18	14	23	RA	,,	—	—	Survival
19	15	68	Z	Pent. N_2O O_2	—	—	Survival
20	14	45	RV	Pent. N_2O O_2	—	—	Died 21 hrs. post-op.

RV = Right ventriculotomy. RA = Right atriotomy.
X (dog no. 12) = Induced cardiac arrest (7 min.) with 3 c.c. of pot. cit., cardiac massage to re-start and intravenous 1/1000 adrenaline given.
Y (dog no. 16) = Right ventriculotomy and induced cardiac arrest with pot. cit. Fibrillation for 17 min. Electrical defibrillation.
Z (dog no. 19) = Right atriotomy + ventricular fibrillation for 5 min. Electrical defibrillation.

the aim of each experiment was the survival of the animal. We did not employ a sterile technique and animals were given penicillin and streptomycin post-operatively.

EEG tracings and pressure studies were not performed. Post-perfusion arterial and venous O_2 and CO_2 content were not estimated as a routine. Such biochemical results as are available have been included in Table I.

We have experienced no difficulty with post-operative bleeding, the average post-operative blood loss from the chest being less than 50 ml.

All our survivors were able to stand (and usually walk) and eat within 18 hours after the operation. All animals survived for a minimum of 7 days; they were then destroyed or used as donors for further experiments. None of the survivors showed any clinical evidence of cerebral damage.

There were only 2 deaths in this series. The first death (dog 11) followed elective cardiac arrest of 7 minutes' duration, with the Melrose technique.[13] Cardiac massage and intravenous injection of 1/1,000 adrenaline was necessary before the heart commenced to beat. The pulse at the termination of the operation was satisfactory but the animal died 3 hours later. No cardiotomy was performed, and so the injected potassium citrate was not removed from the circulation; we believe that this omission was responsible for the animal's death.

The only other death (dog 20) was almost certainly the result of using unsatisfactory donor blood. The experiment was uneventful and the dog's pulse was satisfactory after the operation. However, the animal took several hours to recover from the anaesthetic (this is unusual, for most of our dogs have been awake within 1 hour of the completion of the operation), would not stand or eat the following morning, and died 21 hours after the operation.

DISCUSSION

In a recent paper read before the Society of University Surgeons, Columbus, Ohio, Diesh *et al.*[3] observed that in spite of numerous publications on the subject of extra-corporeal circulation, there is a dearth of information concerning survival of experimental animals. We have experienced similar difficulty in ascertaining results of other experimental workers for comparison with our own. Also, the fact that many different groups of workers continue to test one oxygenator after another, before applying cardiac bypass clinically, suggests that a significant mortality in experimental animals may be a general phenomenon.

Using a modified DeWall-type bubble oxygenator Diesh *et al.* had no survivors in 14 dogs perfused for 20 minutes at 70 ml. per kg. of body weight per minute and only 10 survivors in 29 dogs perfused for 20 minutes at 35 ml. per kg. per minute. Using dual oxygenators in parallel, they had only 3 survivors in 10 dogs perfused for 20 minutes at 70 ml. per kg. per minute. In a discussion on the above paper Dennis[4] infers that his results, using the bubble oxygenator, were unsatisfactory and Clowes[5] quotes a 50% mortality rate (number of experiments not stated).

King *et al.*,[14] using a further modification of the DeWall-type oxygenator, had only 1 survivor in 5 perfusions of a duration of 1 hour at a flow rate of 40 ml. per kg. per minute (this animal was spastic after the perfusion) and 1 normal survivor in 6 perfusions at a flow rate of 70 ml. per kg. per minute.

Using an unmodified DeWall-type oxygenator, Abrams *et al.*[15] perfused 42 dogs for periods of 10-76 minutes with 26 survivors. In 22 of their experiments potassium-citrate arrest was induced with 14 survivors. In 16 simple perfusions of 10-45 minutes' duration, with no additional operative procedure, there were 8 survivors.

In the light of the above reports our experimental results would appear to be satisfactory, especially as this work has been in progress for only 6 weeks. There is still, however, room for improvement and, in the words of Sir James Leamonth,[16] 'We cannot aspire to *best*; we can constantly strive for *better*.' The ideal of 100% survival after perfusions of longer duration is still to be attained.

CONCLUSIONS

We believe that the helix reservoir bubble oxygenator is a highly satisfactory oxygenator for open-heart surgery, and that its satisfactory operation is dependent on team-work and attention to a multitude of details, the omission of any one of which may lead to disaster. The death of a patient due to an avoidable error in perfusion technique is a tragedy which can be obviated only by repeated experimentation, and the familiarity of all concerned with the apparatus used.

In the description of our technique we have stressed those details which we consider to be of importance and have attempted to point out where errors are likely to occur. Provided that the oxygenator is correctly used, bubble traps and other modifications would appear to be unnecessary and may even be harmful.[6]

SUMMARY

The preparation and assembly of the helix-reservoir bubble oxygenator is described in detail, with particular reference to certain points which we consider to be essential for its proper function.

The technique of bleeding donor animals, anaesthesia, cannulation and perfusion is described.

The results of our first 20 consecutive dog experiments, using the oxygenator, are reported and discussed. There were only 2 deaths in this series.

It is concluded that the satisfactory operation of the oxygenator depends on team-work and meticulous attention to many details. Provided that it is correctly used, the helix-reservoir bubble oxygenator is a highly satisfactory apparatus for use in open-heart surgery.

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