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An ultrasonic analysis of the comparative efficiency of various cardiotomy reservoirs and micropore blood filters

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Pearson, D. T., Watson, B. G., and Waterhouse, P. S. (1978). *Thorax*, **33**, 352–358. **An ultrasonic analysis of the comparative efficiency of various cardiotomy reservoirs and micropore blood filters.** The ability of 12 commercially available cardiotomy reservoirs to remove bubbles from aspirated blood was investigated by means of a simulated cardiopulmonary bypass circuit and an ultrasonic microbubble detector. Performance varied considerably. The number of gaseous microemboli remaining after passage of blood through the reservoir was reduced by (*a*) holding the blood in the reservoir, (*b*) reducing the volume of air mixed with the aspirated blood, and (*c*) using a reservoir that did not induce turbulence and that contained integral micropore filtration material. Further micropore filtration of the blood after passage through the cardiotomy reservoir was beneficial, and significantly more bubbles were extracted when the microfilter was sited below the reservoir than when it was placed in the arterial line.

Several investigators have described the deleterious effects resulting from the functional replacement of the heart and lungs by a pump oxygenator during open-heart surgery (Aguilar *et al.*, 1971; Brennan *et al.*, 1971; Aberg, 1974; Branthwaite, 1975; Aberg and Kihlgren, 1977). As well as disturbances produced by systemic arterial hypotension (Tufo *et al.*, 1970) and non-pulsatile flow (Wright and Sanderson, 1972), the significant part played by microemboli in altering cerebral physiology is well documented (Patterson and Kessler, 1969; Solis *et al.*, 1974; *Lancet*, 1975). Emboli of fat, silicone, aggregates in stored blood, calcium, and gas have been implicated in the widespread organ dysfunction that can occur. Improvement in oxygenator design and perfusion technique can reduce the number of microemboli during surgery (Karlson *et al.*, 1974; Siderys *et al.*, 1975). Cardiotomy suction, however, is an important source of gaseous microemboli even when clinically acceptable cardiotomy reservoirs are used (Gallagher and Pearson, 1973; Solis *et al.*, 1976).

The extended duration of cardiopulmonary bypass for open-heart surgery requires the aspiration of intracardiac blood and its return to the extracorporeal circuit. The volume of this blood varies considerably, depending on factors such as aortic clamping, type of cardiac defect, and the presence of bronchial or other extracardiac collateral flow. Most oxygenators in common use alter the blood in a manner that is detrimental to the tissues being perfused (Loop *et al.*, 1976), and these effects are exaggerated after blood has been aspirated from the heart with resultant red cell destruction and the formation of gas and particulate emboli. Most cardiotomy reservoirs contain a defoaming substance and filters to remove these emboli. Arterial line and cardiotomy microfiltration reduce the incidence of cerebral microemboli and reduce mortality (Hill *et al.*, 1970; Clark and Reed, 1974).

Commercially available cardiotomy reservoirs do not completely remove all bubbles from the blood passing through them so that when cardiotomy suction blood is returned to the oxygenator the number of gaseous microemboli passing along the arterial line to the patient is increased (Gallagher and Pearson, 1973; Loop *et al.*, 1976). We report an assessment of the comparative efficiency of gaseous microemboli extraction by 12 cardiotomy reservoirs and show how this can be improved by further microfiltration.

Methods and materials

An *in-vitro* cardiopulmonary bypass circuit was constructed as shown in Fig. 1. The main circuit

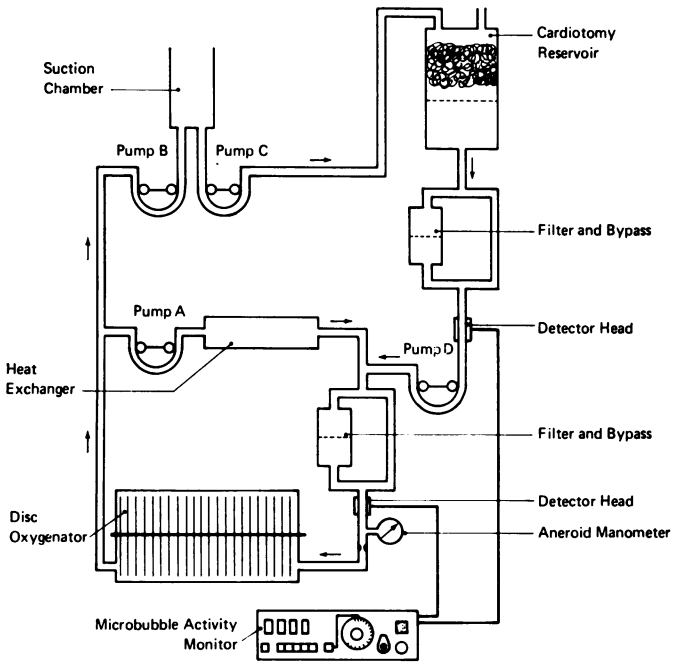

Fig. 1 *Schematic diagram of* in-vitro *cardiopulmonary bypass circuit (see text).*

consisted of a polycarbonate disc oxygenator with the arterial and venous connections joined by a loop of $\frac{3}{8}$-inch diameter polyvinyl chloride tubing. The circuit was primed with heparinised acid-citrate-dextrose blood, which was then circulated at a constant flow rate of 2·5 l/min by a double arm non-pulsatile roller pump (pump A). The temperature of the blood was maintained at 37°C by a heat exchanger. The detector head of the TM8 Microbubble Activity Monitor* was applied to the external surface of the circuit tubing. A continuous narrow beam of ultrasound was propagated by the transducer into the blood passing through the tubing, and as gaseous microemboli passed this beam the receiving transducer picked up modifications in the signal, which were processed by an electronic unit. The bubble counts were presented by a digital display in the size range selected on the sensitivity control. This detector position in the arterial line was used to compare the efficiency of the micropore filter in the cardiotomy return line and the micropore filter in the arterial line in removing microbubbles.

The blood was circulated without rotation of the discs in the oxygenator until the main circuit was free of gaseous microemboli. Blood was then pumped at 0·5 l/min from the main circuit to the base of an open-ended jar by pump B. At the same time blood and air were aspirated from the jar by pump C, whose flow rate could be adjusted to vary the proportion of blood and air. This mixture simulating cardiotomy suction was discharged into the cardiotomy reservoir under investigation.

When a suitable volume of blood had collected in the cardiotomy reservoir it was returned to the main circuit either directly or through a micropore filter at 0·5 l/min by pump D immediately or after a variable delay. The microbubble detector head was applied to the tubing distal to the cardiotomy reservoir, micropore filter, and bypass to assess the number and size of gaseous microemboli remaining in the blood.

Our first experiments showed that with a given cardiotomy reservoir the numbers of gaseous microemboli varied by less than 5% in successive experiments when the effluent from the reservoir was monitored. This consistency enabled us to compare the efficiency of microbubble extraction of different types of cardiotomy reservoir and to measure the further improvement produced by microfiltration either immediately below the reservoir or in the main circuit. Each experiment was repeated three times, and the main circuit was allowed to become bubble-free between each experiment.

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Cardiotomy reservoirs and micropore filters tested

CARDIOTOMY RESERVOIRS

A Polystan HL 282 DF cardiotomy reservoir
B Polystan HL 280 DF cardiotomy reservoir
C Polystan 40 cardiotomy reservoir
(Albert Browne Ltd, Chancery House, Abbey Gate, Leicester LE4 0AA)
D Bentley Q220 disposable expanded volume cardiotomy reservoir
E Bentley Q120 disposable cardiotomy reservoir
F Bentley Q220F disposable expanded volume cardiotomy reservoir with filter
(Bentley Laboratories Ltd, 50 Mount Street, London W1Y 5RE)
G Travenol 2-litre cardiotomy blood reservoir 5M0391
H Travenol rigid cardiotomy reservoir 5M0305
(Travenol Laboratories, Caxton Way, Thetford, Norfolk IP24 3SE)
I Cobe cardiotomy reservoir 42-301
J Cobe cardiotomy reservoir with Swank filter 42-300
(Cimid Ltd, Barnfield Road, Park Farm Industrial Estate, Folkestone, Kent CT19 5EX)
K Harvey disposable cardiotomy reservoir model H500
(GU Manufacturing Co Ltd, Plympton Street, London NW8 8AB)
L Bromlus cardiotomy suction filter and defoamer
(Avon Medicals Ltd, 1649 Pershore Road, Birmingham B30 3DR)

MICROPORE FILTERS

Intersept arterial extracorporeal blood filter
Intersept cardiotomy extracorporeal blood filter
(Johnson and Johnson Ltd, 260 Bath Road, Slough, Berks SL1 4EA)
Pall Ultipor blood filter (Pall Biomedical Ltd, Walton Road, Portsmouth PO6 1TD).

Results

Using a Polystan HL 282 DF cardiotomy reservoir sequential experiments were carried out after collection of blood in the reservoir. This blood was pumped without micropore filtration past the detector head immediately after collection or after it had remained in the reservoir for varying periods. Figure 2 shows the decline in numbers of gaseous microemboli greater than 10 μ in diameter remaining in the blood related to increasing storage time.

The relative speeds of pumps B and C determine the blood/gas volume ratio of the simulated cardiotomy suction blood. The effluent from a Polystan

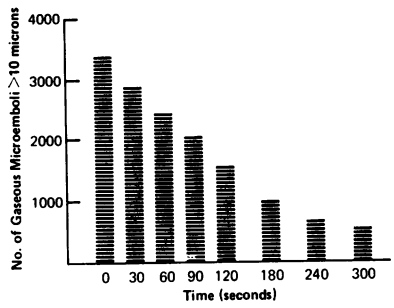

Fig. 2 *Numbers of gaseous microemboli >10 microns remaining in effluent from Polystan HL 282 DF cardiotomy reservoir in relation to duration of storage time.*

HL 282 DF cardiotomy reservoir showed an increasing number of gaseous microemboli as the proportion of air in the blood injected into the reservoir increased (Fig. 3).

Using a blood/gas volume ratio of 1/2·7 in the simulated cardiotomy suction blood an equal volume was successively injected into each of 12 commercially available cardiotomy reservoirs. The effluent was immediately pumped past the detector head without micropore filtration or after passage through an Ultipor filter. The results (Fig. 4) showed a wide variation in the ability of the reservoirs to remove gaseous microemboli, but in all cases performance was improved by using a micropore filter below the reservoir.

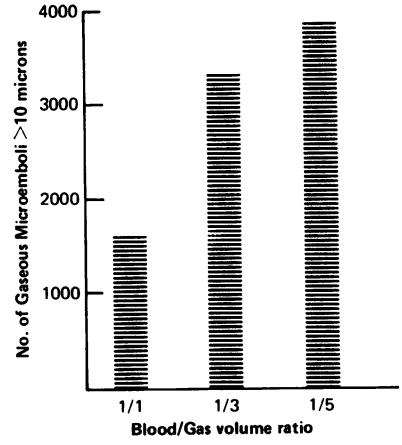

Fig. 3 *Numbers of gaseous microemboli >10 microns remaining in effluent from Polystan HL 282 DF cardiotomy reservoir in relation to blood/gas volume ratio of aspirated blood.*

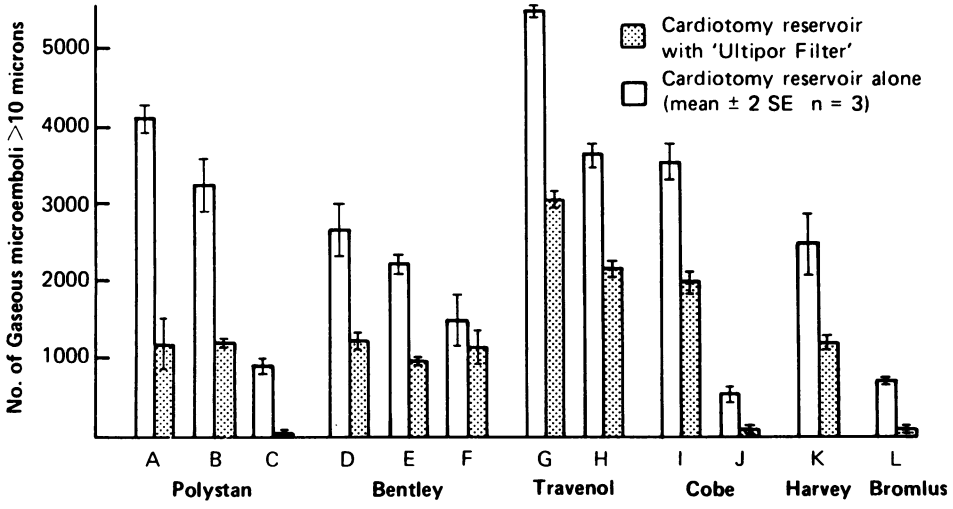

Fig. 4 *Comparative numbers of gaseous microemboli >10 microns remaining in effluent from various cardiotomy reservoirs with and without filtration by a 40-micron Ultipor filter. Reservoirs type A–L (see text).*

When a micropore filter and bypass were inserted into the main circuit the effluent from the cardiotomy reservoir could be discharged directly into this circuit with the detector head applied to the tubing distal to the filter (Fig. 1). In this way the ability of a micropore filter to retain gaseous microemboli when sited in the simulated arterial line could be compared with its efficiency when sited below the cardiotomy reservoir. As the priming volume of the main circuit exceeded 3 l and the flow rate of pump A was maintained at 2·5 l/min no gaseous microemboli were counted twice, provided the duration of the counting did not exceed one minute. An aneroid manometer was placed in the main circuit and the line pressure distal to the filter was adjusted to 13·4 kPa

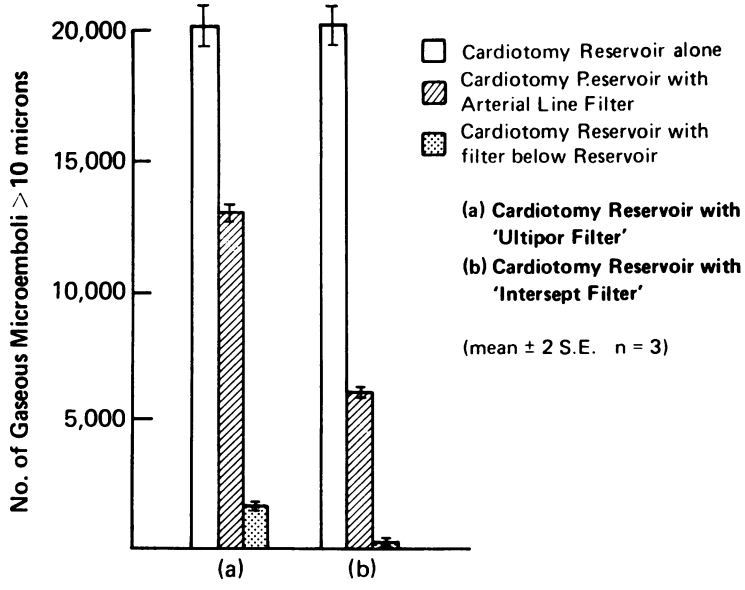

Fig. 5 *Comparison of efficiency of micropore filters sited below cardiotomy reservoir and in a simulated arterial line.*

(100 mmHg) by means of a screw clamp. The results (Fig. 5) showed that the numbers of gaseous microemboli from a Polystan HL 282 DF cardiotomy reservoir were reduced by a micropore filter inserted in the arterial line, but a much greater reduction was achieved by inserting the filter below the cardiotomy reservoir. A greater overall reduction in the number of gaseous microemboli was obtained when the 40 μ pore size Ultipor filter was replaced by the 20 μ pore size arterial line and cardiotomy Intersept filters (Table 1).

The insertion of the 20 μ Intersept filter and the 40 μ Ultipor filter in parallel in the main circuit allowed direct comparisons of their efficiency by subjecting them alternately to a standard load of gaseous microemboli from the effluent of a cardiotomy reservoir. In addition, the size profile of the bubbles that passed through the filters could be compared. The results (Table 2) confirmed the greater efficiency of the 20 μ filter. Most gaseous microemboli passing through this filter were in the 10–20 μ range, while the majority passing through the 40 μ filter were in the 10–30 μ range.

Table 1 *Percentage reduction in gaseous microemboli from standard cardiotomy suction using a Polystan HL 282 DF cardiotomy reservoir and two types of micropore filter*

	Micropore filter below cardiotomy reservoir	*Cardiotomy reservoir with micropore filter in arterial line*
Intersept filter (20 micron)	99%	68%
Ultipor filter (40 micron)	92%	48%

Table 2 *Size profile of gaseous microemboli detected beyond arterial line filter*

Bubble size (microns)	*40-micron Ultipor filter* No. (%)	*20-micron Intersept filter* No. (%)
> 10	13609 (100)	6064 (100)
10–20	8025 (59)	5372 (88)
21–30	5064 (37)	658 (11)
31–40	470 (3)	34 (1)
> 40	50 (1)	

Discussion

Previous work in this unit has indicated the importance of cardiotomy suction as a source of gaseous microemboli (Gallagher and Pearson, 1973). These emboli are potentially more dangerous than those originating from a bubble oxygenator because they consist mainly of nitrogen, a relatively insoluble gas. The persistence of these microemboli after passage through both the defoamer of the cardiotomy and the oxygenator indicates their stability.

We show the wide variation in the ability of 12 commercially available cardiotomy reservoirs to remove bubbles from aspirated blood and produce an effluent relatively free from gaseous microemboli. The design of a reservoir can affect its performance. Some of those tested induced turbulence and frothing before admitting blood to the defoamer and also allowed a proportion of the blood to pass through the reservoir without coming into contact with the defoaming substance. Other reservoirs, having defoamed the blood, allowed it to splash into the storage part of the reservoir. All these factors increase the number of gaseous microemboli in the effluent.

A cardiotomy reservoir with improved filtration characteristics (Solis *et al.*, 1976) needs to be developed, since in the reservoirs tested those that incorporated a 40 μ nylon mesh or Dacron wool filter performed best. The three Polystan reservoirs are essentially similar in overall design but show a progressive improvement in efficiency as the pore size of the filter in the storage part of the reservoir is reduced from 180 through 120 to 40 μ. The Bentley Q220F reservoir incorporating a 27 μ filter did not perform as well as expected. Not only did this unit suffer from splashing of the defoamed blood but it induced turbulence at the blood inlet ports.

An analysis of the design features of the reservoirs, assessed by correlation of their *in-vitro* performance with the overall configuration of the reservoir, type of defoamer, and pore size of the incorporated filter material suggests that optimal efficiency can be achieved by direct injection of aspirated blood into the defoaming substance and filtration by either Dacron wool or 40 μ nylon mesh. Defoamed and filtered blood should not be allowed to fall freely into the storage part of the reservoir.

Alterations in perfusion technique will influence the performance of the cardiotomy reservoirs. If the blood is stored in the reservoir for as long as possible within the confines of an adequate level in the oxygenator, not only will maintenance of a higher level reduce splashing of the defoamed blood but gaseous microemboli will have more time to settle out. The greater the proportion of air to blood in the aspirate from the open heart and pericardium the more difficult it is for the

cardiotomy reservoirs to remove gaseous microemboli completely. The speed of the suction pumps should be monitored continuously to allow as low an admixture of air with the blood as is compatible with the surgical technique.

Filtration of blood after passage through the cardiotomy reservoir reduces further the numbers of gaseous microemboli. The size and number of gaseous microemboli remaining is related to the pore size of the micropore filter used. However, microfiltration is only a partial solution to a problem best solved by avoiding factors responsible for the formation of microemboli (Wright and Dunn, 1975) and by choosing the most efficient cardiotomy reservoir. A simulated arterial line micropore filter is not as effective in removing gaseous microemboli as the same type of filter sited below the cardiotomy reservoir. During clinical perfusion, defoamed blood is returned to the oxygenator at a low flow rate by gravity, but when the filter is placed in the arterial line it is subjected to a much greater flow of blood. During the experiments the arterial line filter released gaseous microemboli into the main circuit when it was tapped. Considerable care was needed during priming of the filter to ensure that no gas was trapped in the filter medium.

The TM8 Microbubble Activity Monitor is calibrated by the manufacturer using a technique of releasing single bubbles of known size into a stream of liquid flowing past the transducer head. The bubbles are electrolytically generated, and their size is measured by microscopy. This calibration is confirmed in the experiments by counting the numbers of bubbles that passed through filters with different pore sizes: only 1% of bubbles passing through the 40 μ filter exceeded 40 μ in diameter, and only 12% of those passing through the 20 μ filter exceeded 20 μ in diameter.

No reference has been made to the ability of the cardiotomy reservoirs and filters tested to deal with non-gaseous microemboli. Other workers have evaluated various devices used in the cardiotomy reservoir system in this respect (Loop *et al.*, 1976; Solis *et al.*, 1976). We have not tested the long-term comparative efficiency of the reservoirs and filters.

Cerebral damage after open-heart surgery has a multifactorial aetiology (*Lancet*, 1975). Constant vigilance should be exercised in eliminating all sources of gaseous microemboli originating in the oxygenator and cardiotomy reservoir system. Probably by improving perfusion technique using oxygenators that do not generate gaseous microemboli (Karlson *et al.*, 1974; Siderys *et al.*, 1975) and incorporating an efficient cardiotomy reservoir with a 20 μ filter into the cardiopulmonary bypass circuit the number of gaseous microemboli delivered to the patient will be substantially reduced.

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