

ECC Sources of Gaseous Microemboli

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Abstract

We have tried to locate sources of gaseous microemboli during the ECC using a newly developed ultrasonic detector. The detector was calibrated with filters of known pore size and the recorder setting was kept constant at all times. We studied, at the oxygenator, the effect of low and high fill volume, refilling with or without air into the cardiotomy line, mechanical disturbance, rewarming and high pO_2 . Arterial line filters were examined for their capacity to retain microemboli.

All bubble oxygenators tested released microemboli, especially at low fill volume when operated at high blood flows. Any mechanical interference (shock) either to the oxygenator or the filter will cause massive release of microemboli. This was also seen during fast rewarming of the blood, fast refilling of the oxygenator and high pO_2 . Slow rewarming of the blood as well as slow refilling of the oxygenator, even with air in the cardiotomy line, did not cause any excessive microemboli. All filters tested retained microemboli to a great extent. Membrane oxygenators demonstrated no measurable microbubble formation at normal flows or with mechanical interference (shock) to the unit.

Microemboli detection during ECC has helped to trace various sources of gaseous microemboli which could be avoided using better perfusion techniques. Arterial line filters do reduce the amount and the size of gaseous microemboli during ECC.

Introduction

Microemboli are a major source of complications during extracorporeal circulation (ECC) and death can result if massive air embolism occurs. Many authors, using different devices, have attempted to detect microbubbles with variable success^{1,3-7}.

The purpose of our study was to further identify sources of microemboli using a newly developed mi-

crobubble detector and, with this knowledge, improve our current ECC techniques. A comparison between the various brand named components was not intended.

Material and Methods

Detector—A prototype transmission ultrasonic microbubble detector^a was used for our study. The transducer, attached to a special connector (ID 3/8" or 1/2"), sends a 2 MHz ultrasonic beam across the entire cross-section of the arterial line. The resulting signal is detected by the receiver and amplified. Artifacts produced by changes in flow or pressure are removed by electronic filtration.

Detector "Calibration"—Our "calibration" circuit is shown in Fig. 1. The circuit was primed with lactated Ringer's solution and debubbled. The bypass line around the 40 micron filter^b as well as the inlet side of the 25 micron filter^c were clamped and circulation at 4 l/min. initiated for 3 hours. Air was injected through a 25 G needle using a peristaltic infusion pump. A purge line was connected to the reservoir to drain excess air from the filter. The recorder^d was calibrated in such a

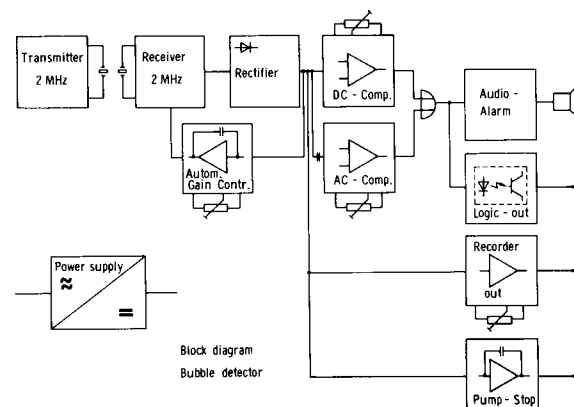


Figure 1: "Calibration" circuit

a Stöckert Instrument, München (FRG)

b Pall Biomedical, Glen Cove, NY 11542

c Shiley, Inc. Irvine, CA 92174

d Gould, Inc., Brush Div. Cleveland, OH 44114

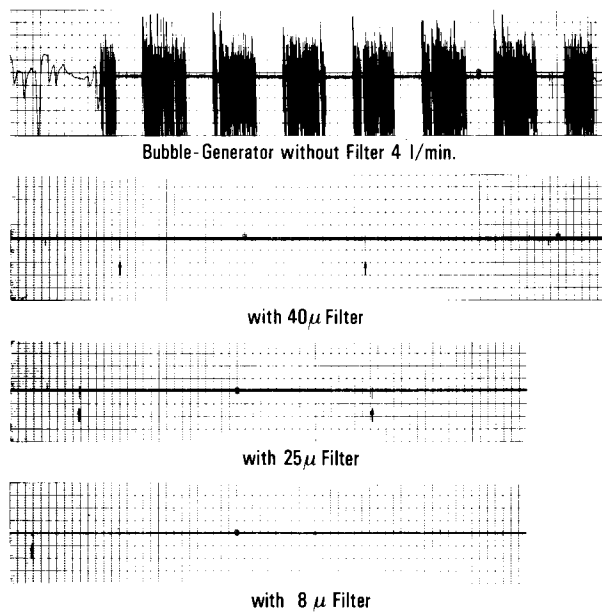


Figure 2: Sample recording of "calibration" run

way that the greatest deflection was 1 cm. The test was repeated in the same way, without altering the recorder setting, with the 25 micron and the 8 micron filter^b.

This "calibration" run was repeated frequently during our study. A sample recording of the "calibration" run is shown in Fig. 2.

In Vitro Evaluation—We tested 6 oxygenators for defoaming capacity: the Polystan VT 5000^e; the Shiley^c S 70, S 100 A and S 100 HED and the Bentley^f Q 130 and Q 110. The oxygenator being evaluated served as a reservoir and was filled with outdated human donor blood (Hct. 37%, Temp. 37 C). Outflow from the oxygenator passed directly through the microbubble detector and was recirculated by a roller pump^g to the venous inlet of the oxygenator using medical grade tubing^h. Each oxygenator was studied at 2/3 maximum and minimum prime volumes beginning with 1 liter/min. flow and increasing in 1 liter/min. increments until the maximum rated flow (MRF) was reached for each oxygenator. The blood was oxygenated with a 95% O₂ and 5% CO₂ mixture. The blood to gas flow ratio was varied to maintain a pO₂ ranging from 20 to 25 kPa. The gas flow was increased to give a pO₂ of approximately 40 kPa for the S100 HED. The entire procedure was again repeated at this new pO₂. To simulate in vivo mechanical disturbances that do some-

e Polystan A/S, DK-2730 Herlev

f Bentley Laboratories, Irvine, CA 92174

g Sarns, Ann Arbor, MI 48103

h Rehaus, "Raumedica RAU-PVC 8056"

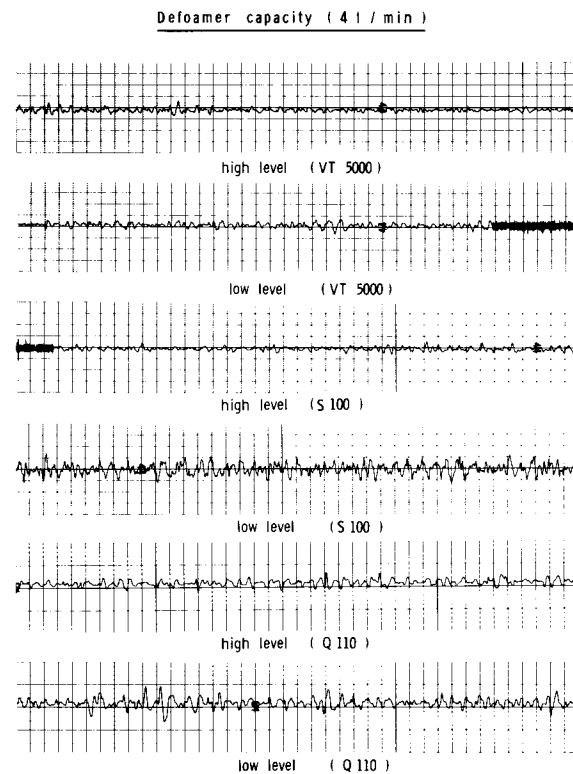


Figure 3

times accidentally occur^d during clinical ECC, the oxygenator was sharply tapped at random and any excess microbubble production was recorded. With an arterial line filter (Shiley SAF, 20 micron^c or Pall Ultipor 40 micron^b) added to the circuit between oxygenator and detector, microbubble release was monitored when the filter was similarly disturbed and again when the filter shunt was opened during circulation.

In Vivo Evaluation—Our microbubble detector was applied to routine laboratory and clinical ECC (mean bypass time greater than 1 hour) in two series to evaluate microbubble activity, first leaving the oxygenator and second, leaving the arterial line filter. In the first series of 29 ECC procedures, routine ECC techniques were evaluated for their propensity to increase microbubble activity leaving the oxygenator. The measurements were recorded continuously during cooling, refilling, circulating with high pO₂, and rewarming. Two membrane oxygenatorsⁱ were similarly tested in our laboratory. The second series of 22 ECC procedures were performed with the detector just distal to the arterial line filter. Again detector response to microbubble activity was recorded continuously during the routine ECC maneuvers as outlined above.

i SciMed Life Systems Inc., Minneapolis, MN 55441

Results

Defoaming Capacity—Representative examples of microbubble activity from three of the tested oxygenators are demonstrated in Fig. 3. All bubble oxygenators tested produced detectable microbubbles even under the most favorable conditions.

Microbubble activity at high fill volume was much smaller than at low fill volume. This observation, well pronounced for the Shiley S 100, led us to conduct any further investigation, whenever possible, with high and low fill volumes.

Mechanical Disturbance—Fig. 4 illustrates a typical response to shock and was seen for all oxygenators tested. Notice that low filling volume has a marked effect on the microbubble activity. When tapped, both filter types released a similar shower of microemboli as illustrated in Fig. 5b.

Filter Shunt—With the detector situated distal to the filter, the filter shunt clamp could be opened to document pre filter microbubble activity. Fig. 6 demonstrates the typical result. This signal indicates a large amount of gas either in the form of many small bubbles or a few relatively large bubbles. Later, close visual observation of the shunt line revealed that gas bubbles would settle proximal to the clamp and could coalesce forming a bubble large enough to be visible.

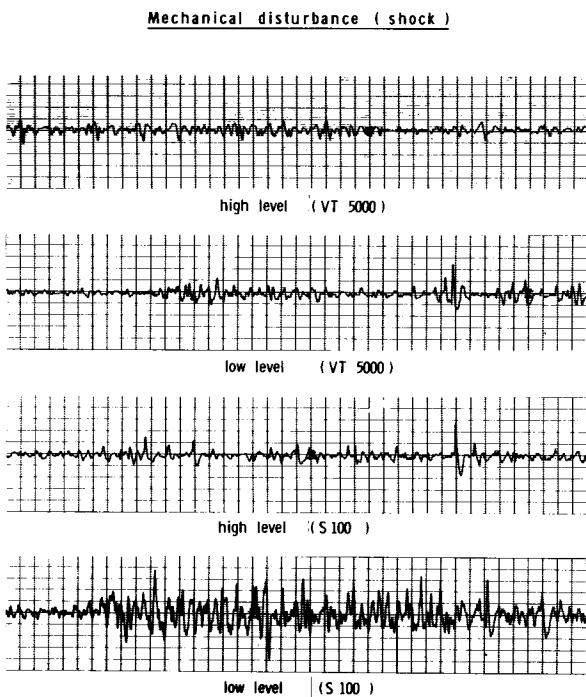


Figure 4

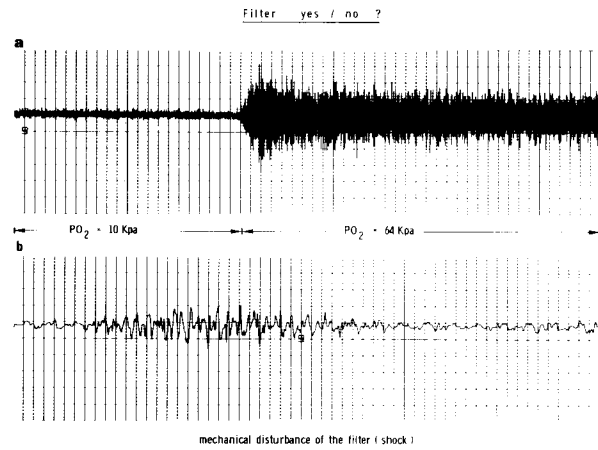


Figure 5: a) High pO_2 causes foam which can pass the arterial line filter.
b) Every filter type tested released shower of microbubbles when tapped.

Cooling—Typical results seen in a preliminary laboratory study during slow cooling are depicted in Fig. 7. When this was attempted in the clinical studies, rapid cooling produced artifacts which were apparently caused by thermo-mechanical changes of the ultrasonic gel and detector. Despite using several different ultra-sonic gels this remained a problem and prevented documentation of microbubble activity during fast cooling as used clinically.

Refilling—The effect of refilling the oxygenators from the cardiotomy reservoir was seen to be dependent on several factors. Generally fast refilling always caused an increasing microbubble activity coming out of the oxygenator (Fig. 8). The lower the MRF was for an oxygenator, the greater was this increase. However, our results indicate that this increase in microemboli activity can almost be avoided by slow (max. 9.5 l/min.), careful refilling, even if air is in the tubing (Fig. 9).

Circulating at High pO_2 —The results from the Shiley S 100 and S 100 HED are represented in Fig. 10. For the S 100 HED, a slight increase of microemboli activity is associated with the higher pO_2 s, and is most

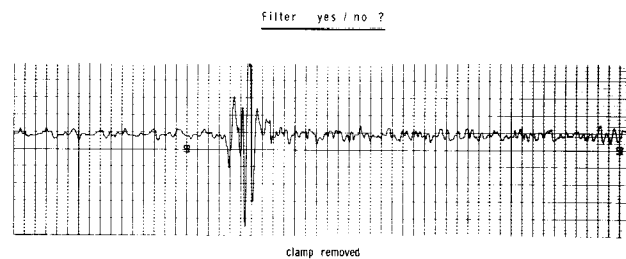


Figure 6: Microbubbles can coalesce to a large bubble behind the filter-shunt clamp.

RATE OF μ -EMBOLI DURING COOLING (PO_2 35 KPa, Flow 3 l / min. , Level 1000 ml)

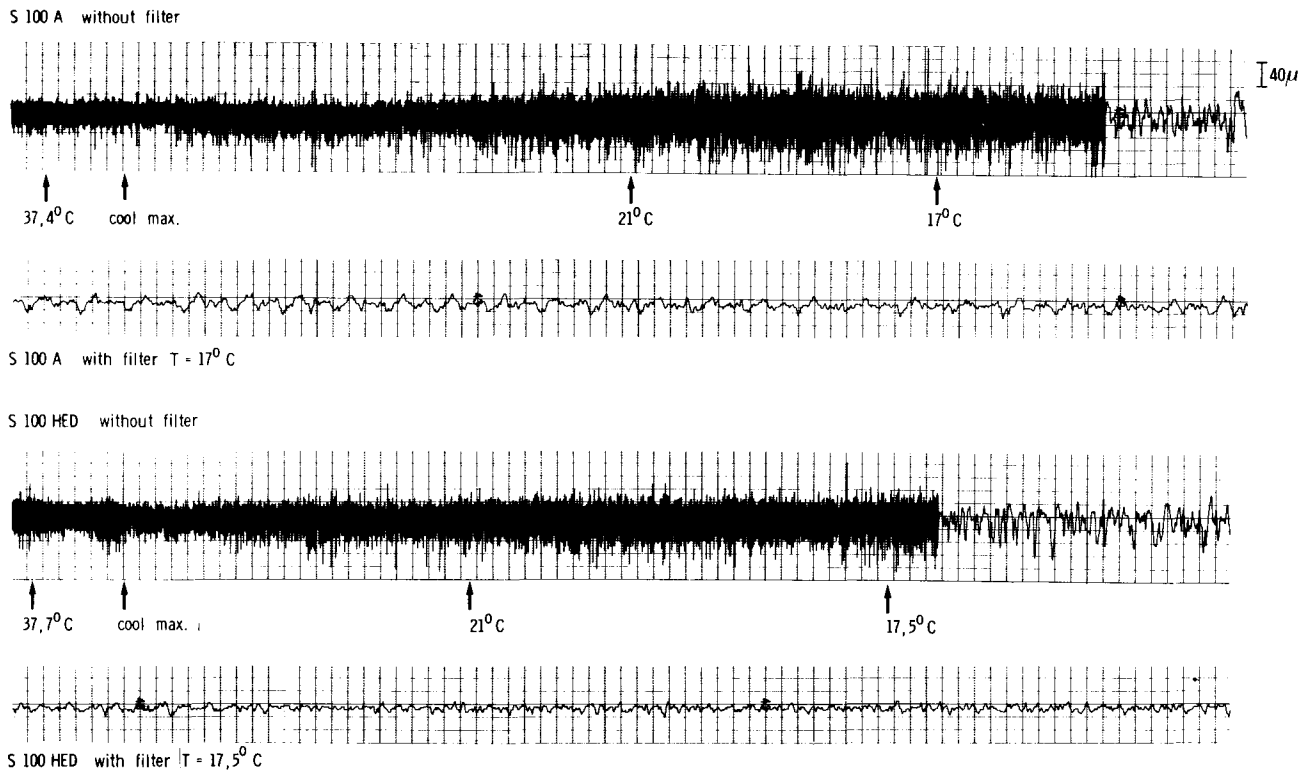


Figure 7

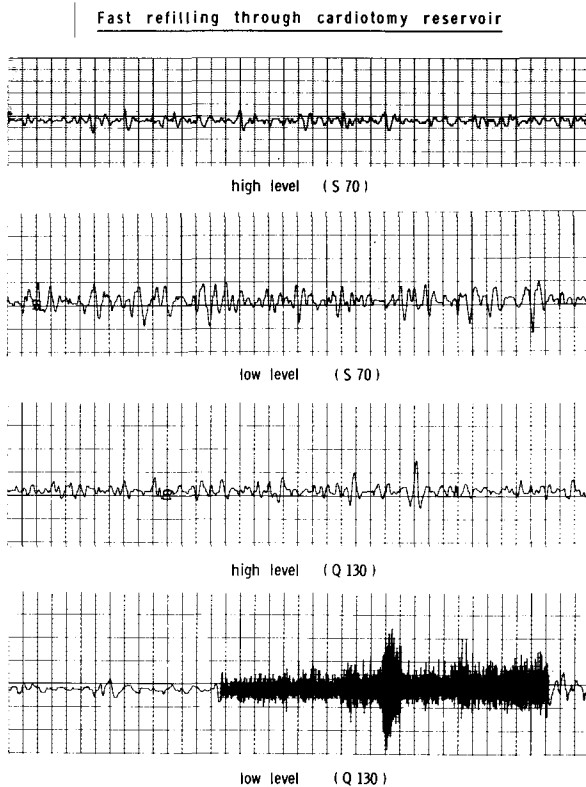


Figure 8

marked at low fill levels. This finding was further supported by our clinical experiences, where a high pO_2 , used at the beginning of bypass to assure good oxygenation, was again associated with higher microbubble activities. As oxygen flow was increased to extreme values, large numbers of microbubbles were formed, and passed into the arterial line. The capacity of the arterial line filter to retain these bubbles may be rapidly exceeded, resulting in a continuous shower of microemboli moving towards the patient (Fig. 5a).

Rewarming—Fig. 11 is a typical example of the results obtained during the rewarming phase of an ECC procedure. It documents the association between each rewarming step and the transient increase of microbubble activity produced. This activity was minimized simply by keeping the temperature gradient between blood and water for each step as small as possible.

Filter Performance—The ability of the filter to remove micro-gaseous emboli leaving the oxygenator is documented in Fig. 12. Under normal operating conditions, arterial line filters rarely released bubbles which could be interpreted to be greater than filter pore size. Only during the abnormal circumstances of mechanical disturbance directly to the filter and operation at extremely high pO_2 (greater than 50 kPa) was this seen.

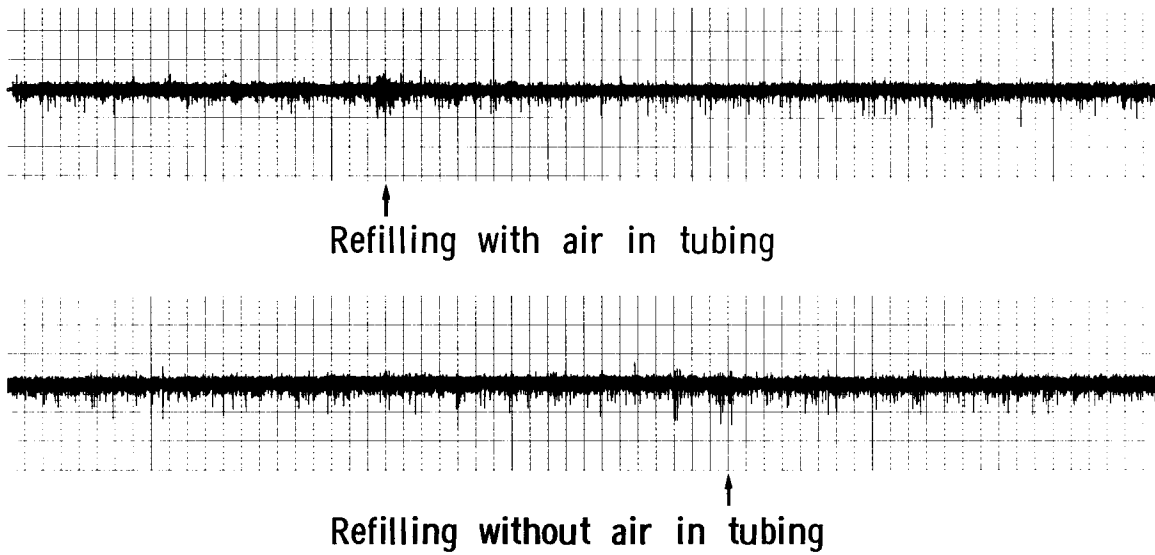


Figure 9: Slow refilling, even with air in the cardiomy line, will not cause excess microbubbles.

RATE OF μ - EMBOLI WITH NORMAL (20 KPa) AND HIGH (40 KPa) PO_2 UNDER VARIABLE FILLVOLUME

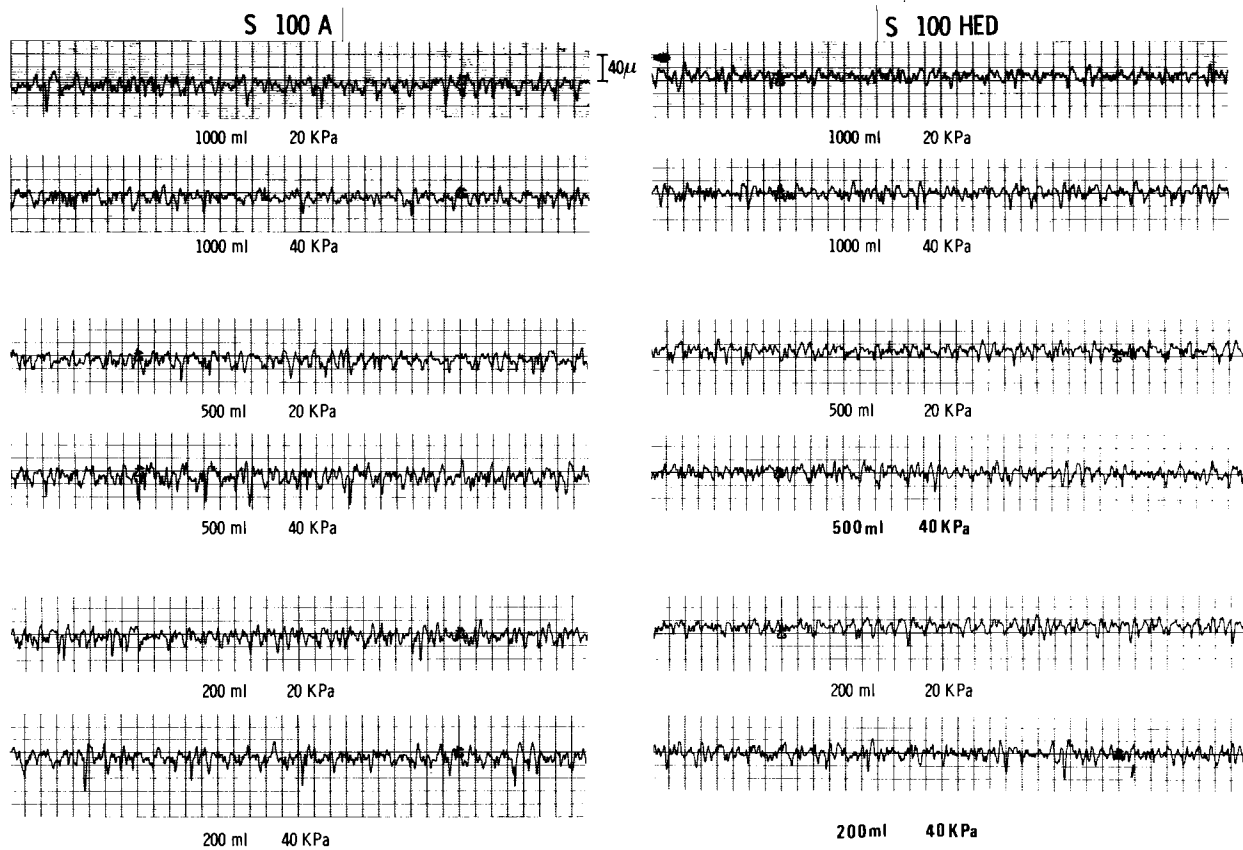


Figure 10

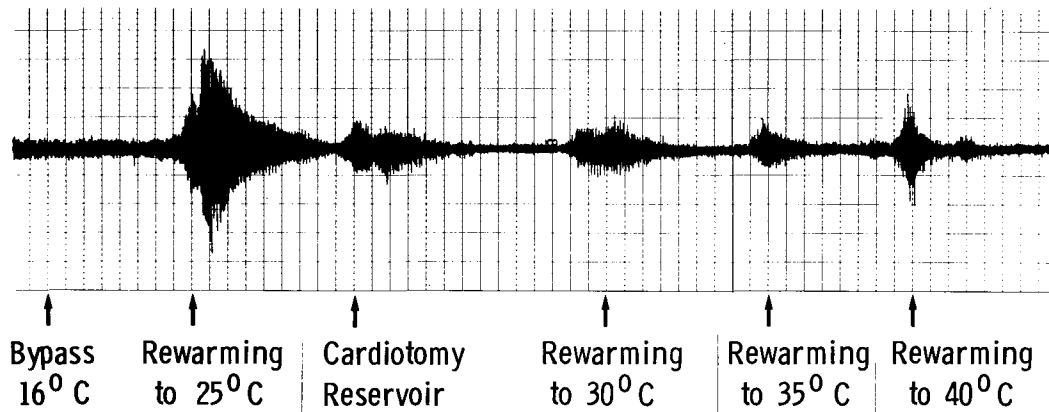


Figure 11: Large temperature gradients between blood and water during rewarming will cause showers of microemboli.

Membrane Oxygenator—With the detector directly in outlet flow, no recordable deflections were observed regardless of blood flow, gas flow or mechanical disturbance. Only when 20 ml of air were injected into the blood entering the oxygenator, could an extremely small signal be recorded (Fig. 13).

Discussion

Gas embolization has plagued cardiac teams since introduction of ECC. Several authors have published using various kinds of “Detection” and several ways of “calibration”¹⁻⁷. We do believe that our “calibration”

methode was accurate; as it was not intended to specifically quantitate the microbubbles passing through the detector, but only to establish the source of large numbers of microbubbles. Any other interpretation could be misleading. For these reasons, we do not wish to imply that any components are better than others.

Gallagher¹ documented that a surprisingly large number of gaseous microemboli passed undetected into the patient carotid artery during routine ECC. He and other authors¹⁻⁷ have identified several sources of excess microbubble production such as: low filling volumes, fast refilling, agitation or mechanical disturbance of the oxygenator and the arterial line filter as well as high gas flow.

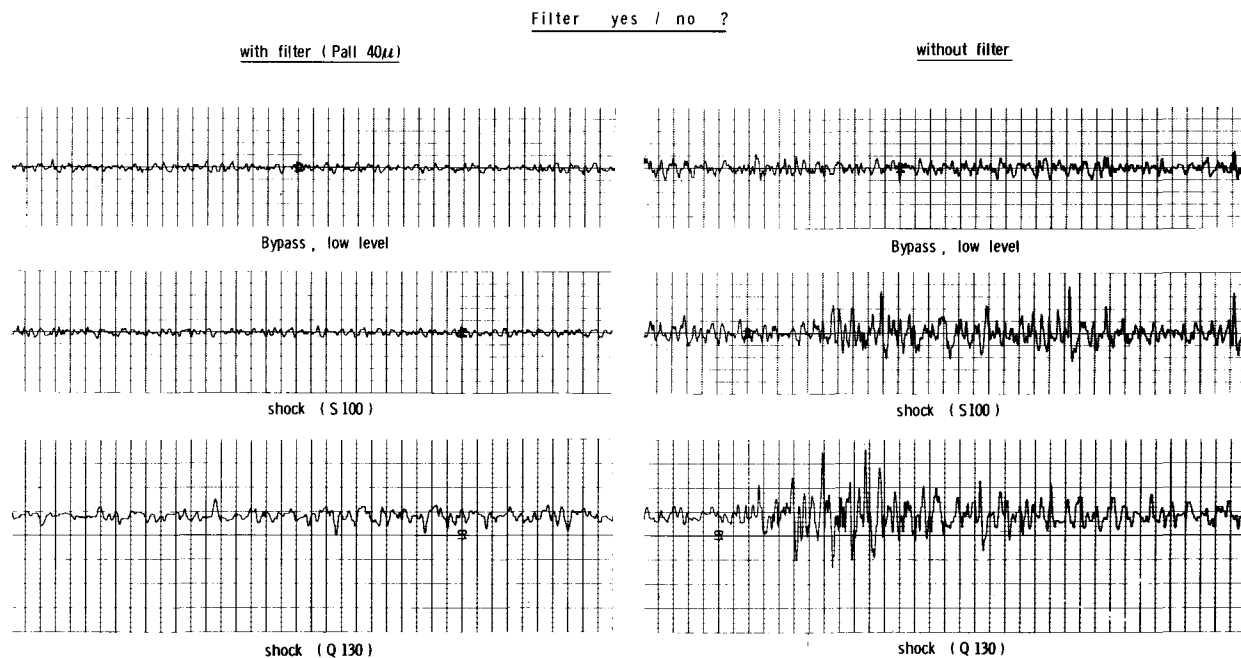


Figure 12: Arterial line filters do retain microbubbles to a large extent.

Membrane Oxygenator

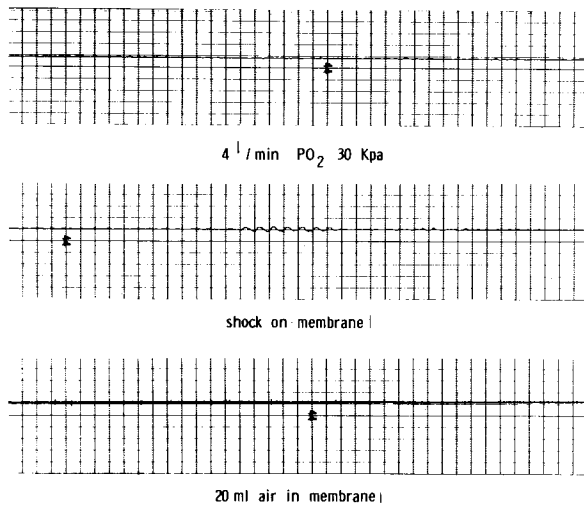


Figure 13: Practically no microbubbles could be detected with this type of membrane oxygenator (SciMed).

Our results support these findings and document four new observations. First, microbubble settling behind the clamp on the filter shunt can produce a single large bubble which will be released to the patient should the clamp be removed. Secondly, circulating at exceedingly high pO_2 s causes foam formation that will pass the arterial line filter. Thirdly, excess microbubble production caused by rapid refilling of the oxygenator can be avoided simply by slow release of the volume from the cardiomy reservoir. We would explain the excess microbubble formation associated with fast refilling by pointing out that flow from the patient combined with the flow from the cardiomy reservoir, can rapidly exceed the MRF for an oxygenator. In effect, this pushes microbubbles into the arterial reservoir. Fourthly, a large temperature gradient during rewarming will cause showers of microbubbles which can be

simply avoided by keeping the temperature gradient between blood and water as small as possible.

Some authors recommend the use of an additional arterial line filter in the cardiomy return line. Based on our explanation, this filter, while useful to remove debris from suction as well as gross air, will be of little use to reduce excess microbubble production leaving the oxygenator.

Our studies with the SciMed membrane oxygenator document the absence of measurable microbubble flow or mechanical disturbance artifacts and emphasizes the specificity of our detector to respond only to microgasemboli. In conclusion, careful evaluation of ECC techniques identifies sources of microbubble production which could be avoided.

Acknowledgment

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