Evidence-Based Used, Yet Still Controversial: The Arterial Filter

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Abstract: Arterial line filters are considered by many as an essential safety measure inside a cardiopulmonary bypass circuit. There is no doubt that this was true during the bubble oxygenator era, but we can question whether the existing arterial line filter design and positioning of the filter are still optimal seeing the tremendous progress in cardiopulmonary bypass circuit components. This overview gives a critical overview of existing arterial line filter design. Keywords: arterial filter, cardiopulmonary bypass, microemboli, bubble dynamics. JECT. 2012;44:P27–P30

Although there has been a major improvement during cardiac surgery in surgical, perfusion, and anesthesia management, cardiopulmonary bypass (CPB)-related morbidity does still exist. Especially, the incidence of neurocognitive deficits remains a concern because this can have a major impact on the quality of life of a given patient. There is no doubt that the cause of neurocognitive deficits is multifactorial. Manipulation of the aorta (1,2), cannulation (3,4) and deairing techniques, and return of pleuropericardial aspiration (5,6) into the systemic circulation all attribute to neurocognitive deficits. During CPB, solid microemboli and gaseous microemboli (GME) are a problem because they can traverse from the venous circulation into the systemic circulation. To attenuate the transmission of emboli, arterial line filters (ALFs) have been introduced. As such, it is no surprise that in a recent evidence-based review of CPB practice, the use of an ALF was listed as Class I, Level A evidence (7). However, one can question if this statement is still correct because the majority of evidence on which this statement was based dates from an area when the bubble oxygenator was the standard. Mass transfer in a bubble oxygenator was achieved by bubbling gas into the blood (8,9). Defoamer efficiency was not optimal and the antifoam-A, used to reduce the surface tension of the gas bubbles, was washed off over time (9,10). To diminish the number of gaseous and solid microemboli, depth filters were developed. These filters were very effective in removing emboli but did also remove an important number of blood platelets. To overcome this problem, screen filters were introduced. Although less effective in GME removal (11), their impact on blood elements was considered marginal. This review critically examines today’s use of ALF during CPB.

BASIC PRINCIPLES OF FILTRATION

The working principle of a “mechanical” filter is that the filter medium acts as a porous screen, removing and retaining particles too large to pass through the openings that provide the porosity but allowing the “carrier” fluid to pass. Two types of filters can be distinguished.

Depth Filter

This mechanical filter uses a medium with a significant amount of thickness providing filtering in depth. In general, larger particles will tend to be trapped in the surface layers with the finer particles trapped by succeeding layers. A typical example is a hollow-fiber membrane oxygenator. If necessary, the structure of the filter can be density-graded. This has a particular advantage where the particle sizes are widely distributed. An example of a graded depth filter is the cardiotomy reservoir filter. Filtering in depth will generate a higher pressure drop than screen filtration as a result of its higher resistance.
Surface or Screen Filter

Screen filtration works by direct interception. Particles larger than the pore of the filter medium are captured at the upstream surface of the filter. The effective pore size can be determined either by microscopy techniques or by determination of the bubble point pressure (BPP). BPP is defined as:

$$\Delta P = \frac{4 \cdot \gamma \cdot \cos(\phi)}{D}$$

where $\Delta P$ = bubble point pressure, $\gamma$ = surface tension fluid, $\phi$ = wetting angle, and $D$ = pore diameter.

If the pressure drop over the filter medium (measured just before and after the medium) exceeds the BPP, gas bubbles will pass the filter medium (Figure 1).

Impact of ‘Working Conditions’ on the Efficiency of Screen ALF

Most 40-μm AFL filters have a BPP of approximately 40 mmHg in water. Based on the previous formula, it is quite obvious that the smaller the pore size of the filter medium, the more efficient an ALF will become in filtering out GME. Bubble point pressure will increase from 41 mmHg to 83 mmHg by decreasing the pore size from 40 μm to 20 μm. This increase in efficiency has been demonstrated in vitro (12). However, an increase in pressure also means less open area for fluid flow. In our example, the open area would decrease from 25% to 16%. The possible impact of this decrease on local shear stress and platelet and white blood cell activation has not been established yet.

Another important consideration is that the BPP is not static but will change with the operating conditions during CPB. When a crystalloid priming solution is exchanged by blood after initiation of CPB, surface tension will decrease from 72 dyne/cm² to 50 dyne/cm² (13) with a resulting decrease in BPP from 41 mmHg to 29 mmHg. The latter might be an additional reason why GME count always shows a peak when going on bypass.

Finally, filters are now more effective than when they were introduced because most filters are today standard treated with a hemocompatible surface treatment. Most of these treatments make the material more hydrophilic, thus reducing the contact angle between fluid and material. A direct consequence of this change is that filters have become a lot easier to prime. At the same time, however, it has also increased the efficiency of the filter for capturing GME as a change in contact angle from 70° to 50° increases the BPP from 13 mmHg to 24 mmHg.

THE PHYSICS OF BUBBLE REMOVAL

When gas bubbles are present in a fluid, two forces will apply: buoyancy and drag (Figure 2). Buoyancy will make a bubble rise in a fluid and it is a function of the volume of the bubble. Drag, the force opposing buoyancy, will be dependent on the frontal area of the bubble. When the fluid has no momentum, buoyancy is always higher than drag. Once the fluid is moving, also the velocity and viscosity of the surrounding fluid will play a major role.

In an ALF, air bubbles are removed by a combination of a bubble trap and a bubble barrier (14). The bubble trap works on the tendency of bubbles to rise in a liquid if given the opportunity. This is accomplished by reducing the velocity of the incoming blood so that the natural buoyancy of the bubbles becomes the dominant force. As a consequence, the bubble trap will only remove larger bubbles. The filter screen will act as a bubble barrier as explained previously. Interestingly, the design of an average ALF has not changed over the last 30 years plausibly because there has been no major interest from clinicians. The only attempt to improve ALF design, by further reducing drag and by replacing the purge port by a hydrophobic membrane, was not a commercial success. The design showed superior GME removal (15) but was difficult to prime. Recently some new interesting research has been done looking at the impact of fluid dynamics, buoyancy, and drag on bubble removal capacity of a screen filter (14,16).

Bubble-Removing Components in the CPB Circuit

Beside the ALF, there are several other components that aid in removing GME. All reservoirs (venous, cardiotomy)
will reduce GME because blood velocity will be reduced at the entrance of the reservoir, thus favoring buoyant forces. Unfortunately, reservoirs can also increase GME depending on the reservoir fluid volume (17), turbulence, suction volume (18), and administration of drugs (19).

Another component capable of removing air is the microporous hollow-fiber membrane oxygenator with extraluminal blood flow (20). The different layers of fibers will act as a depth filter. If we consider the fiber bundle a porous medium, we can calculate the hydraulic radius (21), which will give us an indication of the filtration capacity. Most oxygenators have a hydraulic radius between 40 and 100 µm. However, in opposition to a normal depth filter in which the fibers act as a mechanical barrier, the microporous fibers in an oxygenator are not only a barrier, but also capable to remove the captured GME (20,22–24). Recently several oxygenator manufacturers have incorporated the ALF in the oxygenator.

MEASUREMENT OF MICROEMBOLI

Measuring microemboli remains a challenge because blood is an opaque fluid. Although efforts have been made to measure solid emboli (25–28) and deformable fat emboli, no reliable device is available for the moment.

For measurement of GME, several commercial devices are available. Whereas the initial devices were not very reliable and difficult to calibrate (29), second-generation devices are a lot more reliable. Nevertheless, one should know the limitations of these devices. As long as the devices are used for monitoring existing perfusion techniques, there are no major problems. However, when used for studying a so-called “worst case scenario,” several problems may arise (30). These problems find their origin in limitations of the measuring principle. Few clinicians are aware of these limitations. So is it for example impossible to measure GME with diameters below 10 µm and the error on the diameter is approximately 10%. The latter has a major impact if one wants to calculate the volume of gas administered to a patient. First, the counting device considers each bubble as a perfect sphere, which is only true for very small bubbles. Because the radius is used for obtaining the volume of the sphere, the error will increase to 30% (30). Beside dedicated devices, GME can also be observed by transesophageal echo, but these machines do not allow emboli count or quantification of the total volume of gas.

THE FUTURE OF ALF

The occurrence of GME, solid particles, and deformable particles remains a problem. The most dangerous particles are with no doubt deformable fat emboli because we have no effective filters available that can capture them. The most effective strategy for avoiding fat emboli is avoiding the return of pleuropericardial aspiration into the systemic circulation (31). However, this is not feasible in operations with large blood losses.

Solid microemboli are today much less of a problem than in the era of bubble oxygenators. Indeed, thrombus level dropped significantly from 20% in a bubble oxygenator to .2% in an extraluminal microporous hollow-fiber oxygenator (32) and probably below .1% with a coated extraluminal hollow-fiber oxygenator. However, no simultaneous improvement has been made for the arterial filter. The pleated plate configuration of most ALFs with lateral
flow results in less favorable hemorheology and thrombus formation both inside and outside the filter (32,33). For this reason, most institutions will also not include an ALF in their extracorporeal membrane oxygenation circuits.

GME can be removed by combining strategies to improve buoyancy with a mechanical barrier. An ALF is effective in achieving these goals to a certain extent. However, one could question if its existing position in the arterial line is the best position because larger bubbles will be first fragmented by the pump, heat exchanger, and fiber bundle. The resulting smaller bubbles can be smaller than the pore size of the ALF and are less sensitive to buoyant forces (14). A better ALF position could be at the entrance of the oxygenator.

Based on this, it seems desirable to readdress the problem of filtration during CPB.

REFERENCES