Surface Tension Changes of Perfusates: Implications for Gaseous Microemboli during Cardiopulmonary Bypass

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Abstract

Surface tension (ST) analysis was performed on solutions used to prime bubble oxygenators in order to determine what changes, if any, took place during preparation and clinical use of the cardiopulmonary bypass (CPB) circuit. Samples were taken as follows: crystalloid solution prior to its addition to the circuit; after 5 and 20 minutes of pre-CPB recirculation; after addition of albumin; and post-CPB. ST values, as measured with a Du Nouy tensiometer dropped from 71 dynes/cm to values in the mid 60s, with additional decreases (mid 50s) following the albumin. Post-CPB values of plasma derived from centrifugation of perfusate were in the upper 40 dynes/cm range. This pre-CPB drop in ST raises the question of wash-off of defoamer and its possible effect on gaseous microemboli (GME) removal by arterial screen filters. Removal of GME by filtration is dependent, in part, upon ST phenomenon according to the "bubble point" concept and the equation of capillarity. Another concern is the potential removal of defoamer during pre-CPB filtration with subsequent inadequate oxygenator debubbling.

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Introduction

Surface tension (ST) is defined as the force of attraction between molecules in a liquid that puts the surface film between the air and liquid in a state of tension[1]. The measurement of ST of CPB perfusates provides data regarding the efficacy of screen filtration of GME and the behavior of intravascular GME. Examination of ST changes also provides a means of qualitatively and quantitatively estimating wash-off of defoamer material from the bubble oxygenator or cardiotomy reservoir.

Screen filtration dynamics have been described by the force-balance relationship commonly called the bubble point equation[2]. This relationship is:

$$BPP = 4\gamma/d$$

where BPP is bubble point pressure, γ is surface tension, and d is the diameter of the filter pore. Above a certain critical value, BPP will predict the failure of a filter to retain gas bubbles.

The goal of this study was to determine what changes took place in the ST of perfusates at stages during the prebypass wash and recirculation. Two factors that potentially could alter ST during the prebypass phase are: 1) wash-off of defoamer; and 2) the addition of albumin which, like plasma, has a lower ST than water.

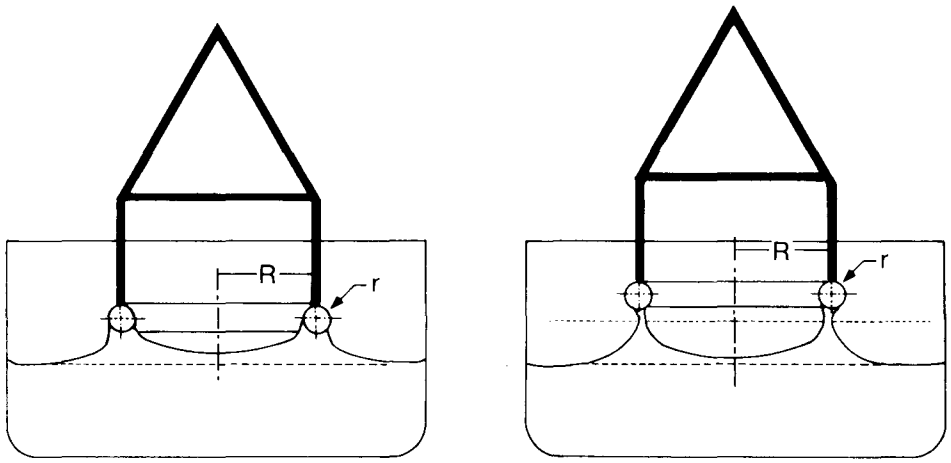

Figure 1: Illustration of how surface tension is determined using the method of Du Nouy (*J. Gen. Physiol.* 1:521-524, 1919). R = radius of ring; r = radius of wire. As ring is pulled out of fluid, a liquid film is drawn upward, until, at some point, the film breaks. Surface tension is measured at this breaking point which represents the weight of the ring plus the downward force due to surface tension of both the inner and outer surfaces of the liquid film. (Redrawn from Cenco Instruments Corp.)

Materials and Methods

Principle—Surface tension (γ) of the perfusate fluids is measured using the ring method of Du Nouy[3]. The measurement of ST is determined as the force (f) divided by the wetted perimeter (L) of a platinum ring that is pulled from an immersed state within a fluid bath through the surface, such that:

$$\gamma = f/2L$$

Employing the principle of Du Nouy for ST analysis enables the measurement of true ST, independent of any contact angle. As the platinum ring is pulled from the immersed state, peak force is directly proportional to the ST where the inner and outer surfaces of the fluid are both vertical (Figure 1). Once the pull of the ring exceeds the critical detaching force, the surface is ruptured and peak force (f) is measured per unit perimeter of the ring.

Sample Collection—Samples of CPB perfusate were collected for ST analysis in the following sequence: 1) crystalloid solution directly from plastic bag containers[a]; 2) from the arterial line of the CPB circuit after five minutes of recirculation; 3) from the arterial line of the CPB circuit after 20 minutes of recirculation; 4) after the removal of excess crystalloid and the addition of 25% albumin[b], sodium heparin (beef lung, 5,000 Units) and 8.4% sodium bicarbonate (20 mEq). The albumin concentration of the resulting perfusate was 2.3 to 2.5%. Recirculation was at a flow of five liters per minute, and the total volume of crystalloid solution added to the circuit for recirculation was three liters (Plasma-Lyte/5% Dextrose and 0.45% Sodium Chloride ratio 2:1). Two bubble oxygenators were used: the Cobe Optiflo II[c] and Bentley BOS-10S[d]. All solutions were added to the CPB circuit via the filtered cardiotomy reservoir[e]. The samples were collected in two groups, one of which had a 5 μm prebypass filter[f] in the circuit and the second a 0.2 μm prebypass filter[g]. Samples were collected and stored in 50 ml sterile, capped polypropylene specimen tubes[h]. Control mea-

a Plasma-Lyte A Injection, pH 7.4 and 5% Dextrose/ 0.45% Sodium Chloride Injection, Travenol Laboratories, Inc., Morton Grove, IL 60015
b Normal Serum Albumin (Human), U.S.P., Buminate, Hyland Therapeutics Division, Travenol Laboratories, Inc., Glendale, CA 91202
c model 42-221, Cobe Laboratories, Inc., Lakewood, CO 80215
d model BOS-10S, American Bentley, Inc., Irvine, CA 92714
e model Q-200F, American Bentley, Inc., Irvine, CA 92714
f model PB-005, Delta Medical Industries, Inc., Costa Mesa, CA 92626
g model PP3802, Pall Biomedical Products Corp., East Hills, NY 11548
h number 25330, Corning GlassWorks, Medical Products Division, Corning, NY 14830

surements were undertaken to ensure that no change in ST was attributable to the specimen tubes. Tubes containing fluid samples were refrigerated until time of ST analysis, and all measurements were made at room temperature. All CPB circuits were subsequently used clinically, and samples of blood remaining in the circuit postbypass were collected and centrifuged (5,000 RPM × 10 minutes). ST measurements were made of the resulting plasma to determine if additional ST changes took place during CPB.

Surface Tension Analysis—ST measurements were made using a surface tensiometer[i] (Figure 2). Fifteen milliliters of perfusate sample were transferred to the sample dish, which had been precleaned with phosphate-free detergent, acid-washed, distilled water and chloroform rinsed. The measurement of ST is taken as the peak force required to pull a clean platinum ring through a fluid surface, and values are corrected to the perimeter of the particular ring used for each measurement. Two ST measurements were made for each of the perfusate samples. A total of nine prebypass perfusate combinations and seven postbypass plasma samples were analyzed for true ST.

Data Analysis—Data were analyzed using a one-way analysis of variance using the Bonferroni method of multiple comparison ($p<0.05$ significant).

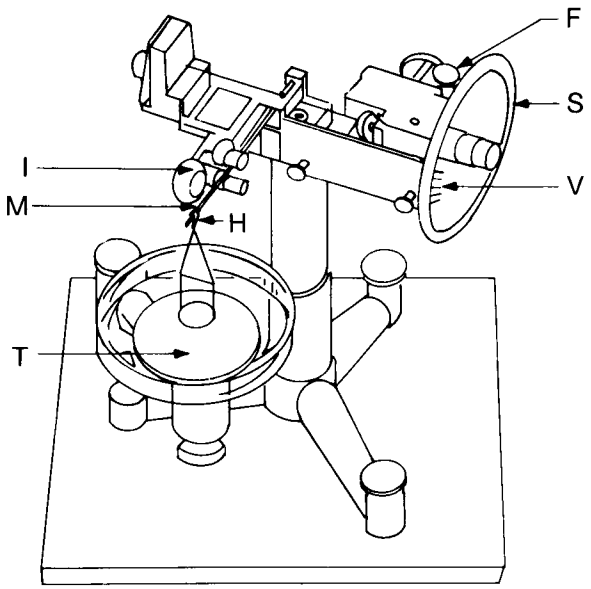

Figure 2: Drawing of Du Nouy surface tensiometer. I = Index; M = Torsion Arm; H = Hook; T = Sample Table; F = Fine Adjustment Screw; S = Dial; V = Vernier (Redrawn from Cenco Instruments Corp.)

Results

Prebypass ST values are shown in Table 1. There was no significant difference between samples from the 5 μm or 0.2 μm prebypass filter groups except for those samples that contained albumin. There was a decrease from the crystalloid sample (71.8 and 70.9 dynes/cm) to 68 and 68.4 dynes/cm at 5 minutes and 66.5 dynes/cm at 20 minutes. The greatest drop occurred after the addition of albumin (56.7 and 55.6 dynes/cm). Postbypass plasma ST samples dropped to 48.9 ± 3.6 dynes/cm. All the groups were significantly different from the crystalloid group ($p<0.05$).

Discussion

During early clinical application of CPB with bubble oxygenators, several articles appeared that dealt with the issue of defoamer wash-off and microembolic phe-

Table 1
Surface Tension of CPB Prime Solutions (dynes/cm)

	Crystalloid	5 min. wash *	20 min. wash *	Perfusate w/albumin *
5μm filter n=4	71.8±0.5	68.0±1.1	66.5±1.6	56.7±0.9
0.2μm filter n=5	70.9±0.2	68.4±0.5	66.5±0.2	55.6±0.5

Note: *significantly different (<0.05) when compared to crystalloid; all values are means ± S.D.

i model 70535, Cenco Instruments Corp., Chicago, IL 60623

nomenon in extracorporeally oxygenated animals and patients[4-11]. Two authors confirmed the release, circulation, and removal in perfused tissue of defoamer as blood passed through bubble oxygenators, and both concluded that the effectiveness of defoamer was dependent on its activity in the blood[5,7]. The quantities involved are generally quite small. Valentin and Vilhelmsen [12] found that 0.1 parts per million (ppm) Antifoam-A determined by spectrophotometry of arterial and venous blood samples was effective in defoaming bubble-oxygenated blood, while Penry and co-workers[6] reported blood levels of 1 to 10 ppm were required. Antifoam A in concentrations of from 1 to 50 ppm are effective in the suppression of foam in most systems, according to the manufacturer[13].

The most commonly used blood defoamer in bubble oxygenators is dimethylpolysiloxane polymer (Antifoam A)[j] which contains 4-4.5% silicon dioxide particle filler to enhance defoaming activity. The ST of Antifoam A has been reported as 18 or 27.5 dynes/cm[14,15]. While the polymer alone can defoam blood, both polymer and filler are generally required for most effective defoaming. Each device manufacturer has a different method for applying defoamer to oxygenators which generally involves dipping or spraying the substance onto sponge material. Application of defoamer is verified by weighing the treated material; generally, several grams are added to oxygenators which then are baked on during the sterilization process.

The beneficial effects of circulating defoamer in reducing ST with a subsequent lowering of intravascular gas bubble stability was noted by Eiseman and coworkers in 1959. They found that the lethal effect of coronary air embolism in dogs could be lowered by 50% if small injections of Anti-Foam A or B were injected into the left ventricle at the time of air embolism[15]. They attributed these results to the decreased ST of blood which presumably allowed passage of the intravascular gas bubbles through the coronary vascular bed with a concomittant decrease in bubble-induced tissue ischemia.

One group investigated the hemolytic effect of defoamer found in cardiotomy reservoirs and measured the ST of plasma from seven patients at the beginning of CPB and at the conclusion[14]. In six out of the seven patients, the ST of plasma decreased from an average of 57.6 dynes/cm to 50.5 dynes/cm. The postbypass values reported in the present study (48.9 dynes/cm) are close to these figures, and the slight difference may be accounted for by the use of two different techniques (Wilhelmy apparatus versus Du Nouy tensiometer). Other ST values of blood or plasma found in the literature[16] report ranges of from 55.5 to 61.2 dynes/cm (blood) and 75.1 or 75.4 dynes/cm for plasma in men and women, respectively. Another worker, using the Du Nouy method, reported plasma values ranging from 48.1 to 53.8 dynes/cm with a mean value of 50.2 $\pm$ 0.1 SEM[17].

The question raised in this study is two-fold. The first concerns wash-off of defoamer from the bubble oxygenator or cardiotomy reservoir, and the second regards changes in perfusate ST as a result of this wash-off. The results indicate a statistically significant decrease in perfusate ST during prebypass recirculation. With the addition of a protein solution (albumin) the perfusate ST decreased to a greater degree from 66.5 dynes/cm to 56.5 dynes/cm. This change is presumably independent of any additional defoamer wash-off. Samples of albumin in different concentrations were measured to determine the effect on ST: decreasing the concentration from 5 to 1.25% showed a rise from 55.3 $\pm$ 0.78 to 58.9 $\pm$ 0.46 dynes/cm, confirming the ST reducing effect of adding albumin to the perfusate. The postbypass values (48.9 dynes/cm) may reflect a change in the blood due to additional defoamer wash-off or to native plasma proteins from the patient mixing with the perfusate. Another factor may be the release of plasma free hemoglobin. The patient that had the lowest postbypass ST (42 dynes/cm) also had the highest postbypass plasma free hemoglobin (82 mg/dL or 0.81 mg/dL per minute on bypass).

Changing the pore size of the prebypass filter had no detectable effect on ST except for the samples containing albumin. An initial concern was the possibility of decreased oxygenator defoamer activity by use of the 0.2 μm pore filter which presumably removed some of the silicon dioxide particles and which have been reported to range in size from 2-3 μm and up to 20 μm[10]. Conclusions drawn from these observations indicate that defoamer is most likely washed off, and although the changes in ST are statistically significant, their biological relevance may be minimal. The pore size of the prebypass filter does not change this relationship.

Another concept raised with regards to perfusate ST is that of arterial screen filter function as it pertains to the pressure differential across the screen and which affects bubble retention or passage. This concept is explained in the relationship of capillarity as derived from Young and La Place[18]. It has also been described

j Dow Corning Corp., Midland, MI 48626

more recently as the bubble point concept which expresses the same equation:

$$\Delta P = 2\gamma\cos\theta/r$$

where ΔP is the hydrostatic pressure difference on either side of a pore, γ is surface tension, θ is the contact angle at the triple point between the air: liquid: solid interface, and r is pore radius. It is apparent from the above relationship that as ST drops, the required ΔP to push a bubble through a pore is decreased. Thus at some point a filter would be predicted to fail in its operation of preventing GME to pass downstream. For a screen filter with 40 μm size pores, varying the ST from 40 to 65 dynes/cm yields a range of BPP from 29.99 to 48.73 mmHg which is above the ΔP at clinical flow rates.

This study has addressed the fundamental issue of filtration of GME by screen filters focusing on ST as it applies in the above relationship. Another aspect of this relationship can be applied to a bubble trapped within a vessel segment of a patient. Contrary to the situation with a screen arterial filter, the opposite condition exists within the vasculature; that is, a low ΔP with ST values as reported in this study would tend to hold GME in place, blocking off arteriolar blood flow. If the driving pressure (ΔP) is insufficient to "push" the bubble past the trapped point, then blood flow would diminish to downstream tissue causing ischemia and possibly infarction[19].

At this point in our evaluation of fundamental aspects of blood filtration by arterial screen filters, we suggest that the changes observed in ST of prebypass perfusate are not sufficient to alter normal operations. Future studies should include the analysis of perfusate samples for defoamer concentrations and examination of the role of plasma free hemoglobin in altering the ST of CPB perfusates. Ultimately, fundamental questions regarding both the length and rate of prebypass wash and filtration may be addressed as they apply to oxygenator defoaming capabilities.

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