
Roller Pump Induced Tubing Wear: Another Argument in Favor of Arterial Line Filtration

M. Kurusz, B.A., C.C.P.; E. W. Christman, B.S.; E. H. Williams, M.D.; and G. F. O. Tyers, M.D.

The Department of Surgery
Division of Cardiovascular and Thoracic Surgery
The University of Texas Medical Branch
Galveston, Texas 77550

Abstract

Pump head tubing was studied to determine if internal wear occurred during routine cardiopulmonary bypass. Several segments of silicone rubber tubing were examined in a scanning electron microscope following clinical perfusion. In each case, the proper degree of occlusion had been set just prior to beginning bypass. The roller pump was a six-inch dual roller type, and the tubing was 3/8 inch ID with 3/32 inch wall thickness. Blood flow rates ranged from 3.8 to 5.2 liters per minute, and duration of the pump runs ranged from 35 to 220 minutes. Evidence of tubing wear on the luminal surfaces was observed and was related to time and flow rates. Two grooves opposite one another and corresponding to the location of maximum flexure were present in every sample examined. Alterations in the tubing surface were seen in the areas adjacent to the grooves. Craters ranging from $<10\ \mu\text{m}$ to $>50\ \mu\text{m}$ along with some degree of smoothing of the normal surface texture were seen. Presumably, some spallation had occurred, and particles had been pumped downstream. Use of an arterial line filter with this type of tubing is recommended.

Introduction

The possibility of outright pump head tubing failure rarely concerns perfusionists today, although there have

been reports of this rare accident occurring during cardiopulmonary bypass.^{1,2} A less dramatic type of tubing failure occurs during perfusion when silicone rubber is used in a roller pump head despite the proper degree of occlusion being set and the rollers being properly balanced within the manufacturer's tolerances. This type of failure appears to be time and flow rate dependent and consists of abrasion and erosion of the luminal surface of silicone rubber tubing during roller compression during pumping. As a result, another source of microemboli is produced within the extracorporeal circuit. In 1975, Hubbard and co-workers³ filtered fluid pumped in a mock circulatory loop and demonstrated spalled particles with light microscopy to point out the superiority of a constrained vortex centrifugal pump. This paper presents additional information obtained by scanning electron microscopy (SEM) of clinical segments of pump head tubing to illustrate the nature and extent of tubing wear that occurs when this type of tubing is used in a roller pump. SEM has been used previously to characterize blood surfaces found in the typical extracorporeal circuit,⁴ but this is the first report of the application of SEM to segments of roller pump tubing that have been used clinically.

Materials and Methods

Medical grade, close tolerance silicone rubber tubing* measuring 3/8 inch internal diameter with a 3/32 inch wall thickness was used during clinical cardio-

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Address correspondence to: M. Kurusz, Division of Cardiovascular and Thoracic Surgery, M-603 John Sealy Hospital, The University of Texas Medical Branch, Galveston, Texas 77550

* Medical Engineering Corporation, Racine, Wisconsin 53404
✓ Sarns, Inc., Ann Arbor, Michigan 48103

pulmonary bypass in a six-inch dual roller pump[✓] for arterial infusion of blood. Immediately prior to bypass, the degree of occlusion was carefully set to be just under occlusive.^{5,6} Both roller-to-housing tolerances were checked prior to surgery, and both were found to be nearly identical and within the pump manufacturer's tolerance of .0015 inches. (Personal communication, Mr. Herb Hammond, Sarns, Inc.)

Following cardiopulmonary bypass, the arterial pump head tubing was carefully removed from the roller pump in the same direction as it was used during the perfusion. Blood was drained from the tubing, and a 2–3 centimeter segment of whole tubing was cut and removed from the center portion of the pump head segment using a clean #21 scalpel blade. The distal end was notched to note the direction of roller movement. Because no attempt was being made to study blood/tubing interaction, the segment was immediately rinsed in flowing tap water and then ultrasonically cleaned in detergent[#] for approximately five minutes. Following this cleaning to remove blood, the segment was again rinsed in flowing tap water and blown dry with compressed air. It was then immediately covered to prevent surface contamination by air-borne particles. At no time was the luminal surface to be examined touched with any instrument.

In preparation for SEM, the segments were transected with a clean #21 scalpel blade leaving approximately one centimeter segments. The ends were discarded, and the center segment was split longitudinally into quarters. One quarter segment exhibiting groove formation visible to the naked eye was chosen for SEM examination. This groove corresponded to one of the two areas of maximal flexure caused by roller compression of the tubing against the pump housing.

Segments for examination were then mounted on 1.5 centimeter aluminum stubs with quick-drying epoxy cement and sputter-coated with gold-palladium in a Hummer II⁺ apparatus to make them conductive. They were coated for one minute at 5 mA current which deposited a very thin layer of metal approximately 100 Å in thickness. A stub-to-tubing trail of silver paint ensured conductivity between the sample surface and the stub. Following application of the gold palladium, the tubing samples were immediately examined in an ISI Super III[%] scanning electron micro-

scope at 15 kV and 45°–50° tilt from the horizontal to enhance surface topographical features. Control samples of tubing were prepared in a similar fashion as clinical tubing samples including the ultrasonic cleaning.

Results

Figures One and Two are SEM micrographs of the luminal surface of unused silicone rubber tubing as received in a sterile custom tubing pack.[∅] The bore of the tubing runs vertically in the micrograph, and the surface features consist of gentle undulations with occasional smooth-edged blebs and pits. On a blood cellular level, such a surface would be termed fairly smooth. This surface texture is produced by the tubing manufacturing process as silicone rubber tubing is extruded and cured. (Personal communication, Mr. Tom Brown, Dow Corning Corp.)

Clinically used tubing samples (Figs. 3–11) showed evidence of tubing wear on the luminal surfaces. This wear appeared to be related to bypass time and flow rate, in that, an increased number of roller strokes on a tubing segment coincided with a more altered surface. Determination of the number of strokes a particular tubing segment received was calculated by multiplying the average number of revolutions per minute (RPM) times two (for each roller) times the pump time in minutes. Typically, a longitudinal groove was seen in every sample examined. Figure 3 is a low magnification view of this groove, and it corresponds to the location of maximum tubing flexure caused by roller compression. Figure 4 is a higher magnification of the same sample and shows blebs arising from the tubing material itself. Surrounding areas of tubing are relatively smooth with occasional shallow, smooth-edged craters. Figure 5 shows groove formation and bleb formation running parallel to the groove on a tubing segment that was used clinically for 121 minutes. Figure 6 is a higher magnification view of the blebs which are clearly shown to be part of the tubing. Small pits (<5 μm) are also present.

Relatively short pump runs also produced tubing alterations, although, to a lesser degree. Figure 7 is a sample from a 35 minute pump run, and the typical crater and bleb formation is present. Further SEM evidence that the luminal surface of tubing not only is damaged but can erode potentially dangerous mi-

Liqui-Nox, Alconox, Inc., New York, New York 10003

+ Technics, Inc., Alexandria, Va. 22310

% International Scientific Instruments, Inc., Mountainview, Ga. 94043

∅ Cobe Laboratories, Inc., Lakewood, Co. 80215

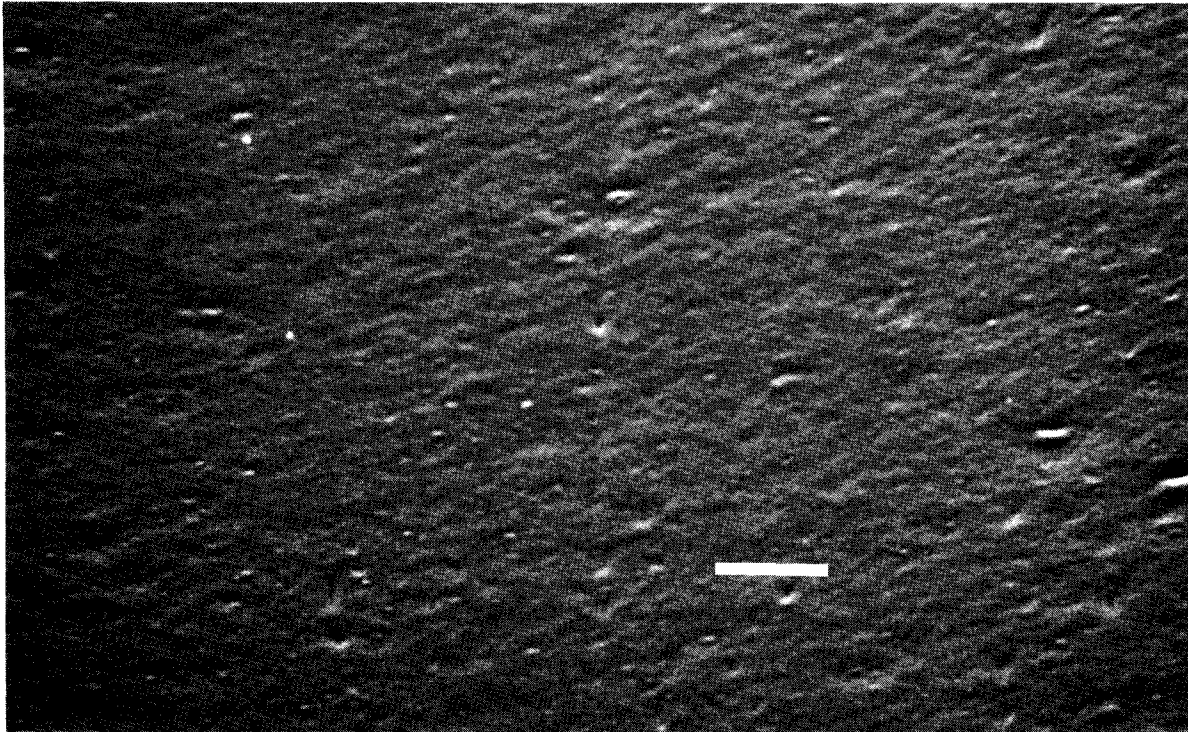


FIGURE 1. Control silicone rubber tubing. Medical grade, close tolerance; $\frac{3}{8}$ inch internal diameter and $\frac{3}{32}$ inch wall thickness. Bore of tubing runs vertically in the micrograph. Bar = 100 μm .

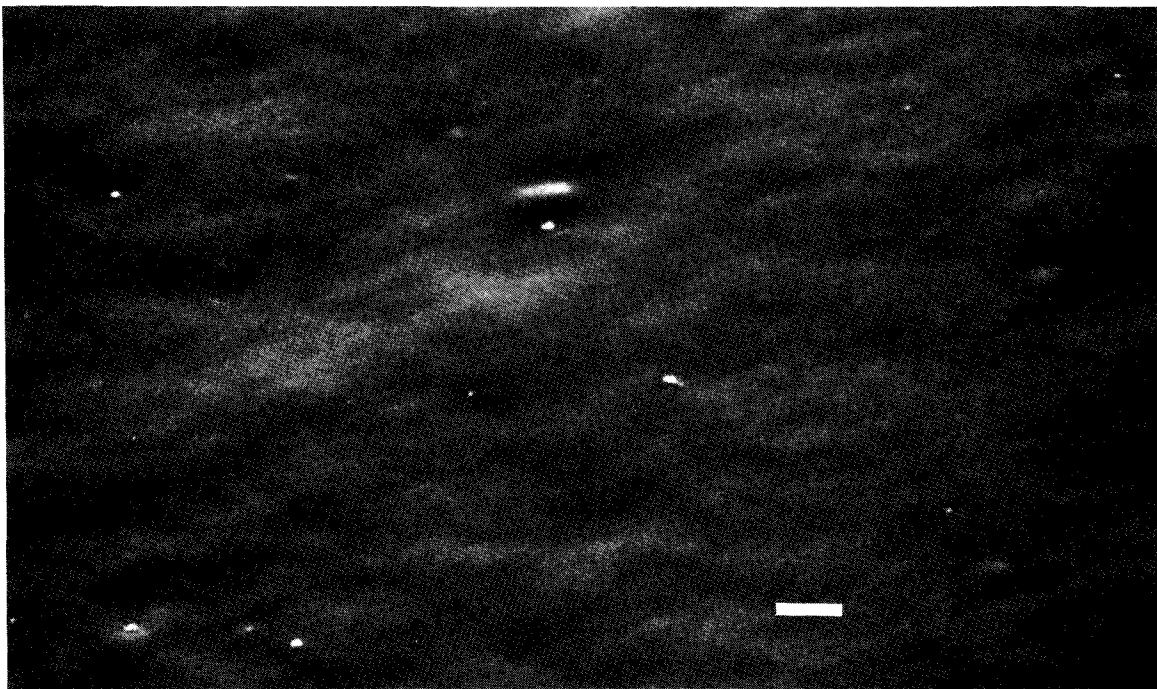


FIGURE 2. Control silicone rubber tubing at a higher magnification than Figure 1. Note the generally smooth, undulating surface. The occasionally adherent white particles were presumably deposited during specimen preparation and represent air-born contaminants. Bar = 10 μm .

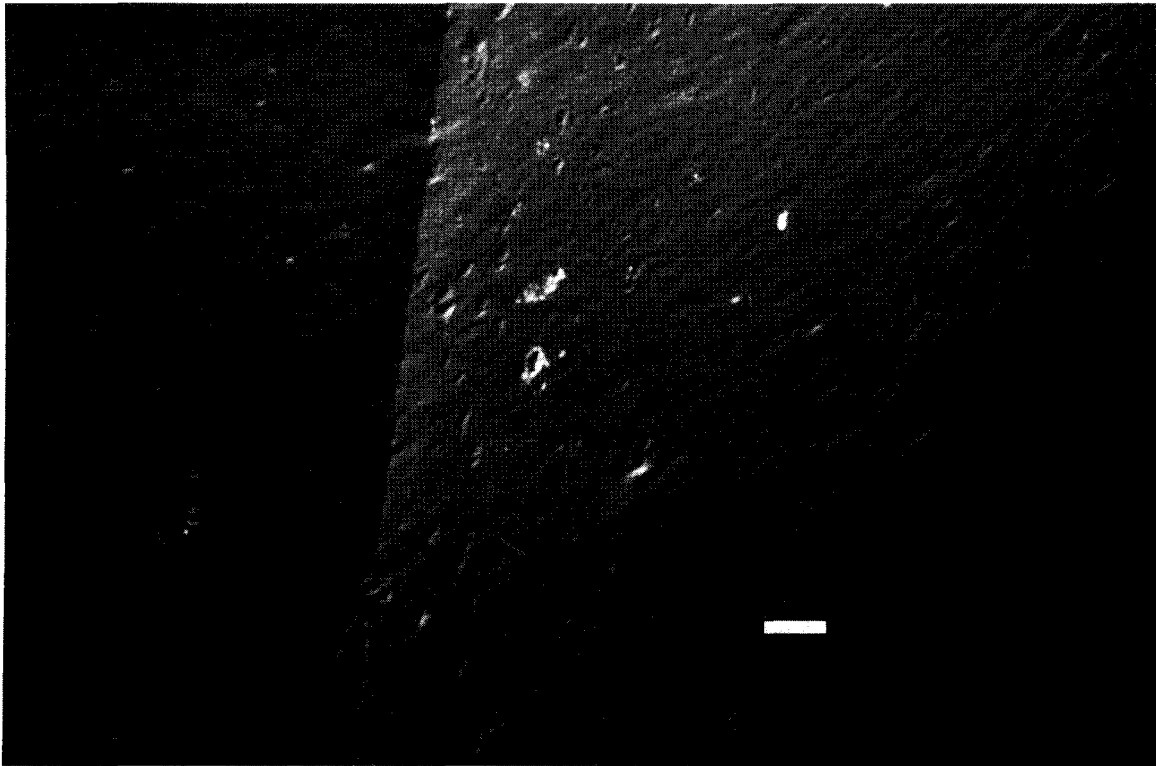


FIGURE 3. Clinically used silicone rubber tubing. Pump time 78 minutes; average flow rate 5250 ml/minute (190 RPM) or approximately 29,640 roller strokes. Note the distinct groove formation and areas of increased surface roughness adjacent to the groove. Craters are up to 25 μm in width. Bar = 100 μm .

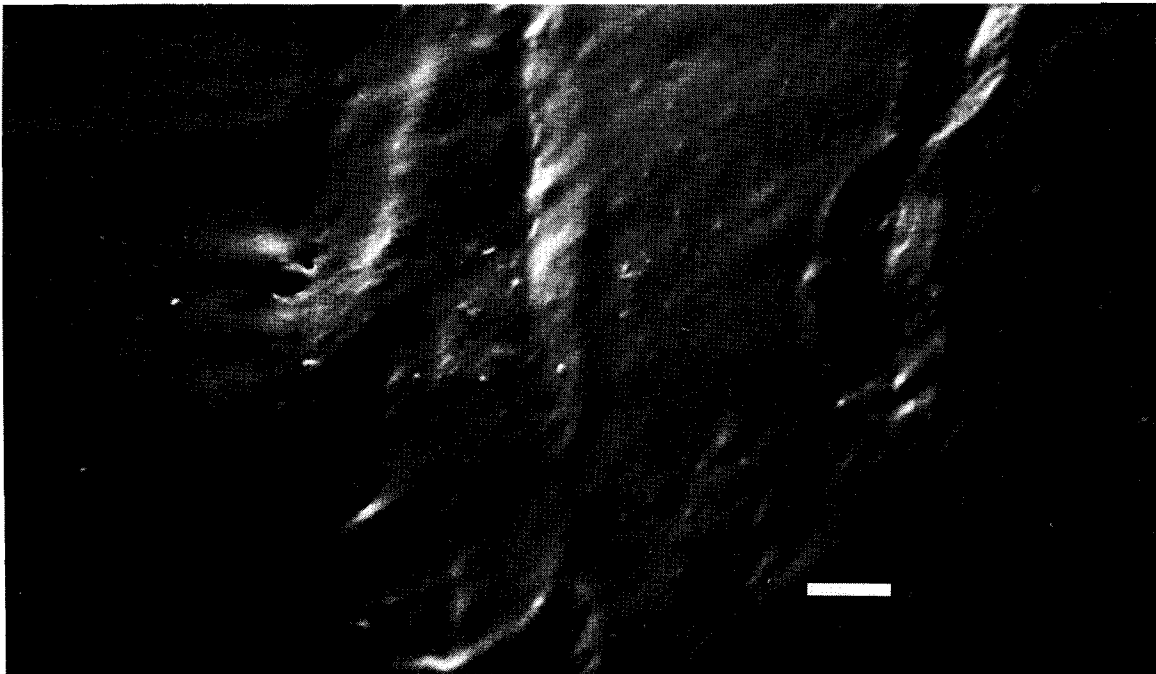


FIGURE 4. Clinically used silicone rubber tubing. Same sample as Figure 3 but at a higher magnification. Note craters adjacent to the groove and pitting. Bar = 20 μm .

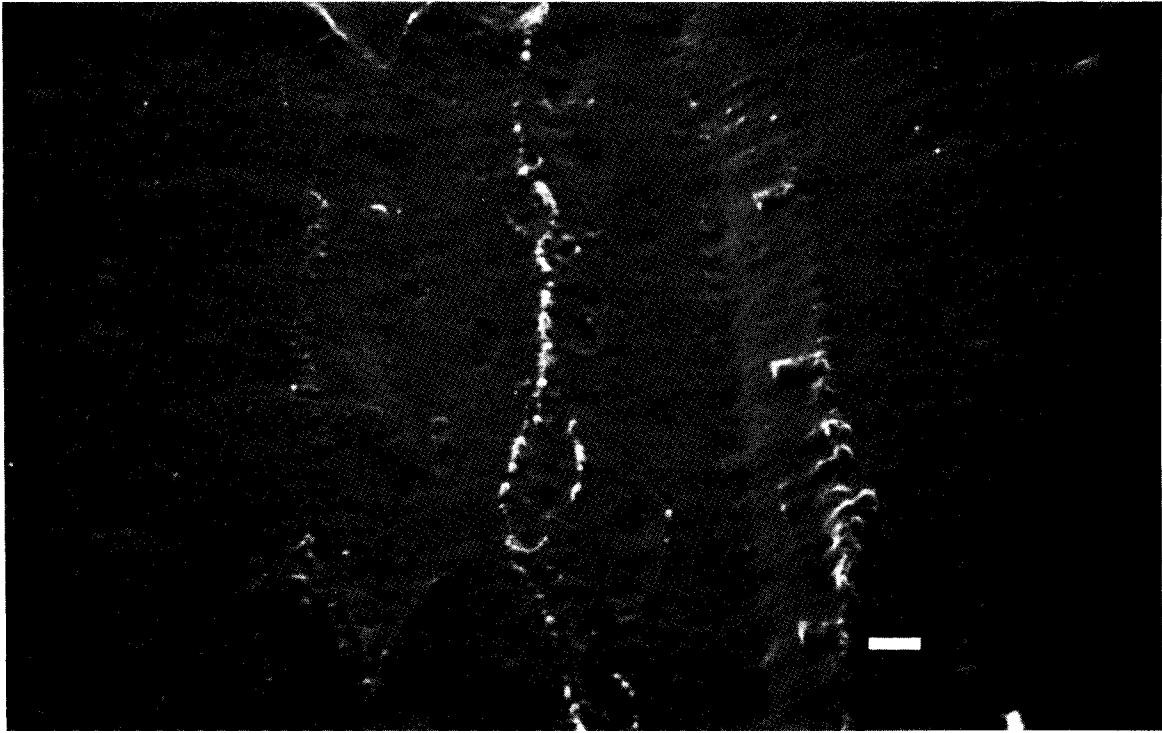


FIGURE 5. Clinically used silicone rubber tubing. Pump time 121 minutes; average flow rate 4500 ml/minute (165 RPM) or approximately 39,930 roller strokes. Note material near the groove and normal silicone rubber surface on either side of the groove. Bar = 50 μ m.

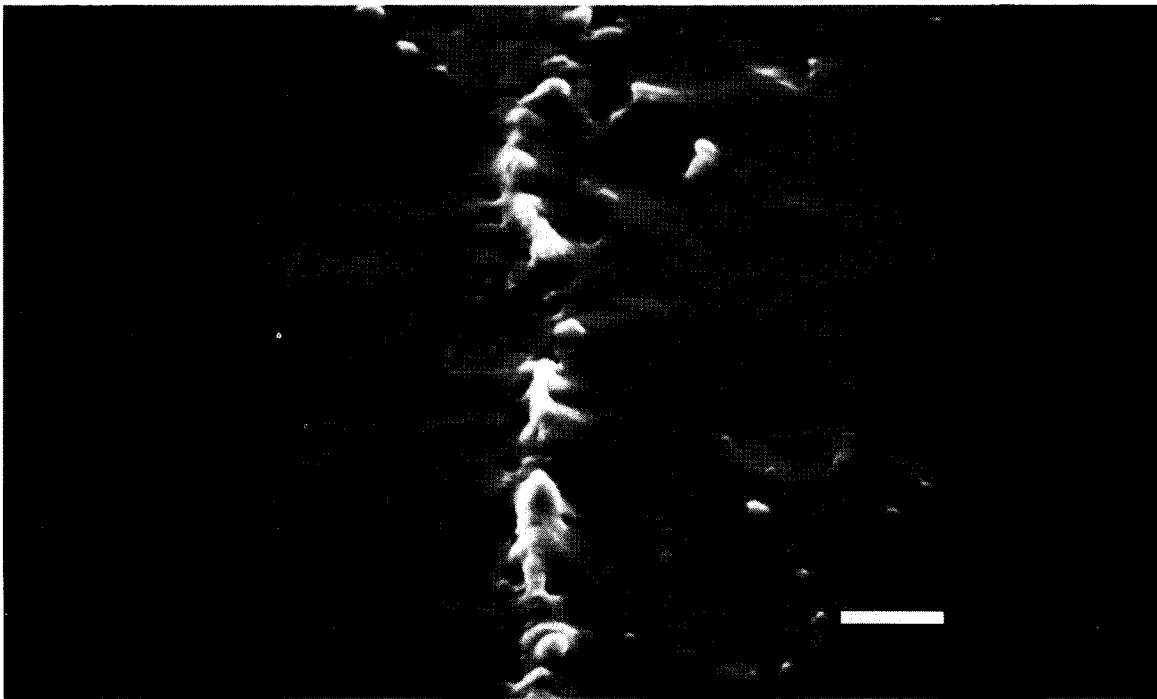


FIGURE 6. Clinically used silicone rubber tubing. Same sample as Figure 5 but at a higher magnification. Note multiple bleb formation running parallel to the groove. Bar = 20 μ m.

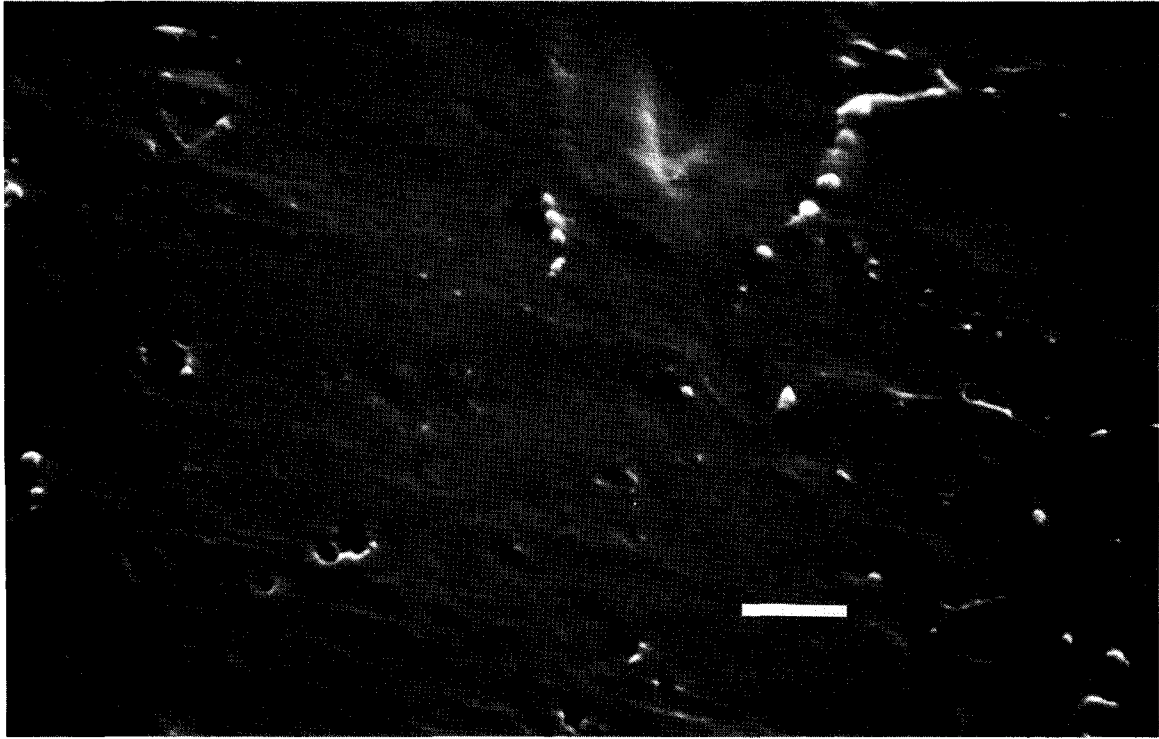


FIGURE 7. Clinically used silicone rubber tubing. Pump time 35 minutes; average flow rate 4250 ml/minute (155 RPM) or approximately 10,850 roller strokes. Note blebs near large (50 μm), shallow crater and smaller rough-edged craters to the left. Bar = 20 μm .

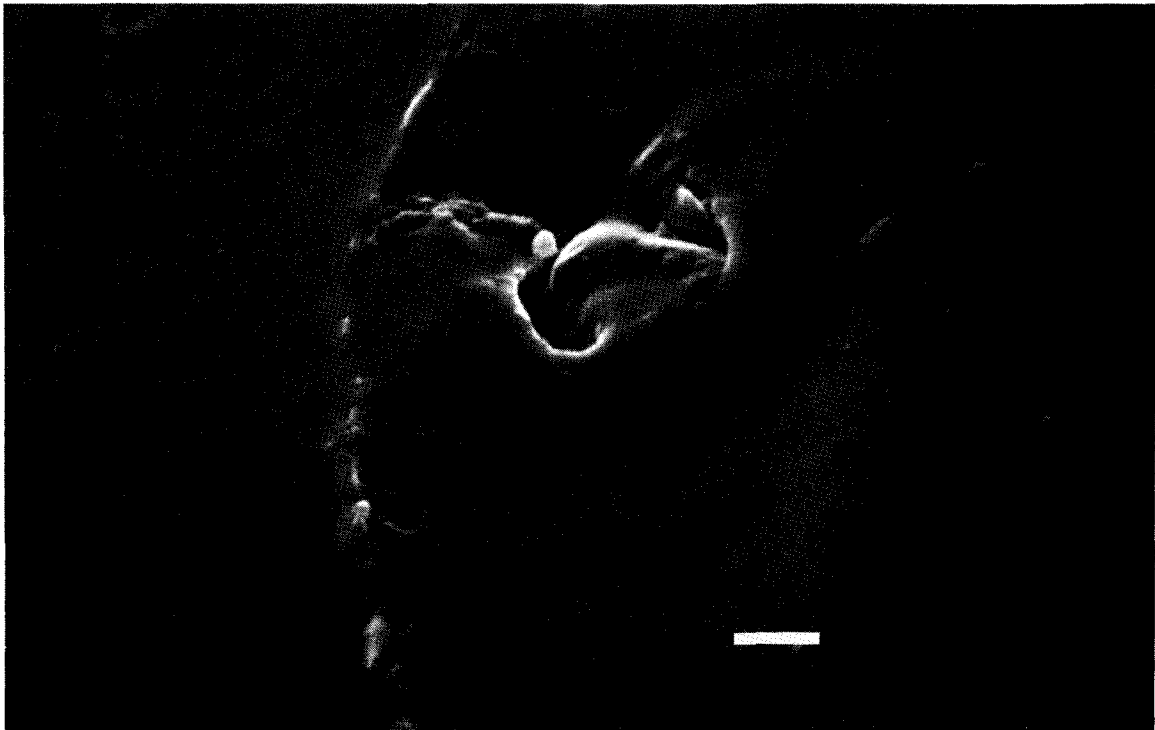


FIGURE 8. Clinically used silicone rubber tubing. Pump time 220 minutes; average flow rate 3850 ml/minute (140 RPM) or 61,600 roller strokes. Note disruption in the tubing surface and a particle partially detached from the tubing. Bar = 10 μm .

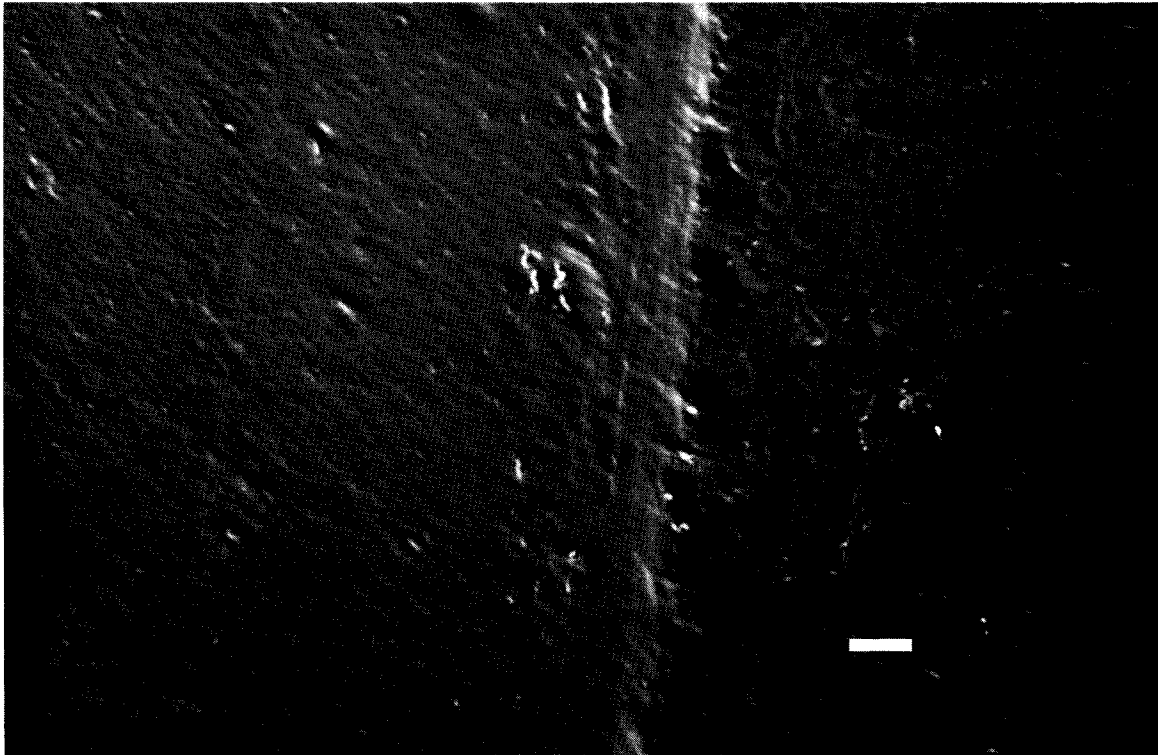


FIGURE 9. Clinically used silicone rubber tubing. Pump time 165 minutes; average flow rate 4650 ml/minute (170 RPM) or 56,100 roller strokes. Note the typical groove formation and surface irregularities adjacent to the groove
Bar = 100 μ m.

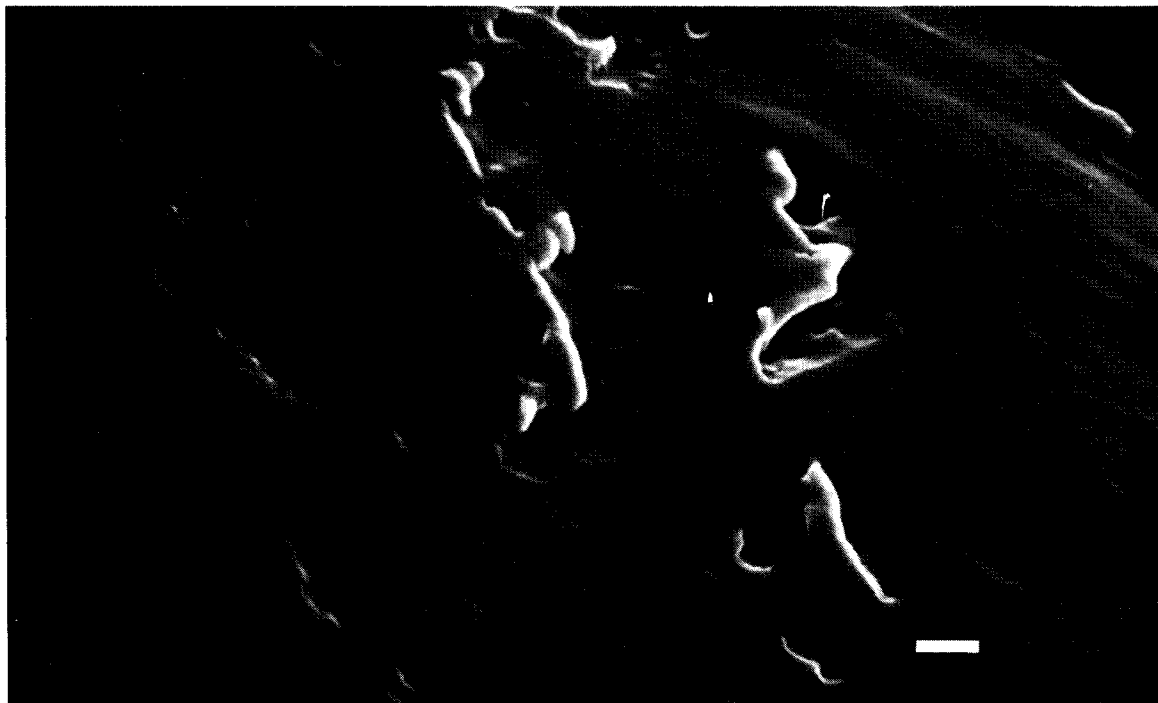


FIGURE 10. Clinically used silicone rubber tubing. Same sample as Figure 9 but at a higher magnification. Note jagged tears and pitting on the surface of the tubing.
Bar = 10 μ m.



FIGURE 11. Clinically used silicone rubber tubing. Same sample as Figures 9 and 10 but at a higher magnification. Note partially eroded particle within a crater that measures approximately $12.5\ \mu\text{m}$ in diameter. Bar = $10\ \mu\text{m}$.

croemboli is shown in Figure 8. This sample was taken from a tubing segment that was used clinically for 220 minutes. The center of the micrograph shows a relatively large particle (approximately $20\ \mu\text{m}$) of silicone tubing partially eroded from the tubing surface. One side of the particle is continuous with the surrounding surface, so, presumably, it was not deposited during preparation, but instead emanated from the tubing material. The area around this particle is smoother than the control silicone rubber tubing.

The last three micrographs show the effects of roller damage to tubing that was used clinically for 165 minutes. Figure 9 is an overall, low magnification view of the characteristic groove formation. As in previous samples, the area on either side of the groove shows signs of crater formation and pitting. In areas away from the groove the tubing surface is normal. Figure 10 shows severe pitting of the tubing surface. Rough-edged craters have formed in the area immediately adjacent to the groove. Figure 11 shows a particle from the same sample that was nearly detached from the bulk tubing. The diameter of the particle is approximately $12.5\ \mu\text{m}$. Smaller pits are seen immediately below the particle.

As these SEM micrographs demonstrate, changes in the normal surface features of silicone rubber tubing

employed in a dual roller pump at clinical flow rates routinely occur. These changes appear to be time and flow rate dependent. That is, with longer pump runs or increased flow rates, the tubing damage is more severe. The two predominant features are pitting or crater formation and bleb formation. Both types of surface changes can presumably lead to spallation of the tubing material into the flowing blood. The largest craters consistently observed were in the range of 20 to $30\ \mu\text{m}$.

Discussion

Two facts of life of extracorporeal circulation for open-heart surgery are hemolysis and microemboli. Both are relevant to this study and present a dilemma to the perfusionist. That is, in an effort to decrease hemolysis, silicone rubber tubing has been the tubing of choice for clinical cardiopulmonary bypass circuits. However, as shown in this study, it is likely that silicone rubber tubing is susceptible to roller pump damage and most likely erodes small particles of tubing material into the flowing blood.

Sources of hemolysis during clinical perfusion are numerous. The most commonly cited causes are cardiotomy suction,⁷ the air-blood interface,^{8,9,10} and

contamination of blood by pericardial fluid.¹¹ However, the mode of pumping may be an important source as well. Bernstein and co-workers,¹² in 1967, studied several factors that contributed to hemolysis with roller pumps including the importance of the degree of occlusion of the rollers and the type of tubing material used. They concluded that silicone rubber was the best material available for use in a roller pump in terms of hemolysis. It was also found to be the material that produced the least hemolysis even when the rollers were set in the occlusive mode. Also important as a source of hemolysis with roller pumps is the number of rollers and the number of RPM the roller makes to pump blood. Head and co-workers,¹³ in the early days of extracorporeal circulation, found a dual roller pump to be the least hemolytic. Furthermore, as might be expected, increasing the RPM led to increased hemolysis. RPM of 30 to 60 was cited as optimal in terms of reducing hemolysis. In the current study, 3/8 inch tubing was used, and the settings required to obtain adequate flow rates for perfusion ranged from 140 to 190 RPM. The possibility of decreased tubing wear by increasing the internal diameter of the pump tubing in order to lower the RPM required has not been investigated.

Microemboli have been described and implicated in the pathogenesis of post perfusion complications,^{3,14-23} and their presence has been confirmed several ways. Neurological evaluation of patients following cardiac surgery²⁴ and postmortem examination of brains of animals²⁵ and humans²⁶ post-bypass have shown cerebral damage due to microemboli lodging in the vasculature of the brain. More recently, Doppler or ultrasonic probes have been placed in the extracorporeal arterial line^{16,22,27} or on patients' temporal artery²⁸ during clinical perfusion. From these studies three major types of microemboli may be characterized: 1) gaseous, 2) biological, and 3) non-biological.

Kessler¹⁶ found 50% of microemboli to be microbubbles and, importantly, never observed a perfusion employing an oxygenator to be free of microemboli. Similarly, use of bubble oxygenator has been cited as the source of most microemboli measured during clinical perfusion.²³ Brennan¹⁷ was unable to identify microemboli during animal experiments but speculated that they consisted primarily of platelet or denatured protein aggregates and gas bubbles. Solis¹⁹ studied the presence of biological microemboli during cardiopulmonary bypass and attempted to quantitate the numbers and volumes with a Coulter counter. His solution to the problem was to filter the cardiomy blood in

order to remove platelet aggregates created by cardiomy suction. Reed and co-workers²⁰ reported that significant numbers of microemboli were caused by particulate debris found in disposable oxygenators. They identified the majority of the debris to be fibers and plastic chips using filtration with light microscopy and manual counting methods. The possibility that a portion of their measured particulate contaminants could have consisted of spalled tubing particles exists as no control studies were done without an oxygenator in the circuit. Page and co-workers²¹ identified most microemboli in extracorporeal circulation as platelet/leukocyte aggregates using the screen filtration pressure method. They noted that an undetermined amount of amorphous material or debris was also present. Cardiomy blood contained the highest number of microemboli. However, as they pointed out, microemboli found in the arterial line, while much lower in concentration, comprised a substantial total number due to the high volume of blood flow in the arterial line. The possibility exists that roller pump generated particles contributed to the overall increase in screen filtration pressure in their study.

Non-biological microemboli during extracorporeal circulation are relevant to this study and perhaps the most worrisome. As noted by Van Wageningen,²⁹ biological microemboli are potentially reversible in an organism due to phagocytosis and dissolution by the reticuloendothelial system. Gaseous microemboli produced by an oxygenator may be trapped by an arterial line filter³⁰ or dissolve in the blood. However, non-biological microemboli are not readily broken down and may be permanently present in the microvasculature of the patient following extracorporeal circulation.

Several studies investigating roller pump induced tubing wear have been reported. Hodge and co-workers³¹ circulated fluid in a mock circulatory loop by means of a roller pump, filtered the fluid, and weighed the filters. They concluded that captured particles were generated by the abrasion of tubing in the roller pump. Moreci and co-workers³² did a similar study using a mock circulatory loop and compared silicone rubber and polyvinyl chloride (PVC) tubing in both the occlusive and non-occlusive modes. They filtered particulate debris and measured the amounts generated in the loops. Silicone rubber tubing typically produced granular particles while PVC produced thread-like particles; both types of tubing produced more debris at 37°C than at 22°C. These particles were thought to result from severe flexure of the tubing during roller

compression. Creases and pits were observed at these points on the luminal surface post circulation. Control tubing was smooth. Their light microscopic results are confirmed by the present scanning electron micrographs. Boretos³³ used a similar mock circulatory loop but incorporated a filter while pumping fluid in order to quantitate tubing abrasion with 1/4 inch PVC and segmented polyurethane. One conclusion made was that decreasing the wall thickness of the tubing reduced the number of particles generated. Interestingly, silicone rubber was not evaluated in his study due to its poor flex life and high incidence of rupture. Hubbard and co-workers³ reported similar findings to those of Moreci using silicone rubber and PVC in mock circulatory loops. PVC tubing generally produced thread-like particles while silicone rubber produced more granular type of particles. Sizes of particles collected from the silicone rubber tubing loop ranged from 5 μm up to greater than 300 μm , with the majority being less than 50 μm . In the present study most craters observed on the tubing luminal surface were in the range 10 to 30 μm . Occasionally, defects greater than 50 μm were observed, but these were rare.

The presence of mechanical shear stresses caused by a roller pump were reported in the early days of extracorporeal circulation by Wesolowski.³⁴ These shear stresses not only caused hemolysis but were found to be capable of fracturing pump tubing. He noted that such fractures invariably occurred at the junction of the inner and outer wall as the tubing was compressed. This is the same area where damage was observed in our clinical samples. One of the reasons that damage occurs in this area is that the roller is freely moving, while the tubing side against the pump housing has a tendency to remain stationary. This has been called the frictional drag force, and it is believed to have caused the tubing damage demonstrated in this study. Tubing wear then is caused by not only lateral compression and flexing of tubing by the roller but by a slight rubbing of the inner and outer tubing surfaces due to different forces present both. Incidentally, Wesolowski proposed and built a type of roller pump in which not only the roller but the housing was freely moving in order to decrease the frictional drag force. Whether this type of pump would cause less tubing material damage is provocative in light of the present findings.

The present study on randomly chosen, clinically used segments of silicone rubber tubing presents further evidence that pump head produced microemboli are a reality even during short periods of pumping and de-

spite the occlusion being set properly just prior to the commencement of bypass. Bartlett and Gazzaniga³⁵ have reported the gradual erosion of the luminal surface of silicone rubber tubing during prolonged pumping for extracorporeal membrane oxygenator support. One would suspect that longer pump runs or higher flow rates would produce increased tubing damage and presumably an increased number of microemboli. However, this remains to be proven using a more controlled system such as a mock circulatory loop where particles generated can be collected and analyzed. Conceivably, different tubing materials and different tubing sizes could be tested in order to determine the best currently available tubing for use in a roller pump in terms of microemboli generation. Newer types of tubing such as polyurethane lined PVC⁹ or high performance silicone rubber⁸ are becoming available for perfusion, and tests need to be performed on them to determine whether they are superior to either silicone rubber or PVC.

Conclusions

Whether roller pump induced microemboli as described above are clinically relevant remains to be determined, but it seems highly doubtful that they are beneficial. Additional study is required to quantitate the numbers and particle sizes of tubing debris by varying the flow rates, times, and tubing sizes. Until such tubing debris is quantitated and identified, it would be judicious to use some type of arterial line filter whenever silicone rubber tubing is used in a roller pump for clinical perfusion. Based upon the reported tendency of PVC to liberate thread-like particles when flexed by a roller pump, use of an arterial line filter with this type of tubing is also warranted.

Summary

Silicone rubber tubing damage by a roller pump has been studied by scanning electron microscopy following clinical cardiopulmonary bypass. Damage consisted of groove formation in the area of maximum tubing flexure by the roller. Surface irregularities observed were craters or pitting and blebs. Evidence of particle erosion was also observed.

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