Studies of Roller Pump Induced Hemolysis

Lawrence R. Gleason
Eugene F. Bernstein, M.D., Ph.D.*

From the Department of Surgery, University of Minnesota Medical School, Minneapolis, Minnesota 55455.
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* Markle Scholar in Academic Medicine
Assistant Professor of Surgery,
University of Minnesota Medical School

A. INTRODUCTION

A pertinent literature review reveals considerable variation in data and opinion regarding the importance of several considerations in roller pump design and operation. In 1957, McCaughan 1 demonstrated that the Mark-DeBakey roller pump was far more hemolytic when set occlusively. The following year, Hodges 2 reported essentially no difference in hemolysis with occlusive and non-occlusive settings in both roller and Sigmamotor pumps, and emphasized that very carefully approximated occlusion produced essentially the same amount of damage as non-occlusive conditions.

In 1959, Leonards 3 introduced a new 8-inch diameter roller pump, which was compared with the Hercik non-occlusive roller by Cahill. 4 Both were equally hemolytic at low flow rates (200 cc/-min). Further pertinent data were published by Head in 1960, 5 demonstrating that hemolysis was slightly higher when a roller pump was just occlusive, but rose to approximately double with tight occlusion. Head concluded that hemolysis was due to (1) the rotary speed, or rpm, (2) the degree of occlusion, and (3) the number of rollers in the pump. Additional data on the non-occlusive Hercik roller published by Brown indicated an extremely low Index of Hemolysis. 6

In 1960, Esmond 7 tested a single 360° roller pump with spring-loading, and reported three times as much hemolysis with latex rubber, as compared to vinyl tubing. Capelletti's studies 8, 9 of a Mark-DeBakey roller pump with Tygon tubing suggested little dependence of roller pump hemolysis on flow rate.

A number of these papers, particularly those published since 1958, have reported data in terms of Index of Hemolysis, 10 and therefore might be comparable. However, certain differences in experimental technique may have profound effects upon the results. For instance: the method of blood collection (whether in heparin or ACD), freshness of blood, fasting state of animal, whether canine or human blood was used, varying hematocrits in the test blood, design of the in vitro circuit, materials used in the tubing and reservoir, pressure against which the pump operates, and differences in methods of determining plasma hemoglobin can each alter the hemolysis values attributed to a pump run. For these reasons, it seemed wise to obtain comparisons in a single laboratory under comparable conditions.

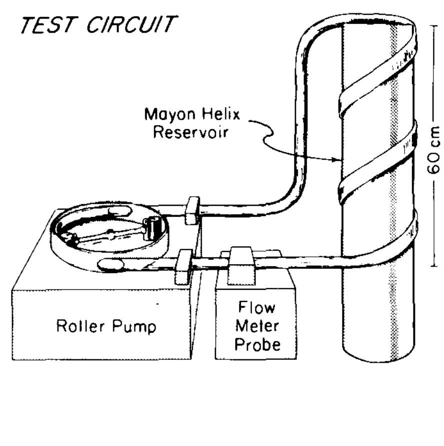
Both Stewart and Sturridge 11 and Kusserow and Kendall 12 have evaluated hemolysis using various tubing materials, and have considered the effects of shear stress and surface roughness upon hemolysis. Critical studies have recently been published by Blackshear 13 in which the importance of surface or wall interaction as the dominant factor in such systems is clearly implied. The effect of rapidly varying positive pressures upon blood was demonstrated to be negligible; shear stress effects were attributed to increased lateral movement of cells to the surface or wall, the postulated site of damage. Occlusion appears to be one of the important factors in surface-induced damage. The physical and chemical properties of tubing used as conduits in extracorporeal systems and the presence of occlusion, or repeated surface contact, in pumping systems therefore has a direct and significant practical value in the selection of extracorporeal circuitry for clinical use.

In recent years, the roller pump has won increasing clinical popularity. Refinements in pump design and construction presently permit spring-loading and accurate occlusive settings, monitoring flow rates with electromagnetic flow meters, gear take-up devices, 14 and the use of varying tubing materials. It therefore appeared appropriate to re-evaluate the contributions of occlusion, tubing material, pump design and construction, flow rate and duration of the test period, to the amount of blood destruction observed following exposure to a roller pump circuit. Additional mechanical considerations in roller pump construction which may effect hemolysis include the radius of the roller, the number of rollers, roller and race geometry and speed, and the stiffness and elasticity of the tubing compressed by the rollers.

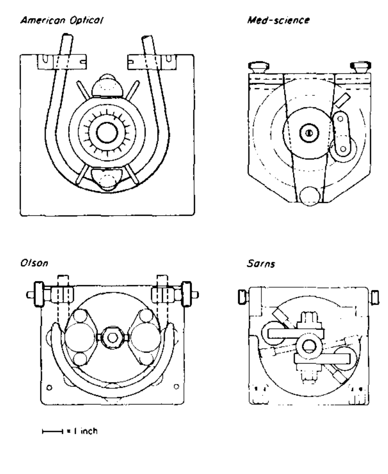
Galleti, 15 and Kusserow, 16 and the present authors 17 have described the phenomenon of "sub-lethal" red blood cell damage. This evidence suggests that while hemolysis (which measures total red blood cell destruction) may concern only a small percentage of those cells exposed to a pumping system, there are significant injuries to many cells. This damage is manifested by a shortened RBC survival time, increased autohemolysis and aerobic metabolism, and membrane structural alterations. Immediate hemolysis, however, still appears to be an important index of damage to red cells and is simpler to determine. Immediate hemolysis, therefore, has been used as the criterion of blood damage in these studies, but these data must be considered only an indication of the total damage sustained by the traumatized blood samples.

B. MATERIALS AND METHODS

1. In Vitro testing circuit. The test circuit employed in these studies



Comparative Geometry of Roller Pump Heads



is illustrated in Figure 1. It consisted of a roller pump with 3/8 inch I. D. and 1/2 inch O. D. tubing set to pump to a height of 60 cm., where the blood was transferred to a 1 inch I. D., 72 inch long, Mayon helix reservoir. Before re-entering the pump from the reservoir, the blood passed through an electromagnetic flow probe.* All studies were run at room temperature, on 600 cc. of fresh sterile canine blood with a hematocrit over 35, drawn from the femoral artery (on the day of the experiment) into acid-citrate-dextrose in plastic bags. Donor animals were lightly anesthetized with Surital, and were not fasted, except for the experiments in which this is specifically mentioned.

The pump circuit was thoroughly washed with water and detergent at the end of each study, and was always rinsed with isotonic saline solution prior to the introduction of blood. After three to five minutes of pumping in the test circuit, to permit good mixing, the initial or control plasma hemoglobin samples in each study was obtained.

2. **Plasma hemoglobin** was measured with the technique of Fling and Watson. 18

3. **Calculation of Index of Hemolysis.** The expression of Index of Hemolysis, as introduced by Allen in 1958, 10 has been used to compare damage to blood under varying circumstances. It is defined as the number of grams of hemoglobin liberated per 100 liters of blood pumped, and takes into account the priming volume, flow rate and duration of pumping.

4. **Experimental variations.** Four roller pumps have been studied. The IMICO pump (Fig. 2) was the American Optical Company, Catalog No. 10-500 Single Precision pump, with a 6 inch diameter race, a 200° arc of the tube compression, with two 3/4 inch diameter rollers, in a self-contained cabinet.** The Med-Science was a single 360° roller unit mounted on a console frame* as specifically modified from the Mayo design by Levy. This pump was factory-set to be precisely occlusive to pressures up to 350 mm Hg. when used with the silastic tubing supplied. Therefore, non-occlusive experiments were not run with this model, and only the special silastic tubing supplied was tested in it. The Olson pumps (Cat. No. 601-57) were part of a console unit, and were characterized by a 5 inch diameter race, a 180° occlusion arc, and two 1 1/2 inch rollers.**The Sarns Model 3500 pump*** had a 6-inch diameter race, two 1 1/8 inch diameter rollers, a custom pumping head, and a 180° roller occlusion arc (Table 1).

TABLE I

GEOMETRIC CHARACTERISTICS OF THE FOUR ROLLER PUMPS STUDIED

Pump	Race Diameter (In.)	No. of Rollers	Diameter of rollers (In.)	Arc of Roller Occlusion(°)
IMICO	6	2	3/4	200°
Olson	5	2	1 1/2	180°
Med-Science	5 1/2	1	1 1/4	360°
Sarns	6	2	1 1/8	180°

Three different tubing materials (3/8 inch I.D. and 1/2 inch O.D.) were used with these roller pumps. Most of the studies were performed with Tygon (polyvinyl chloride) Formulation S-50-HL.**** In some studies, the Tygon was coated with graphite, benzalkonium and heparin (GBH), as introduced by Gott 19 for prosthetic aortic values. This GBH coating reportedly inhibits clotting, and repels formed and protein particles because of increased electronegativity. The rate of hemolysis with this altered tubing surface was determined in the presence of adequately anticoagulated blood (ACD). In addition, tubing of Dow Corning Medical Gradle Silastic and of latex rubber was evaluated.

A non-occlusive setting of the roller pump permitted a 60 cm. column of blood to fall approximately 2 cm. in 5 seconds with the pump rollers stationary. An occlusive setting was obtained by gradually tightenig the rollers to the point where a 60 cm. column of blood was supported indefinitely.

Unless other criteria are specified, the flow rate used was 2 liters per minute and the duration of the experiments was 2 hours. Control samples were taken after 3 to 5 minutes of pumping and then every 30 minutes. In the 24 hour experiments, all surfaces in contact with blood were heat or gas sterilized prior to the experiment, antibiotics* were added to the blood, and every effort was made to preserve sterility. Blood samples obtained at the end of these experiments were cultured for aerobic and anaerobic organisms. Only experiments yielding sterile cultures at the end of the 24 hour run have been included.

C. RESULTS

For comparison, a number of pumps of other than roller types have been evaluated in our laboratory under the same conditions. The results of these studies are presented in Table II. The Sigmamotor TM-2 is a finger pump of the type used at this institution for more than ten years and in over 2,000 cases of clinical extracorporeal circulation. The Army Heart Pump 20 utilizes a silastic ventricle with a fluid amplification control system, and has been studied with

* Medicon E-3000

** Generously supplied by the Medical Division, American Optical Company Chelsea, Massachusetts.

* Med-Science Electronics, St. Louis 3, Missouri.

** Edward A. Olson Co., Inc., Ashland, Massachusetts

*** Generously supplied by Sarns, Inc., Ann Arbor, Michigan

**** U.S. Stoneware Co., Akron, Ohio

* Penicillin G, Potassium, E. R. Squibb and Sons 5,000,000 U.

ball, flap and tricuspid valves.** The Dorman Ventricle is a train of three pneumatically controlled silastic ventricles: the two end chambers act as valves and the central one is the pumping chamber. Bluemle's Triple Ventricle Pump*** was designed for use with an artificial kidney circuit and consists of three mechanically compressed silastic ventricles in parallel, with inlet and oltlet ball valves. The cam pump was a mechanically compressed silastic ventricle with butterfly valves. The Ormonde-Mono B03 heart-lung pump was developed for extracorporeal circulation at the Great Ormonde Street Hospital in London 21 and is an archemedian screw type of pump without valves, and with only a single moving part —the rotor.**** As indicated in Table II, several of the ventricle pumps produced Indices of Hemolysis within the range of those obtained in the roller pump studies.

TABLE II

SUMMARY OF HEMOLYSIS STUDIES WITH FINGER, SCREW AND VENTRICLE PUMPS

Pump	Flow (L/M)	Mean I. H. *	No. Trials	Remarks
Sigmamotor TM-2 Finger	1.5	0.60	6	
Army Heart Pump[15]	2.0	0.09	3	Flap valves Silastic ventricle
Dorman Silastic Ventricle	2.0	0.13	5	Ventricle valves silastic throughout
Bluemle Triple Ventricle	2.0	0.09	3	Ball valves silastic ventricle
Mechanical Cam-driven Ventricle	2.0	0.82	5	Flap valves, silastic ventricle
Ormonde-Mono[16] Archemedian Screw	2.0	2.69	4	Stainless Steel

* Index of Hemolysis = grams of hemoglobin liberated per 100 L. pumped.

TABLE III

SUMMARY OF HEMOLYSIS DATA WITH FOUR ROLLER PUMPS AT 2 L/M FOR 2 HOURS

Pump	Tubing	Occlusive Mean I. H.	Occlusive No. Trials	Non-Occlusive Mean I. H.	Non-Occlusive No. Trials	Ratio (Occl./Non)
Olson	Tygon	0.08±0.026	4	0.02±0.008	7	4.0*
Med-Science	Silastic	0.04±0.006	4	----------		----
IMICO	Tygon	0.16±0.032	2	0.01±0.003	3	16.0*
Sarns	Silastic	0.04± .017	3	0.07± .045	6	0.7
Sarns	Tygon	0.26± .109	5	0.01± .008	3	26.0
Sarns	GBH-Tygon	0.49± .129	3	0.09± .028	4	5.4*
Sarns	Rubber	0.34± .061	3	0.18± .048	3	1.9

I. H. = Index of Hemolysis = grams of hemoglobin liberated per 100 L. pumped (± S. E.)

* P value of the difference between occlusive and non-occlusive less than .05.

Comparison of roller pumps and tubing materials. Hemolysis data obtained with the four roller pumps studied, with various tubing materials, is presented in Table III. Several facts appear pertinent. With rubber, Tygon and GBH-coated Tygon tubing, there was considerably more hemolysis when the pump setting was occlusive, rather than non-occlusive. With Tygon, occlusive settings were from 4 to 26 times as damaging. Further, coating the Tygon tubing with GBH did not improve the tubing surface characteristics influencing hemolysis; even greater damage to the exposed red blood cells resulted in both occlusive and non-occlusive trials.

In both pumps in which silastic tubing was employed, the Indices of Hemolysis at occlusive settings were lower than with any other tubing material. In the Sarns pump, in which both occlusive and non-occlusive runs were performed with silastic tubing, occlusive settings actually produced a somewhat lower I. H. The Med Science pump was factory set for occlusion with silastic tubing; therefore, no non-occlusive studies were performed.

The effect of varying flow rates was determined for two pumps (Table IV). With the Sarns roller pump, identical trials were run with flow rates of 2 and 6 liters per minute; the result were not significantly different. A similar study was done with Bluemle silastic triple ventricle, where flow rates of 0. 9 and 3. 0 liters per minute were employed; again, the results were not significantly different. These data tend to validate the use of the Index of Hemolysis as a sound, comparable measure of pump-induced damage, despie variation in flow rates.

TABLE IV

EFFECT OF FLOW RATE ON INDEX OF HEMOLYSIS

	Flow Rate* (L/M)	No. Trials	I. H **
1. Sarns Model 3500 Roller Pump	2.0	3	0.18
Latex rubber tubing; Non-occlusive setting	6.0	3	0.20
2. Bluemle Silastic	0.3	3	0.07
Triple Ventricle	2.0	3	0.09

* Duration of each experiment was 2 hours.

** I. H. = Index of Hemolysis = grams of hemoglobin liberated per 100 L. pumped.

The effect of longer periods of pumping also was evaluated (Table V). Both the IMICO roller pump and the Bluemle silastic triple ventricle were run for 24 hours under sterile conditions. With the Bluemle runs, additional control blood samples were maintained in sterile containers at the same temperature without pumping, to determine the rate of "spontaneous hemolysis". Plasma hemoglobin levels did not increase in these unpumped samples. These results also tend to confirm the gross validity of the Index of Hemolysis as a characterization of pump-induced damage, although the average values for the 24 hour runs in both studies were lower than those obtained in 2 hour trials.

TABLE V

EFFECT OF DURATION OF TEST ON HEMOLYSIS

Pump	Flow Rate L/M	Duration (Hours)	No. Trials	I. H. *
Bluemle Triple Ventricle Tygon Tubing	2	2	3	0.09
	2	24	3	0.04
Control Sample (No flow)	0	24	3	0.00
IMICO Pump Tygon Tubing	2	2	3	0.01
	2	24	1	0.004

* Index of Hemolysis = grams of hemoglobin liberated per 100 L. pumped.

D. DISCUSSION

While factors such as fat emboli, 22, 23 high pressure suction, 24 exposure to pericardial fat 25 and blood gas interface in oxygenators and reservoirs 26 play major roles in the total amount of hemolysis produced during open heart surgery, the continuing development of techniques for the prolonged use of pumping systems for partial bypass and assisted circulation has again focused the attention of the cardiovascular surgeon on the pump and blood conduits. When more proloned perfusions are undertaken, the tolerance of the animal to chronic blood destruction may be approached or even surpassed. 17, 27, 28.

In these experiments, canine blood was circulated through tubing systems with identical dimensions and surface areas. The flow rate, and therefore the average velocity of the flowing blood, was kept constant. The major differences in the test systems were, therefore, in the mechanical and chemical properties of the four materials tested, and in the detailed geometry of the rollers, the number of rollers, the length of the arc of roller occlusion, and the radius of the pump heads.

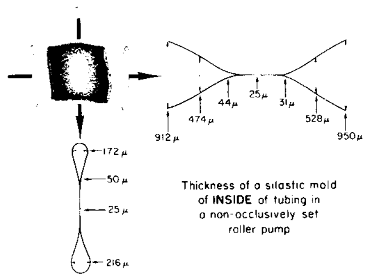
** Made available through the courtesy of Mr. Kenneth Woodward, Harry Diamond Laboratories, Wash., D.C.

*** Made available for these studies by Dr. Lewis W. Bluemle, Jr., Hospital of the University of Pennsylvania, Pittsburg

****Obtained from Mono Pumps Limited, London, England

The difference between barely non-occlusive and just occlusive pump settings appeared to be a major factor in pump-induced hemolysis in these studies, confirming the report of Blackshear. 13 Changing the settings to an occlusive position increased hemolysis due to the entire circuit from 4 to 26 times with Tygon tubing, and to a lesser degree with both GBH-coated Tygon and latex rubber. However, in the one pump in which both occlusive and non-occlusive settings were compared with silastic tubing, there was somewhat less hemolysis with complete occlusive. The explanations for these phenomena remain obscure, but the evidence appears to point strongly to the importance of the surface, and of wall surface interactions in the development of mechanically induced hemolysis.

To study the form and shape of a "non-occlusive" pump setting, a mold of the inside of uncoated Tygon tubing was prepared, after the pump head had been set non-occlusively, as described under "Methods". After the blood was drained, Dow Corning RTV 372 silastic was poured into the tubing and permitted to set in the pump over 48 hours. The tubing was then removed from the pump, split open, and the silastic mold removed. Measurements of the thickness of this mold at the area of maximum occlusion were performed first with a vernier micrometer, and then with the fine adjustment of a Bausch and Lomb microscpoe, at 100x, focusing at the top and bottom of the mold at various sites. The results are depicted in Figure 3, and



Thickness of a silastic mold of **INSIDE** of tubing in a non-occlusively set roller pump

demonstrate a minimal channel of 25 microns through the central portion of the compressed tubing, with significantly wider spaces at the ends (172 to 216 microns). These data indicate the significant absence of occulsion of any portion of the opposing tubing surfaces when the pump has been set non-occlusively, by the method described.

The data in Table III, which is summarized in Table IV, indicates a considerable increase in roller pump-induced hemolysis when occlusive settings are compared to non-occlusive ones. In three such comparisons, the P values are less than 0.5 (Table IV), and a scan of the data (Table III) indicates the general lack of overlapping data points, except for silastic tubing. This lack of overlapping data points true for all experiments with GBH-coated Tygon and latex rubber. Such lack of overlap implies more significance than the widely spread data indicates upon conventional analysis. The harmful effects of repeated occlusions therefore appears to outweigh the damage associated with incompetence and blood regurgitating at high velocity through the thin non-occlusive space. These data are in agreement with those of McCaughan, 1 and Head. 5

It is worthy of note that the only mechanical factor listed in Table I which could be correlated with hemolysis rate is the race diameter - in comparing the three pumps in which polyvinyl chloride tubing was emplayed. Under occlusive conditions, the Olson pump, with a 5 inch race, produced less hemolysis (IH .08) than either the IMICO (IH .16) or Sarns (IH . 26), both of which have a 6 inch race.

Roller diameter or arc could not be correlated with hemolysis. The number of rollers did not appear to effect hemolysis either; a single roller with a 360° arc is likely to be, and proved to be, the equivalent of two rollers, each with a 180° arc.

The effect of occlusion on the four tubing materials tested was somewhat surprising. With all but silastic, occlusion resulted in a considerable increase in hemolysis. With silastic, little difference was noted - and an actual decrease in hemolysis was recorded. Such differences must be ascribed to chemical or physical aspects of the materials. Stiffness, elasticity, surface roughness and wettability are some of the tubing properties which may be involved and should be studied. The damage due to occlusion may also be a result of turbulent flow created in front of the roller, or the negative pressure area just behind the advancing roller. The present data suggest that the small leak present with a barely non-occlusive setting is not harmful under the conditions of our experiments, but do not necessarily imply that larger leaks, associated with greater degrees of roller incompetence, would be as benign.

It was of considerable interest that the coating of polyvinyl with graphite benzalkonium and heparin (GBH), which has been demonstrated to inhibit clotting markedly and to increase surface electronegativity, failed to reduce surface damage. In fact, the measured in vitro hemolysis was approximately twice as great in the series of Tygon tests in which this coating was employed. The important change in the polyvinyl surface due to GBH coating may be an increase in surface roughness, since it would appear unlikely that the presence of a heparin lining would be chemically harmful to red clood cells. Latex rubber, which proved to be the most hemolytic material, was grossly the roughest of the materials tested.

E. CONCLUSIONS

The data in this study appear to permit several conclusions:

1) Additional evidence has been presented to justify using the concept of the Index of Hemolysis to characterize the immediate blood damaging capacity of pumps of various types, using varying flow rates and varying durations of pumping.

2) Of the materials tested, silastic appears to be the best presently available surface for conduit tubing

with a roller pump. Further, it would appear that silastic tubing may be used in a roller pump with occlusive settings without the additional damage observed with other materials.

3) Occlusive pump settings resulted in considerably higher rates of hemolysis than the non-occlusive settings with all materials tested, except silastic.

4) The use of GBH coating on polyvinyl chloride tubing did not decrease, and in fact increased, the immediate hemolysis observed with polyvinyl tubing.

5) The importance of the physical and chemical nature of the surface of materials in contact with blood in causing blood cellular destruction is emphasized and further work in this area is suggested. Mechanical and geometric considerations of pump rollers and tubing stiffness and elasticity may also be important contributing factors.

BIBLOGRAPHY

1. McCaughan. J. S., Jr., McMichals, H., Schuder, J. C. and Kirby, C. K.: Use of a Total Occlusive pump as a Flowmeter with Observations on Hemolysis Caused by Occlusive and Non-Occlusive Pump-Oxygenator Components. Surgery, 44:210, 1957.

2. Hodges, P. C., Cardozo, R., Thevenet A., and Lillehei, C. W.: Comparison of Relative Merits of Occlusive and Non-Occlusive Pumps for Open-Heart Surgery. J. Thoracic Surg., 36:470, 1958.

3. Leonards, J. R., and Ankeney, J. L.: Completely Occlusive Non-Hemolytic Roller Tubing Blood Pump. Trnas. Amer. Soc. for Ortif. Int. Organs., 4:69, 1958.

4. Cahill,J . J., and Kolff, W. J.: Hemolysis Caused by Pumps in Extracorporeal Circulation. J. Appl. Physiol., 14:1039, 1959.

5. Head, L R., Coenen, J. P., Angola, E., Nogueira, C., Mendelsohn, D. and Kay, E. B.: Operation of Roller Pump for Extracorporeal Circulation. J. Thoracic and Cardiovasc. Surg., 39:210, 1960.

6. Brown, F., Seidel, W., and Kolff, W. J.: Hemolysis Caused by Pumps at Flow Rates of 2 liters. Trans. Am. Soc. Artif. Int. Organs. 7:350, 1961.

7. Esmond, W. G., Attar, S., Baker, B., Chyba, J., Demetriades, A.D. and Cowley, R. A.: An Improved 360° Single Roller Spring Loaded Blood Pump. Trans. Am. Soc. Artif. Int. Organs., 7:167, 1961.

8. Cappelletti, R. R., Domingo, R. T., Dennis, C., Amer, N. S. and Stuckey, J. H.: Controlled Studies in Three Pumping Systems. Trans. Am. Soc. Artif. Int. Organs., 7:162, 1961.

9. Cappelletti, R. R., Domingo, R. T., Dennis, C., Amer, N. S. and Stuckey, J. H.: Studies of Plasma Hemoglobin Formation in Three Pumping Systems Used in Extracorporeal Circulation. Ann. Surg., 156:50, 1962.

10. Allen, J. G.: Extracorporeal Circulation. Spring field, Ill., Charles C. Thomas, 1958, p. 515.

11. Stewart, J. W. and Sturridge, M. D.: Hemolysis Caused by Tubing in Extracorporeal Circulation. Lancet, 1:340, 1959.

12. Kusserow, B. K. and Kendall, L. W.: In Vitro Changes in the Corpuscular Elements of Blood Flowing in Tubular Conduits. Trans. Am. Soc. Artif. Int. Organs, 9:262, 1963.

13. Blackshear, P. L., Jr., Dorman, F. D Effects that Influence Hemolysis. Trans. and Steinbach, J. H.: Some Mechanical Am. Soc. Artif. Int. Organs, 11:112, 1965.

14. Domingo, R. T., Grosz, C., Cappelletti, R. R., Dennis, C. and Wesolowski, S. A.: Gear Take-up Heart Pump: Avoidance of Internal Shear Stresses, Trans. Am. Soc. Artif. Int. Organs, 9:275, 1963.

15. Galletti, P.: Laboratory Experience with 24-hour Partial Heart-Lung Bypass. J. Surg. Res., 5:97, 1965.

16. Kusserow, B. K., Machanic, B., Collins, F. M., Jr., and Clapp III, J. F.: Changes Observed in Blood Corpuscles After Prolonged Perfusions with Two types of Blood Pumps. Trans. Am. Soc. Artif. Int. Organs. 11:122, 1965.

17. Bernstein, E. F., Castaneda, A. R. and Varco, R. L.: Some Biologic Limitations to Prolonged Blood Pumping. Trans. Am. Soc. Artif. Int. Organs 11:118, 1965.

18. Fling, E. B. and Watson, C. J.: A Method for the Quantitative Determinations of Hemoglobin and Related Heme Pigments in Feces, Urine and Blood Plasma. J. Biol. Chem., 146:171, 1942.

19. Gott, V. L., Whiffen, J. D., Koepke. D. E., Boake, W. C. and Young, W. P.: Techniques of Applying a Graphite-Benzalkonium Heparin Coating to Variour Plastics and Metals. Trans. Am. Soc. Artif. Int. Organs. 10:213, 1964.

20. Barila, T E., Nunn, D. B., and Woodward, K. E.: A Blood Pump Powered and Controlled by a Fluid Amplification System. Trans. Am. Soc. Artif. Int. Organs. 8:30, 1962.

21. Hall, J. E., James, P. A., Lucas, B. G. B. and Watsron, D. J.: A Pump for Extracorporeal Circulation. Lancet, 276:-347, 1959.

22. Owens, G. Adams, J. E., McElhannon, F. M. and Youngblood, R. W.: Experimental Alterations of Certain Colloidal Properties of Blood During Cardiopulmonary Bypass. J. Appl. Physiology., 14:947, 1959.

23. Wright, E. S., Sarkozy, E., Dobell, A.| R. C. and Murphy, D. R.: Fat Globulinemia in Extracorporeal Circulation. Surgery, 53:500, 1963.

24. Osborn, J. J., Chon, K., Hait, M., Russi, M., Salel, A., Harkins G. and Gerbode, F.: Hemolysis During Perfusion, Sources and Means of Reduction. J. Thoracic and C-V Surg., 43:459, 1962.

25. Morris, K. N., Kinross, F. M. and Stirling, G. R.: Hemolysis of Blood in the Pericardium: The Major Source of Plasma Hemoglobin During Total Body Perfusion. J. Thoracic and C-V Surg., 49:250, 1965.

26. Lee, W. H., Jr., Krumbaar, D., Fonalsrude, E. W., Schjeide, O. A. and Maloney, J. V., Jr.: Denaturation of Plasma Proteins as a Cause of Morbidity and Death after Intracardiac Operations. Surgery, 50:-29, 1961.

27. Castaneda, A. R., Bernsein, E. F. and Varco, R. L.: Tolerance to Chronic Hemolysis. Surg. Forum, 15:84, 1964.

28. Bernstein, E. F. and Varco, R. L.: Tolerance to Chronic Blood Loss. Surg. Forum, 16:25, 1965.

LEGENDS

FIGURE 1—Diagram of in vitro testing circuit used for testing pump and tubing induced hemolysis.

FIGURE 2—Sketches of the four roller pump heads tested, drawn to the same scale, and modified from those supplied by the manufacturere.

FIGURE 3—Sketch and dimensions of a silastic mold of the inside of a Tygon tube compressed by a roller in the "non-occlusive" position, as defined in the text. Note the absence of occlusion of the opposed tubing surfaces, and the wider path at the ends of the compressed section.