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WORK ACCOMPLISHED BY HEMODYNAMICS RESEARCH, (1964-1965).

1. Early and Subsequent Preparation of Casts of Aortal Systems.

On 15 June 1964 Hemodynamics Research, Inc. undertook research under Office of Naval Research Contract 4484(00). This Project aimed at clarification of flow characteristics in the human aorta. As elaborated elsewhere, there is little or no information available concerning fluid dynamics in this system. Initially it was planned to construct an idealized "aorta" — a curved plastic tube with one or two branches — and to insert this model in a laminar flow system. However, after observing the major differences between such an idealized model and early casts we made of the actual aorta, it was obvious that differences were so many, and of such a large order of magnitude, that almost no test data on the idealized model could be transferable to the more complex model, nor would the test-experience gained with the simple model be of great value. It was our conclusion, after we had constructed the first

dozen or so reasonably exact aorta-casts, that little of the information gained from a mechanical mock-up of the aorta could be transferred to the project goal.

Research efforts of the first six months were, accordingly, devoted to testing various substances for an ideal material and technique with which to construct a precise duplicate of the lumen and inner walls of the animal aorta and its main branches. The aortic-arch system of the calf was selected for study because of its easy availability, and because the artery size and branching are approximately the same as those in man.

A critical problem centered around producing an exact cast of the normally-expanded aorta. This was first approached by using as a casting substance paraffin which had a melting point just above room temperature. Leakage of the paraffin, solidification in cool sections of the aorta and deformation of the cast while solid contributed to the difficulties. An additional difficulty that ruined many specimens, and created a multitude of disposal problems, was the necessity to perfuse artery systems with warmed kerosene prior to instillation of paraffin.

After discarding paraffin as a cast substance, aortas were filled with certain silicone potting compounds, but these proved fragile, and the material fractured easily. Certain liquid plastics were next utilized. Although they gave excellent reproduction of the interior of the aorta, they also posed insurmountable problems when attempts were made to remove them from the final aorta "skin," also plastic, which had been applied by dipping.

A substance which seemed to offer great promise initially, and with which fifteen complete aortal-system casts were made, was a fusible metal (Cerrolow 117). This very dense substance melts at 117° F., but at temperatures

and pressures commonly employed in cast preparation, the alloy freely enters lumina as small as 25 micra in diameter, and will reproduce smallest surface irregularities. The technique used was as follows:

Aortic-arch systems of freshly-killed calves were dissected out through the courtesy of a local meat-packing company. In the laboratory, heavy connective tissues were stripped away carefully, the large and small artery branches being carefully preserved. Specimens were placed in dilute ammonium hydroxide or were frozen, both of which processes produce permanent relaxation in the artery walls (early specimens, not so treated, contracted and became permanently "set" in abnormal shapes). The systems were perfused in hot water (50° C.), and all except the most minute artery branches tied off (each system possesses about 35 branches), producing a relatively water-tight system. Pressures were then induced on the water-filled system at the same levels as those normally present during life (the marked distensibility of the aorta is vividly demonstrated under these conditions). The system was then switched to nitrogen, the distended aorta partially immersed in plaster of paris, and the latter allowed to "set." The hardening plaster adhered to the wall of the aorta, maintaining its inflated contours. The specimen within its plaster mold, was then immersed in hot water, and filled with Cerrolow 117. The few remaining small exit holes in the plaster were successively plugged with modeling clay, and when the plaster-encased aorta system was filled with metal, the entire structure (block of plaster and model) was immersed in ice water. After refrigeration, plaster and aorta were stripped from the metal cast.

Although several Cerrolow metal casts were practically perfect reproductions of the lumina of the system, and faithfully mirrored the inner wall surfaces, a number of factors proved impractical to correct. Pouring temperatures were critical, as were those of the empty aortal system.

Production of cavities in the metal due to shrinkage upon solidification occurred in unpredictable fashion. Bubbles adhering to the wall of the aorta and branches were sometimes reproduced during solidification. Casts were so heavy that it was practically impossible to maintain normal curvatures of the aortal system during potting, yet after solidification the metal tended to "creep," especially at room temperatures, and the finished products, therefore, had to be kept under refrigeration. Finally models were sometimes unexpectedly fragile, and would fracture under sharp impact. Because of these problems, some of them insoluble, metal models were not made subsequent to January, 1965.

2. Artery wall duplication.

We have conducted a time-consuming search for the proper substance with which to form the wall of the aortal system. This material should ideally be liquid (in order to conform closely to small surface irregularities of the cast); capable of solidification at room temperatures; and have absolute transparency in final form. Other desirable characteristics include elasticity similar to that of the normal aorta, wall thickness approximately that of the animal organ, and good resistance to "fracturing." Silicones were given a trial (Silastic) and proved ideally elastic and resistant to handling, but could not be rendered sufficiently transparent to allow clear visualization of injected dye filaments. A U. S. Rubber product of similar type was discarded for identical reasons. Coating of the casts with potting compounds, on the other hand, resulted in an unfortunate tendency to milkiess with slight variations in humidity and room temperature. Attempts were made to correct this with a hot air blower, but this produced heaping-up of plastic on the cast. Since adequate drying apparently necessitated a baking oven

the explosive nature of the mixture became a formidable problem.

Attention was next directed to various kinds of plastics. We believed we had found the answer to our problem. In collaboration with Mr. Richard Merkel of the Plastics Laboratory, Allied Chemical Corp., we managed to prepare several clear, fairly-resilient models, and it appeared that slight variations in proportions of additives would secure the desired elasticity. Metal casts were dipped 50 to 70 times, in a variety of trial solutions, allowing three hours drying time between immersions, and finally a solution composed of 100 parts polyvinylchloride resin (Dow 133-4), 80 parts Plasticizer (Elastex 28-P, Allied Chemical), and 1600 parts methylethyleketone selected as superior for our needs. We have coated a number of casts with this solution, with promising results.

Walls are transparent, and highly elastic, but the method of casting is very time-consuming. It is probable that we will use somewhat similar preparation, perhaps applied with spray gun, for manufacture of our elastic models, and we will continue experiments along this line while initial flow-studies through the rigid model (see under D) are being conducted.

3. Present Status of Model Construction.

Beginning in January, 1965, all aorta-system castings have been produced using a silicone rubber (Silastic RTV 502). Most of the problems associated with casting substances we had previously tried (shrinkage, great weight, production of cavities, fragility, creeping) were remarkable by their absence. The first half-dozen specimens filled with this silicone were prepared in our customary fashion, i.e., by removal from the animal, dissection in the laboratory after freezing or immersion in NH_4OH , and after tedious ligation of all branches exiting from the system. The

silicone was then injected under nitrogen pressure.

Several considerations led us, at this encouraging stage of investigation, to attempt further refinement of our experimental approach. We had been somewhat concerned by the fact that the aortal system, as present in the intact animal, possessed somewhat complex curvatures which undoubtedly were dependent upon adjoining body organ structures, in fact, the aorta was obviously supported and tethered by these tissues. These tissue relationships, of course, were destroyed when the aorta and its components were removed from the cadaver. In addition, we had noted that several major arteries (the renals, for example) were quite fragile, and sometimes torn during dissection, despite the fact that this was done, at the packing house, under bright lights and magnification. Small arteries, measuring less than a millimeter in diameter, were frequently inadvertently torn out of the aortic wall during subsequent dissection at the laboratory.

It seemed obvious that an ideal solution was preparation of the cast while the aorta was undisturbed and before any of its components had been dissected. Accordingly, we obtained a pressure gun capable of handling large cartridges of silicone and attached it to a portable (lecture bottle) source of nitrogen. Only the terminal parts of the aorta branches were identified by dissection and clamped off with hemostats. Injection of silicone was then accomplished at the iliac bifurcation, and the entire aorta, all branches (and the coronary system in its entirety) filled in retrograde fashion. Setting of this viscous substance is usually complete at ten minutes, and removal of the entire system is then safe, for the cast, though remarkably resilient, will retain a permanent set. The silicone has been

found to faithfully follow all intra-arterial contours, and we have now produced a dozen models which precisely reproduce the lumina of the entire aorta and its major and minor subdivisions.

A number of heretofore unpublished observations have been made in the course of this work. First, and possibly most important from the standpoint of fluid dynamics, it has been noted that the mouths of the segmentally distributed arteries leaving the aorta in the thoracic region are elliptical in shape, with the long axis oriented transverse to the direction of flow, and that proximally, for varying distances, a gradually deepening trough leads to each orifice. The effect of such an arrangement in "bleeding off" turbulence will prove a highly-interesting aspect of model testing. Another observation of as yet unknown significance relates to the relative constriction of the orifices of many of these same arteries, in comparison with their diameters distally. A third curious conformation, with undoubted direct influence on fluid flow, took the form of slightly decreased diameter of the ascending aorta proximal to the point of junction of the ductus arteriosus, and relative enlargement of the descending aorta. These unexpected findings are a direct result of our ability now to reproduce exactly, under physiological pressure, in the intact animal, a cast of the aorta system which faithfully mirrors its functioning condition during life.

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13. ABSTRACT Using a pressure gun and cartridges of liquid silicone, the aortal systems of freshly-killed calves were injected under physiological pressures. The injected material attained a permanent set within minutes, allowing dissection and removal of the entire system. Artery walls were removed by corrosion. The resultant casts -- the first precise geometric models of the animal aortal system -- showed a number of heretofore unpublished characteristics, i.e., the orifices of segmentally distributed arteries are elliptical in shape with rostral, gradually deepening troughs. The aorta itself shows a characteristic distortion at the junction of the previously existent ductus arteriosus. The influence of these peculiarities upon blood flow within the system is at present being investigated.		

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casts	6	10				
silicone	10	9				
paraffin	3	0				
Cerrolow 117	3	0				
artery orientation	10	10				
laminar flow	10	3				

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