Construction and characterization of branched, elastic, transparent vessel models

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MELBIN, JULIUS, RAMALINGIER GOPALAKRISHNAN, ROBERT RIFFLE, AND ABRAHAM NOORDERGRAAF. *Construction and characterization of branched, elastic, transparent vessel models.* Am. J. Physiol. 242 (Heart Circ. Physiol. 11): H122–H126, 1982.—A technique is presented for the construction of compliant branched vessel models. Properties include wall transparency and geometric reproduction to any scale. A method for characterization of vessel compliance is discussed, as is the requirement for hydrodynamic similarity.

scaled models; flow visualization

PHYSICAL MODELS are useful to evaluate theoretical models, to visualize events, and to identify contributors to flow and stresses that may be obscured in complex in vivo circumstances.

Vascular models reported in the literature include Tygon, cellophane, and acrylic for studies of sound production (8); perspex with Y-shaped branches (3); acrylic curved bifurcating models, which mimic the aortic arch (13) for flow studies; a polyester arterial cast for studies of wall shear (6); and thin rubber sheets clamped between plastic blocks (4), etc. We have, however, been unable to locate a technique that would provide, in one physical model, wall transparency, geometric duplication (branching), and hydrodynamic similarity as a consequence of compliant, inertial, and frictional properties of the fluid-filled system.

Our interest, centered about the major pulmonary vessels, made the compromise of any of these features undesirable (9). Here we report both a construction technique that enables inclusion of these features and a method to characterize the load response of the completed vessel.

METHODS

A cast of the vessel to be modeled is required. Because it is often advantageous to work with large models and to reduce perturbations introduced by probes while improving resolution and visualization, the initial cast provides dimensions for a scaled-up clay model. Otherwise the initial cast serves as the final master model. If a scaled-up model is desired, a clay model is used to construct the mold from which an epoxy master model is cast. This latter can be utilized repeatedly to construct molds from which alloy or wax models can be cast. The model vessel is formed by coating these alloy or wax models with elastomers.

Initial cast. An initial cast (or other construction) representing the vascular section may be made from a low-melting-point alloy such as gallium or Wood's metal (7). Such materials are advantageous if the cast serves but once and a scaled-up model is not desired. Alternatively, permanent casts can be made by use of a variety of available materials. The model described here was scaled three times larger than the original unloaded dimensions, and the initial cast, which served to provide relative dimensions for the scaled-up clay model, was made from calf pulmonary vessels with dental acrylic (methyl methacrylate, L. D. Caulk, Milford, DE).

Injection or casting pressures depend on the material utilized and the vessels to be cast. In the case of our main pulmonary vessel, a low casting pressure was required to retain the feature of its unstressed elliptic cross-section. Thus the acrylic cast was made under a head equivalent to 1 cmH_2O. Individual decisions and some trials are usually necessary.

Scaled-up templates are made by using dimensions obtained from the initial cast; these guide accurate construction of the clay model. The clay model is coated thinly with petroleum jelly and a mold constructed by thickly coating (approx 1 cm) the model with silicone sealant (790 Building Sealant, Dow Corning, Midland, MI). After setting for 48 h, the mold is cut axially, permitting mold removal in two halves; no attempt is made to salvage the clay model.

The two halves of the mold are lightly coated with petroleum jelly, approximated, and held together by rubber bands. The mold is then positioned to facilitate pouring of the casting material. If complex branching exists, small openings at the tips of the branches are necessary to allow air to escape; this is conveniently accomplished with hypodermic needles. The permanent

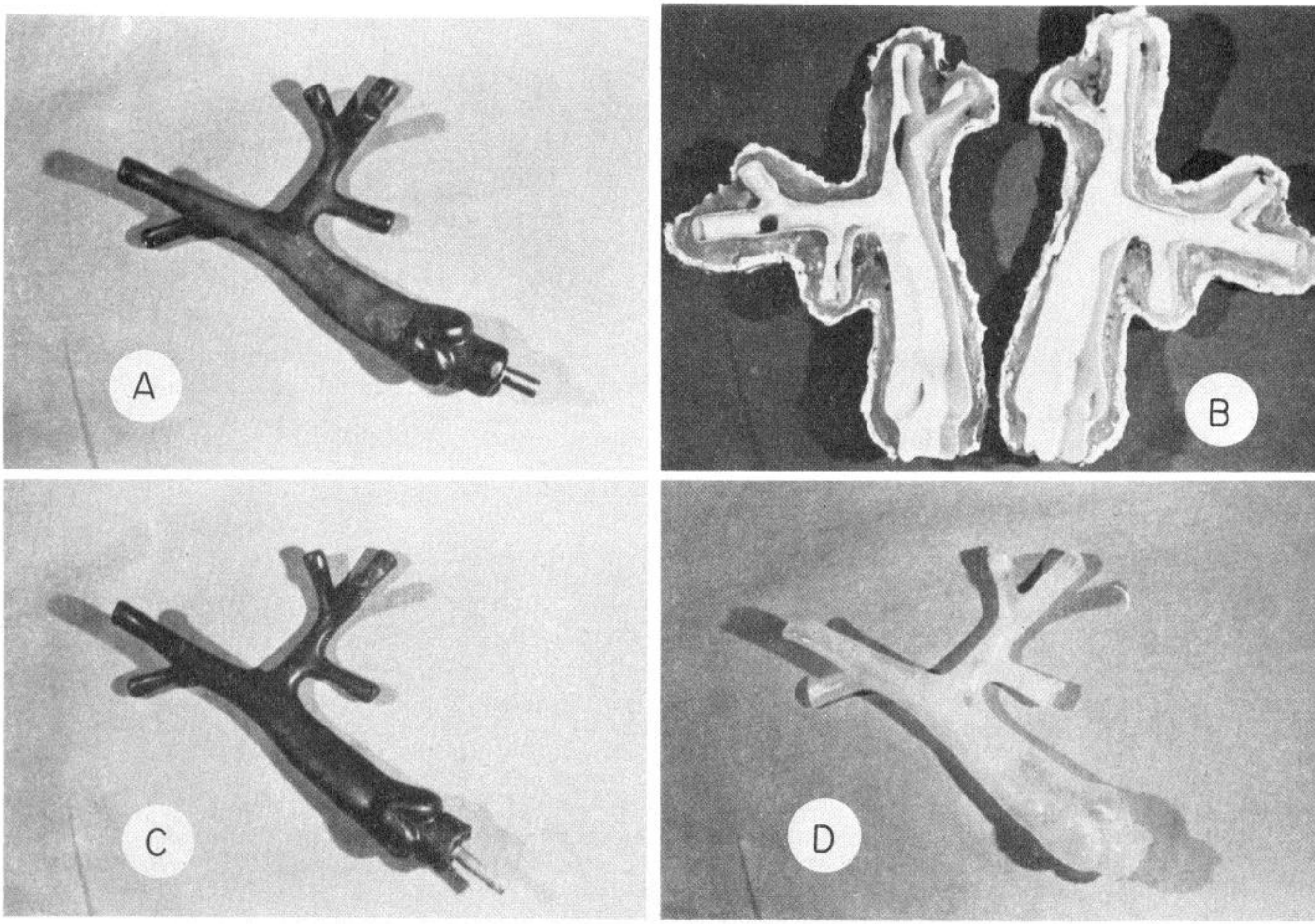

FIG. 1. *A*: final epoxy model of pulmonary vessels. *B*: open mold for the wax cast. *C*: completed wax cast. *D*: completed model vessel.

face irregularities and strength and multiple-use requirements, clay models are not suitable for this purpose.

Final mold. The epoxy cast is positioned horizontally by its shaft in the chuck of a controlled speed drill or similar device that permits slow rotation. The epoxy cast is first coated thinly with petroleum jelly, RTV molding compound (GE RTV 811, General Electric, Waterford, NY) is applied, and the cast is rotated at low speed until the coating is set up but has not completely cured. A second coat is applied and allowed to set up. The RTV compound is then thickly coated with silicone sealant, as for the initial cast. The RTV base provides the smooth inner surface for the next casting procedure. The mold is removed after cutting axially, as described above. An open mold is shown in Fig. 1*B*.

Wax or alloy cast. The inside of the mold is coated with a thin coat of tincture of green soap, and the halves are fitted together and held with rubber bands. The seams are then completely sealed with a coat of silicone sealant.

The mold is positioned, as previously, open end up with hypodermic needles in the branch tips. Microcrystalline wax (Stevenson Bros., Philadelphia, PA) is heated in a double boiler (note that ordinary wax is too brittle and that microcrystalline wax generates toxic fumes so that proper ventilation is necessary). The melted wax is poured into the mold and a shaft inserted into the open end, as was done for the epoxy cast. The mold is removed by cutting along the seams after the wax has hardened.

Seams are shaved with a scalpel, and final smoothing is accomplished with a sponge moistened with toluene. A completed wax cast is illustrated in Fig. 1*C*.

Excellent cast quality can also be obtained with one of many low-melting–point alloys. Indalloy-158 (Indium, Utica, NY), an alloy of Sn, Bi, Pb, Cd, for example, is a eutectic material that melts sharply at 158°F, expands slightly during cooling, is easily handled, and polishes readily. The material forms a strong cast and is reusable for subsequent casts. Its advantages are offset by its considerably greater weight. Again, inhalation of fumes or dust particles should be avoided.

Transparent vessel. The vessel is constructed of the elastomer Sylgard (184, Dow Corning, Midland, MI). This is a clear, high-viscosity liquid that cures slowly at room temperature. Curing may be accelerated (with some compromise of wall strength) with additional heat and with a chemical accelerator (QCF 3-6559, Dow Corning) (1–3%) added to the Sylgard. Being a high polymer, the surface is self-smoothing, resulting in a product that is a clear, strong, elastic vessel that does not absorb water, does not deteriorate in air, exhibits no birefringence, and withstands temperatures to 150°C. Where higher tensile strength is desired, another elastomer (MDX 4-4210, Dow Corning) is added to the Sylgard (10% by wt) with only slight compromise of wall transparency.

A 10-g batch of Sylgard is prepared for each application. The wax cast is positioned like the final mold, and as the cast slowly rotates thin coats are applied with a fine soft-bristled brush. An infra-red heat lamp (250 W) is positioned 30–40 cm from the cast. One coat per day can be applied, and a number of coats may be necessary to achieve the desired thickness. Wall thickness as well as uniformity can be controlled via measurements referenced to the original dimensions. Coating a dummy cylinder along with the vessel also aids thickness determinations, as this cylinder can be cut transversely for direct periodic measurements. In the case of the vessel illustrated herein, a wall thickness of 2 mm required 20 coats. Thin coats must be applied to avoid surface flow and buildup at susceptible sites. Wall thickness enters into the character of the vessel-loading response and is considered in the following section.

After the cast is completed the wax cast and vessel are positioned with the shaft (vessel open end) down. The system is heated with heat lamps or hot air blower to about 120°C to melt out the wax. A completed model is illustrated in Fig. 1*D*.

Vessel characterization. If the vascular cross-section is noncircular or mechanical restraints are imposed, whole-vessel-load response may not be determinable from wall samples or from simple expressions such as the elastic modulus based on Love's (1892) derivation for the circular cylindrical tube (2). A number of techniques for determining the viscoelastic properties of vessels appear in the literature (12). Described herein is a technique that provided whole-vessel-load response for the Sylgard model.

It should be noted that these models are not intended to mimic the elastic wall properties of the original vessel, but rather to provide a load response that allows hydrodynamic similarity to be achieved (vide infra).

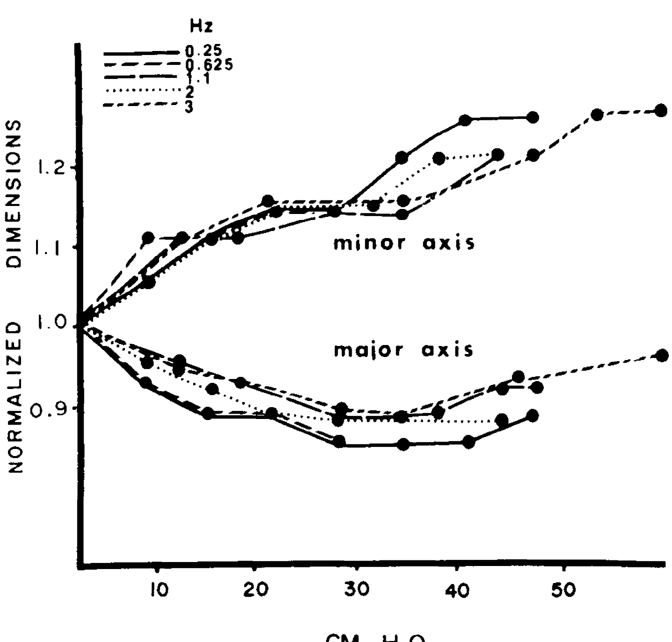

FIG. 2. Major and minor model vessel axes as a function of pressure over a range of loading frequencies. Lack of progressive dispersion of the plots as a function of frequency indicates that behavior was predominantly elastic in this range.

The vessel model was positioned in front of a mirror, angled such that both major and minor axes could be observed simultaneously. A pressure transducer (Millar) was inserted via a branch and positioned at the plane of interest. All branches were stoppered, and the open end was connected to a reciprocating air pump operating in harmonic motion at different frequencies. The pressure was displayed on a calibrated oscilloscope placed above the vessel such that both vessel axes and the pressure trace could be viewed simultaneously.

A video camera and recorder were utilized to record pressure and vessel dimensions at the plane where pressure was measured. Measurements were later obtained utilizing a video monitor and freezing successive images. Since this particular model's cross-section is initially elliptic, distortion with transmural load occurs with both extensible (stretch) and inextensible (bending) deformation; thus load response appears nonlinear, even with a homogeneous wall of Hookean material.

Pump frequency was altered over a range of 0.25–3 Hz; cross-sectional area vs. pressure may then be examined with frequency as the parameter. If the wall material has significant viscous and inertial properties, a progressive dispersion of the plots would be seen as a function of frequency. No evidence of such dispersion was seen (Fig. 2), however, indicating that Sylgard, within this frequency range, is predominantly elastic. Practically, this implies that simple, static dimension-pressure relations are adequate to characterize the load response of the model.

It is advantageous to construct the model with substantial wall strength. This is controlled with wall thickness. The amplitudes of the variables of interest (e.g., pressure) can then provide good resolution and signal-to-noise ratios. These amplitudes, as well as compliant and geometric features, enter into considerations of hydrodynamic similarity.

Figure 3 illustrates alteration of dimensions, at the center of the pulmonary trunk model (subscripts m), with alteration of transmural load. The vessel exhibits deformation typical of such vessels (10), i.e., largely inextensional deformation at low loads and extensional deformation as the vessel cross-section becomes circular. In the real case (calf pulmonary trunk, subscripts r) we find the semiaxes exhibiting greater extension at low loads than does the model, and the vessel appears more compliant (11). In spite of the stiffer model, however, critical features are retained, i.e., large deformation response at low loads reducing as the cross-section becomes circular, then increasing again as the increasing cross-section influences the load response.

In Fig. 3, a is the major semiaxis, b is the minor semiaxis, and A is the cross-sectional area. Knowing a, b, and wall thickness, the wall elastic modulus may be derived (10).

Hydrodynamic similarity. A fundamental issue concerns conditions under which flows of different fluids in geometrically correlated but not identical vessels behave in a similar manner. Flow and stress developed in a model system need not mimic the true situation unless

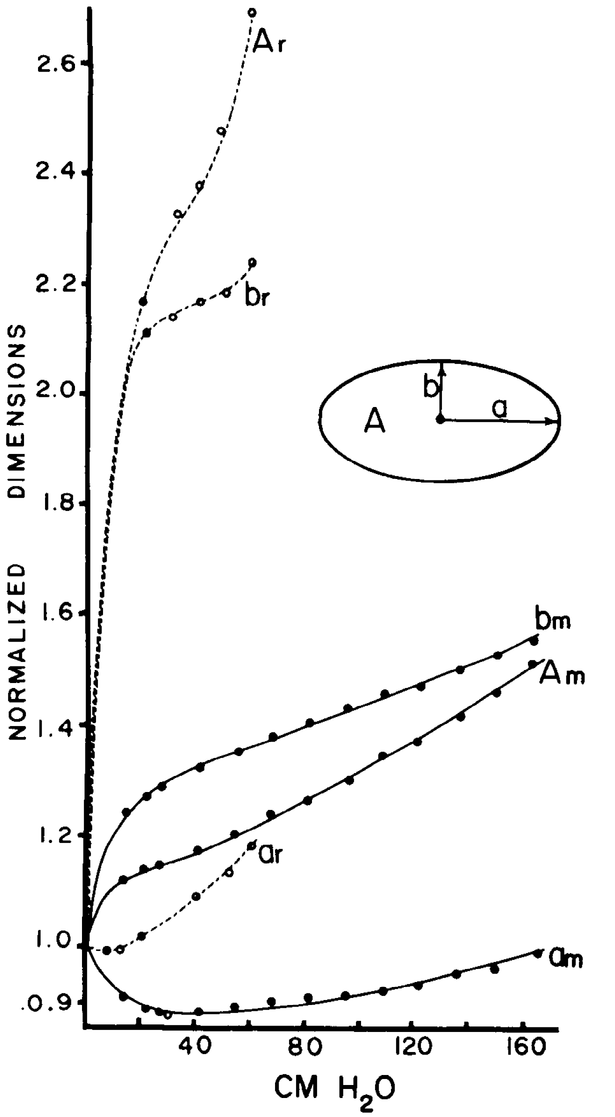

FIG. 3. Static pressure-dimension relationships for model (subscript m) and the real vessel (subscript r). a, major semiaxis; b, minor semiaxis; A, cross-sectional area.

cast is a pour of a tough epoxy (210-296 Epoxy, Emerson & Cuming, Canton, MA). A protruding shaft of aluminum is inserted into the major vessel to serve as a hilt (Fig. 1A).

After the epoxy has set, the silicone rubber mold is removed and discarded. The cast is smoothed and rechecked for dimensions against the acrylic cast. The surface is polished using fine sandpaper or emory and is then buffed to a high shine. This is the master model from which final molds are constructed. Because of surhydrodynamic similarity is established. The problem involves classic principles discussed in texts (14) and is concerned with adjustment of parameters such that the

TABLE 1. *Comparison of real and model data and nondimensional parameters*

		Percent of Ejection Period			
		2	40	50	98
			Peak flow	Peak pressure	
Viscosity, poise	R	0.032	0.032	0.032	0.032
	M	0.093	0.093	0.093	0.093*
Density, g/cm^3	R	1.055	1.055	1.055	1.055
	M	1.003	1.003	1.003	1.003
Frequency, Hz	R	2	2	2	2
	M	2	2	2	2
Pressure, cmH_2O	R	1	31	33	19
	M	2	105	110	64
Flow, cm^3/s	R	25	375	350	15
	M	151	1,880	1,750	73
Reynolds number	R	644	7,350	6,840	300
	M	637	7,299	6,794	295
Strouhal number	R	0.102	0.020	0.022	0.47
	M	0.148	0.018	0.020	0.40
Pressure coefficient	R	0.01	0.0054	0.0066	1.86
	M	0.01	0.0056	0.0069	1.87

R, real data; M, model data. * At 24°C.

equation of motion in the model correlates with that of the real case. With pulsatile flow and nonlinearities the analysis can be extensive.

Implementation to achieve similarity is not necessarily unique because the phenomena developed in the model are dependent on many factors. The source and downstream impedance, i.e., the hydraulic system connected to the model vessel, contribute fluid parameters that participate in developing the variables (flow rate, pressure, etc.). The model vessel termination is a mock circulatory loop that contains adjustable compliant and resistive features. This aspect is extensively documented in literature involved with circulatory input impedance (12). Parameters are adjusted to work in consort to track selected dimensionless numbers, e.g., Reynolds number, Strouhal number, pressure coefficient, etc.

Although parameter values need not be unique to accomplish hydrodynamic similarity, some permit greater convenience, as with higher pressures, etc. It is also advantageous to maintain low fluid viscosity and density close to water since additives in small quantity are usually amenable to linear computations (superposition). An example using a 1% mixture of glycerine in water is shown in Table 1. For flow visualization bentonite is useful. This is a birefringent material that can be visualized with polarized light (1, 5). Various dyes with fluorescent properties may be adsorbed onto the bentonite.

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