

## XXIII. MEDICAL ELECTRONICS

### A. MEASUREMENT OF CARDIAC REGURGITATION

#### 1. The Problem

Developments in surgical technique are making a great variety of previously incurable cardiac defects amenable to surgical correction. One such group of defects includes rheumatic deformities of heart valves resulting in regurgitation (leakage, or backflow). The ventricle of a regurgitant heart may pump what is normally a sufficient amount of blood during systole (cardiac contraction), but if some of the blood leaks back into the atrium (auricle) through a defective valve, the net forward flow may be dangerously reduced. In an attempt to overcome this effect, the cardiac chambers may become overloaded and abnormally distended, and eventual heart failure may result.

It is of vital importance in the selection of such patients for surgery that an accurate diagnosis be rendered – one that defines quantitatively the deviations from normal blood flow. At present, there is no reliable method of measuring cardiac regurgitation. The goal of this project is to devise and evaluate a method of measurement that would not require complex surgical procedures and would not interfere with the operation of the heart. The particular abnormality considered was mitral regurgitation (leakage through the mitral valve, which is located between the left atrium and the left ventricle).

#### 2. Indicator-Dilution Techniques

The technique of indicator-dilution, which is the one selected for the work reported here, yields average flow rates and requires relatively harmless instrumentation of the cardiac chambers. This method has been used successfully to measure net cardiac flow (cardiac output, or forward flow). The procedure is to inject an indicator into a cardiac chamber or large vein and sample the blood for indicator concentration in the aorta or large artery. The concentration is either sampled by a transducer that is mounted at the end of a small, flexible tube (catheter) which is inserted in the blood stream, or else the blood is withdrawn through a catheter and sampled outside the patient. Radioactive tracers, dye, and thermal indicators have been used. Thermal-dilution was used throughout this project. The "indicator" was a physiological saline solution at a temperature different from that of the flow system, and the indicator "concentration" was the temperature change in the system induced by addition of the indicator. The temperature change was detected by a thermistor mounted at the tip of a catheter.

#### 3. Theoretical Analysis

A mathematical model of the two-chamber pumping system (Fig. XXIII-1) was analyzed to show the effect of the flow parameters on the behavior of the indicator

(XXIII. MEDICAL ELECTRONICS)

concentration curves. It is assumed that the system performs the following intermittent function: When the ventricle expands, the atrium contracts; when the ventricle contracts, the atrium expands. Further assumptions are: (i) the indicator contained within a chamber at any instant of time is uniformly distributed within that chamber; (ii) cardiac action repeats from beat to beat; (iii) the indicator does not recirculate and enter

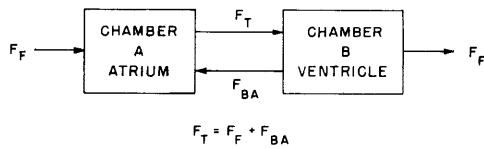


Fig. XXIII-1. Two-chamber flow system.

the atrium from upstream; (iv) all of the indicator that is injected into the system remains in the fluid and is eventually flushed out; none of it escapes through the heart walls. In Fig. XXIII-1,  $F_F$  is the net forward flow (cardiac output) in units of volume per pumping cycle. Since there are no net changes in the volume of either chamber, the flow entering the system must be the same as that leaving the system.  $F_{BA}$  is the flow regurgitated from the ventricle to the atrium;  $F_T$ , the sum of the regurgitant and forward flows, is the total flow from the atrium to the ventricle. For ease of visualization, assume that  $F_T$  is flowing through one short length of pipe that connects the two chambers while  $F_{BA}$  flows simultaneously through another.

Analysis of the flow system yields two difference equations that relate the indicator concentrations in each chamber to the flow and volume parameters and to the index  $n$ . If the indicator is injected into the ventricle in a finite number of beats starting at  $n = 0$ , the system equations show that

$$F_{BA}/F_T = A/B$$

where

$$A = \sum_{n=0}^{\infty} a(n)$$

$$B = \sum_{n=0}^{\infty} b(n)$$

$a(n)$  = concentration of indicator in the atrium.

$b(n)$  = concentration of indicator in the ventricle.

Therefore, the ratio of regurgitation to total flow can be determined from the curves sampled simultaneously in the atrium and ventricle after the indicator is injected into the ventricle. Furthermore, knowledge of the volumes of the chambers or of the quantity

of indicator added is not required.

The above formula applies if injection is periodic, in which case A has the significance of equilibrium concentration in the atrium and B represents equilibrium concentration in the ventricle.

#### 4. Mechanical Model

The instrumentation was tested on a mechanical model, the parameters of which could be controlled or measured directly. This afforded a means to check the accuracy of the thermal-dilution method under non-idealized flow conditions. The model, which was designed to simulate the flow pattern in one side of the heart, contained two chambers (Figs. XXIII-2 and XXIII-3). The pistons, the action of which simulated expansion and contraction of the heart walls, could be moved into and out of the chambers.

In order to ensure a net flow of water in the desired direction, flap valves were appropriately placed. At the outlet, a perfect valve was used to prevent backflow into the "ventricle." The amount of "mitral regurgitation" could be roughly controlled by cutting holes of various sizes in the flap valve between the two chambers.

A propeller blade, powered by an external motor, was located inside Chamber B to ensure adequate mixing of the indicator with the water. This procedure was justified on the assumption that there is good mixing in the physiological ventricle. (Experimental evidence tends to support this assumption.) There was no such auxiliary mixer in Chamber A, since good atrial mixing has never been shown to exist. Recirculation was prevented by draining the outlet reservoir into a separate tub while measurements were being made.

Indicator concentrations (temperature changes) were recorded by thermistors mounted on rigid probes. The ventricular concentrations were actually recorded in the outlet tube approximately 1 inch beyond the outlet valve. Two sampling sites were provided for the atrium, as shown in Fig. XXIII-4. In all experiments, the indicator was injected into Chamber B.

Figures XXIII-5a and b show typical pairs of curves. In Fig. XXIII-5a the atrial curve is recorded from the middle of the chamber (Site No. 1), and in Fig. XXIII-5b the atrial concentrations are sampled near the valve (Site No. 2). Smooth curves were drawn through the original tracings, as shown, and the areas under these curves were used for computations. Two alternative A/B ratios were computed from each set of curves of the type given in Fig. XXIII-5b. The ratio  $A_1/B$  is that obtained from the area under the lower curve only, whereas  $A_2/B$  is given by the average area under both lower and upper curves.

It is considered that a reasonable criterion for physiological measurements is based on the calculated results that fall within 20 per cent of the measured values. All the results from curves sampled at Site No. 1 following a single injection fall in this

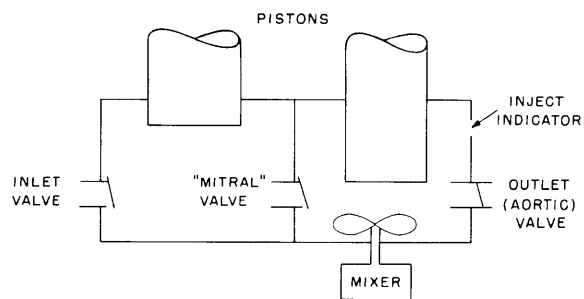


Fig. XXIII-2. The mechanical model.

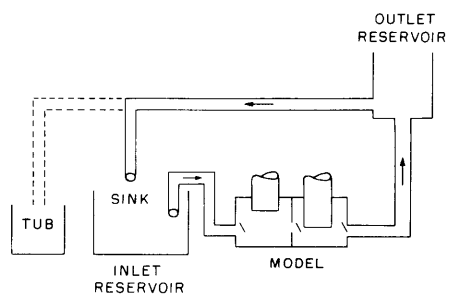


Fig. XXIII-3. Complete flow system for the model.

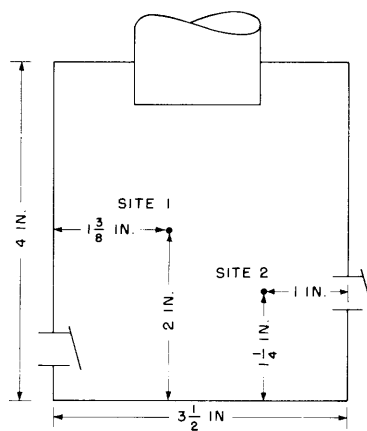


Fig. XXIII-4. Sampling sites in Chamber A.

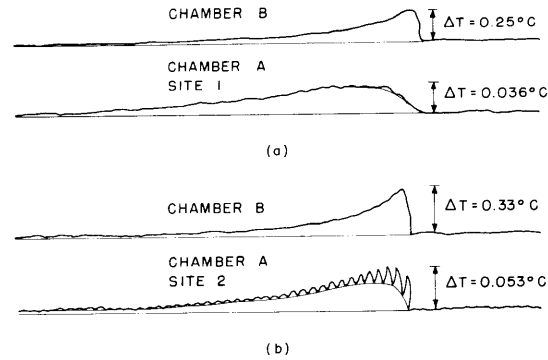


Fig. XXIII-5. Indicator concentration curves.

category. Furthermore, one member of each pair of the results that were derived from a total of eight experiments in which actual concentrations were sampled at Site No. 2 is also satisfactory. Note, however, that in five of these eight cases, the acceptable condition is obtained when  $A_1$  is used, while, for the remaining three, area  $A_2$  has to be taken.

From these experiments made with the model, it was concluded that the indicator-dilution method can be used to give a reliable measure of valvular regurgitation in a two-chamber pumping system when mixing is incomplete in the upstream chamber, provided that concentrations in this chamber are sampled near the middle of it and away from the valve.

The true test of the method, of course, will be its reliability in determining regurgitation in the human heart. Before this can be attempted, however, safe catheterization procedures that provide for the insertion of two sampling catheters and one injection catheter into the left side of the heart will have to be developed. Also, it will be necessary to construct a device that will inject the indicator only during the filling period of the ventricle, so that the indicator has a chance to mix before it is expelled.

W. H. Levison, W. D. Jackson

