Functional Evaluation of Artificial Heart Valves

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INTRODUCTION

Since the first successful experimental use of artificial heart valves many reports about their clinical use have been made. Concurrently, new valve designs are presented, which means that the present valves do not fulfill all intended requirements. Moreover, in artificial heart research, the artificial heart valves are critically important, so we evaluated various types of artificial heart valves and compared their function and efficiency. We used methods common in cardiac catheterization of patients with valvular heart disease 1,2,3 for evaluation of the performance of artificial heart valves.

METHOD AND RESULTS

Artificial aortic and mitral valves were put into a simulated circulatory system (mock circulation) in testing chambers. We simultaneously measured pressures before and behind the valve; that is in the atrium, ventricle and aorta. A Honeywell recorder was used with pressures being either on the same baseline or else to a differential pressure transducer and recording the resultant pressure. For mitral valve evaluation large amplification of pressure curves was used allowing greater accuracy in the recording of the changes in atrial pressure. The curves were recorded at the speed of 100 mm per sec., and then analyzed according to the parameters in Tables I and II. The mean leak was measured as the amount of fluid that flows back through a closed valve in a testing chamber under hydrostatic pressure of 125 to 130 cm. of water.

Sufficient opening of the aortic valve can best be expressed by the aortic valve area1 in sq. centimeters. This allows comparison of various valves tested, even at various flow rates and systolic durations. If we further analyze the stenosis we can see that it is influenced by two factors: inertia of the valve (from the weight and shape of moving parts) reflected by the opening pressure gradient, and the orifice stenosis (expressed by peak ejection gradient). The mean ejection gradient expresses both factors.

Overall closing defects are expressed by the difference between the aortic and left ventricular mean diastolic pressures. The more the valve leaks, the more the aortic pressure decreases and the ventricular pressure increases during diastole and the area between them is smaller. The closing of the aortic valve is analyzed in two parts: closing resistance (inertia) and leak of the closed valve. During delay of closure some regurgitation takes place; the rest is from leak of the closed valve. The performance of the mitral valve can be analyzed and evaluated in a manner similar to that for the aortic valve. Results are summarized in Tables III and IV.

AORTIC VALVES (FIG. 1).

The best valve areas were obtained with Gott and teardrop valves. Although the Starr-Edwards valve has a large orifice, the higher opening inertia raises the mean pressure gradient. Therefore the valve area is less. In evaluating the closing, the best results were obtained with the Starr-Edwards and teardrop. The closing resistance was best in valves with tiny leaflets; namely the Gott or leaflet valves. The mean leak on the other hand was least in the Starr and teardrop valves. The Gott valve has quick closing but it also has a greater leak. The aortic valve is closed twice as long as it is open (because of the longer duration of the diastole) and so the regurgitation is more important than the stenosis. Moreover, regurgitation of the aortic valve also prevents sufficient filling of the ventricle from the inflow side. Of the valves tested the most suitable for aortic position seem to be the Starr-Edward and teardrop valves.

MITRAL VALVES (FIG 2).

In both opening and closing respects the Gott valve is better than the others. Compared to the aortic valve the duration of closing (in systole) is short and the peak pressure is even shorter. That emphasizes the importance of a quick closing (small inertia) of a valve. The regurgitation is less influenced by the mean leak of the valve than by the closing resistance. Therefore, for the mitral position the Gott valve has a smaller regurgitation than the Starr valve.

DISCUSSION

Every valve has its advantages and disadvantages (Table V). This must be taken into consideration in regard to its proposed use. For the aortic position the greatest drawback is the regurgitation which means that the performance of the valve in regard to its closure is critical. For the mitral position the speed of opening is of first importance. The short duration of systole determines that this factor is more important than the leak of a closed valve. Evaluation and comparison of artificial heart valves under standard experimental conditions in a mock circulation may indicate the direction of improvement of design for new valves. For example, the weight of moving parts and their shapes can be correlated to the speed of closing. Soft, compressible materials in firm seats give better results in regard to leaks than hard material on both sides. A diminished valve area expresses the lack of sufficient opening. No valve with insufficient valve area should be considered for use. Yet, most of the valves have less area than that required for an ideal valve.

CONCLUSION

By simultaneous and differential pressure recordings of a valve in aortic or mitral position in a mock circulation we compared valve function with the performance of an ideal valve. The efficiency of various artificial heart valves was evaluated and expressed in mathematical values in standardized parameters.

REFERENCES

1. Gorlin, R. et al, Hydraulic formula for calculation of the area of the stenotic mitral valve, other cardiac valves and central circulatory shunts. Amer. Heart J., 41:1 1951.

2. Wright, J. L., et al, Left ventricular and aortic pressure pulses in arotic valvular disease. Proc. Staff Meetings, Mayo Clinic, 31:5, 120, 1956.

3. Fox, I. J., et al, Left atrial and ventricular pressure pulses in mitral valvular disease. Proc. Staff Meetings, Mayo Clinic, 31:5, 126, 1956.

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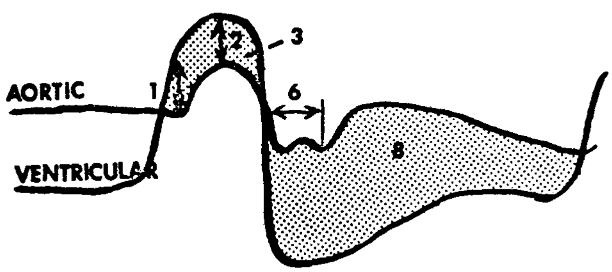
TABLE I. AORTIC VALVE PARAMETERS

	Function Factor	Equated Values
	Opening	
1.	Opening resistance	Pressure gradient at time of opening of aortic valve (mmHg)
2.	Peak ejection gradient	Maximal systolic pressure gradient (mmHg)
3.	Mean ejection gradient	Mean systolic pressure gradient (mmHg)
4.	Stenosis index	Square root of mean systolic pressure gradient
5.	Aortic valve area	$AVA = \frac{\text{aortic valve flow in ml. per systolic second}}{44.5 \times \text{square root of mean systolic pressure gradient}}$
	Closing	
6.	Closing resistance	Delay of aortic valve closure in milliseconds
7.	Mean leak	Milliliters of backflow of a closed valve under hydrostatic pressure of 130 cm. H_2O
8.	Mean diastolic gradient	Gradient between mean diastolic aortic and ventricular pressure in mmHg or planimetric units (indirectly proportional to the amount of regurgitation)

SIMULTANEOUS PRESSURE



DIFFERENTIAL PRESSURE

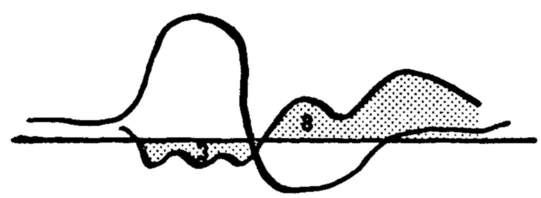
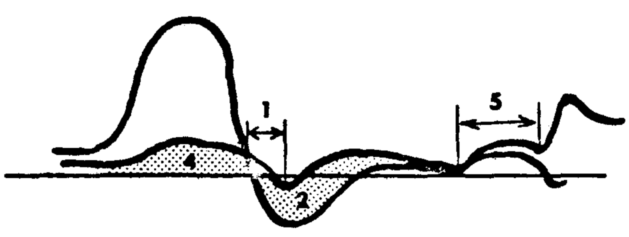


TABLE II. MITRAL VALVE PARAMETERS

	Function Factor	Equated Values
	Opening	
1.	Opening resistance	Delay of the peak of the pressure drop in milliseconds
2.	Mean diastolic filling gradient	Gradient between mean diastolic atrial and ventricular pressure (mmHg)
3.	Mitral valve area	$MVA = \frac{\text{mitral valve flow in ml. per diastolic second}}{31 \times \text{square root of diastolic pressure gradient}}$
	Closing	
4.	Atrial systolic mean pressure	Directly proportional to the amount of regurgitation (mmHg)
5.	Closing resistance	Delay of closing in millisec. from pressure drop to closing notch
6.	Mean leak	Milliliters per minute of backflow of a closed valve under the hydrostatic pressure of 130 cm H_2O

SIMULTANEOUS PRESSURE



5 X AMPLIFICATION

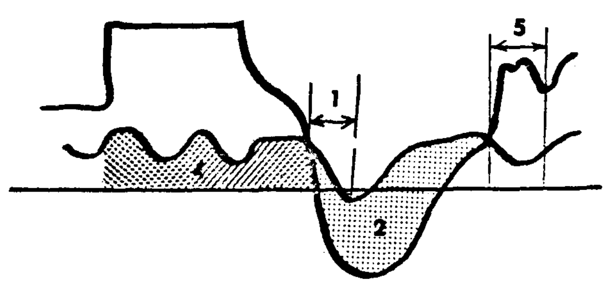


TABLE III. AORTIC VALVES TESTED

FACTOR	IDEAL	GOTT	TEAR-DROP	PIN	STARR-EDWARDS	LEAFLET	HEAVY TEFLON
Opening resistance (mmHg)	0	0	12	0	42	0	0
Peak ejection gradient (mmHg)	0	36	36	48	36	42	48
Mean ejection gradient (mmHg)	0	13.5	15.7	19.5	22.2	24.3	26
Aortic valve area (sq. cm.)	3-4	1.45	1.33	1.18	1.11	1.07	1.03
Closing resistance (msec)	0	150	180	170	180	140	160
Mean leak (ml/min)	0	78	45		5		10
Mean diastolic gradient (relative planimetric units)		80	94	78	83	78	75

NOTE: All values measured at a flow of 213.5 ml/systolic second

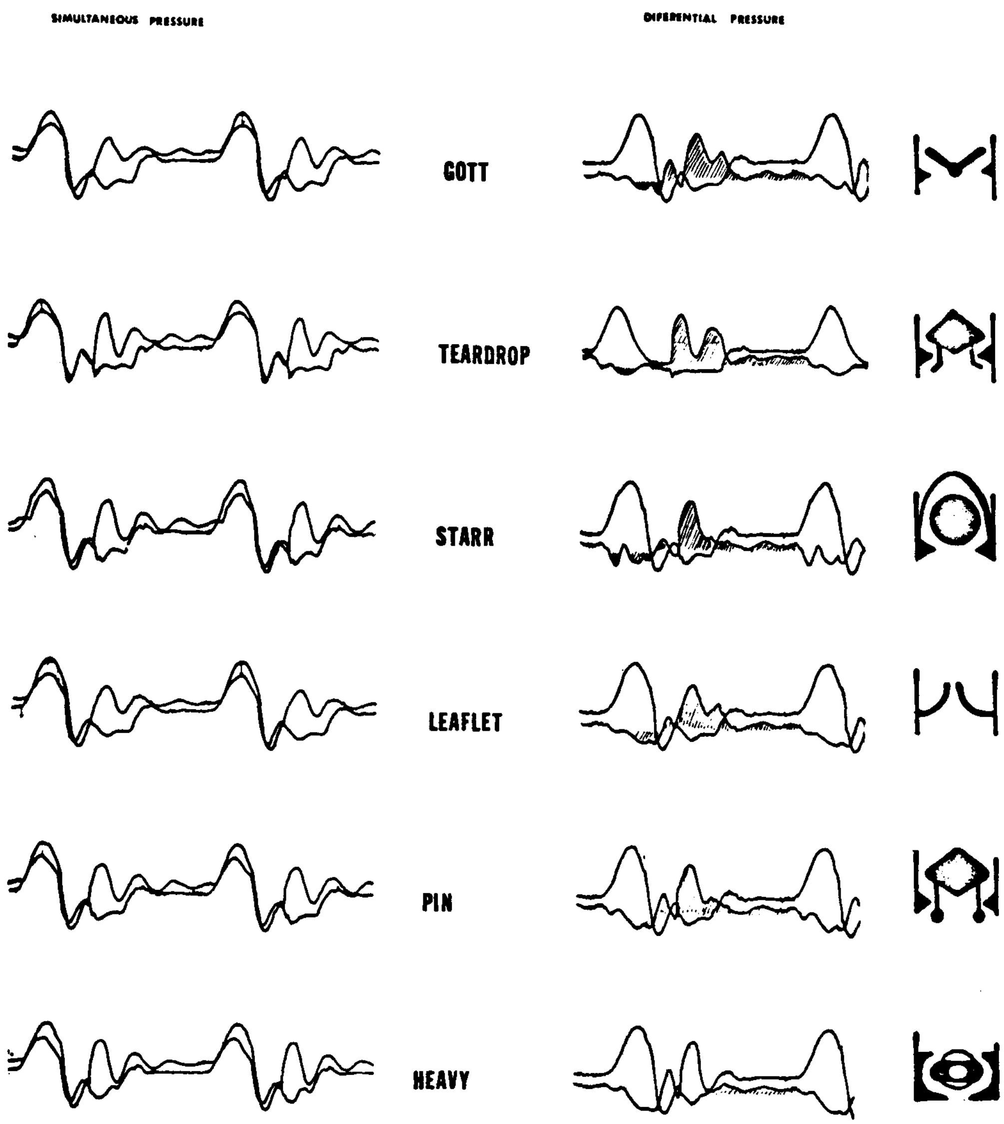


TABLE IV. MITRAL VALVES TESTED

FACTOR	IDEAL	GOTT	HAMMER-SMITH	STARR-EDWARDS	TEARDROP	HEAVY TEFLON
Opening resistance (msec)	0	30	30	60	40	40
Mean diastolic filling gradient (mmHg)	0	4.1	4.1	4.9	5.2	6.0
Mitral valve area (sq. cm.)	4.5	1.24	1.24	1.16	1.15	1.02
Atrial systolic mean pressure (mmHg)		2.7	14.9	15.8	12.3	13.2
Closing resistance (msec)	0	60	90	60	90	90
Mean leak (ml/min)	0	78	1500	5	45	10

NOTE: All values measured at a flow of 80.75 ml/diastolic second

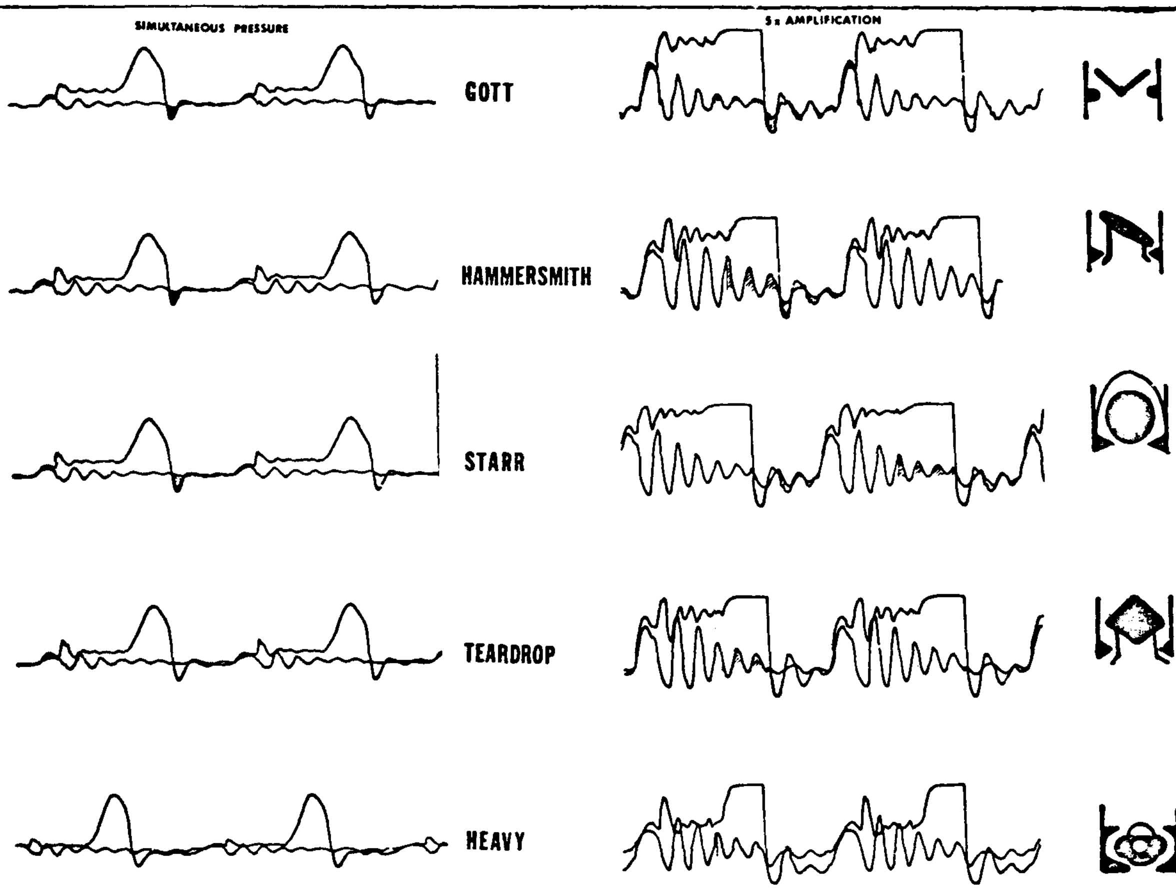


TABLE V. COMPARISON OF VALVES TESTED

VALVE	ADVANTAGE	DISADVANTAGE	POSITION OF CHOICE
Gott	Quick opening & closing Large orifice	Great regurgitation	Mitral
Teardrop discoid	Large orifice Small regurgitation	Middle opening resistance Slow closing	Mitral or aortic
Pin teardrop	Quick opening	Tiny orifice	---
Starr-Edwards	Large orifice Small regurgitation	Opening resistance, slow closing	Aortic
Leaflet	Quick opening & closing	Smallest orifice, great regurgitation	---
Heavy Teflon	Quick opening	Tiny orifice, great regurgitation	---
Hammersmith	Large orifice	Slow closing, great regurgitation	Mitral