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METHOD OF CHECKING THE FUNCTION OF IMPLANTED ARTIFICIAL VALVE BY PULSED DOPPLER ECHOCARDIOGRAPHY — IN VITRO STUDY

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The usefulness of pulsed Doppler echocardiography for verifying the function of implanted Björk-Shiley tilting disc valve prosthesis was checked experimentally in vitro. The valve was built into a physical model of central blood circulation. This arrangement permitted simulating examination of the implanted valve by a pulsed Doppler device with the advantage of simplified and well defined hydrodynamic conditions.

Detection of valvular insufficiency is very sensitive and specific in contrast to valvular obstruction. This is due to the masking of the hydrodynamic signs of obstruction by flow disturbances downstream the valve despite its normal function.

The same experience was made following the clinical application of pulsed Doppler echocardiography in our Institute. The examination technique has become a routine part of the periodic postoperative follow-up of patients with implanted artificial valves.

1. Introduction

The diagnostic criteria for a routine evaluation of the function of a natural valve by pulsed Doppler echocardiography (PDE) have already been established [1, 3]. However, they cannot readily be applied to artificial valves because of some of their hydrodynamic peculiarities. Such special properties are also inherent to the Björk-Shiley (B—S) tilting disc valve prosthesis, which is most commonly implanted in our institute.

In order to define the role of PDE in the postoperative follow-up of patients with implanted B – S valves, we used two parallel approaches: the direct clinical experiment and the experiment in vitro on a hydrodynamic model of the heart. The latter approach, which has the advantage of defined circulatory conditions, is the object of this paper.

2. Method and instrumentation

The study was performed under three basic conditions:
1. normal valve function, 2. regurgitation, 3. obstruction.

The circulation model schematically represented in Fig. 1 was filled with a liquid, resembling blood in density, viscosity, electric conductivity and corpuscular character [2]. It is composed of distilled water, glycerine, sodium chloride and stabile copolymeric spherical particles averaging 10 μm in diameter.

Valve obstruction was achieved by reducing the valve disc opening angle, while regurgitation was simulated by mechanical prevention of the disc closure.

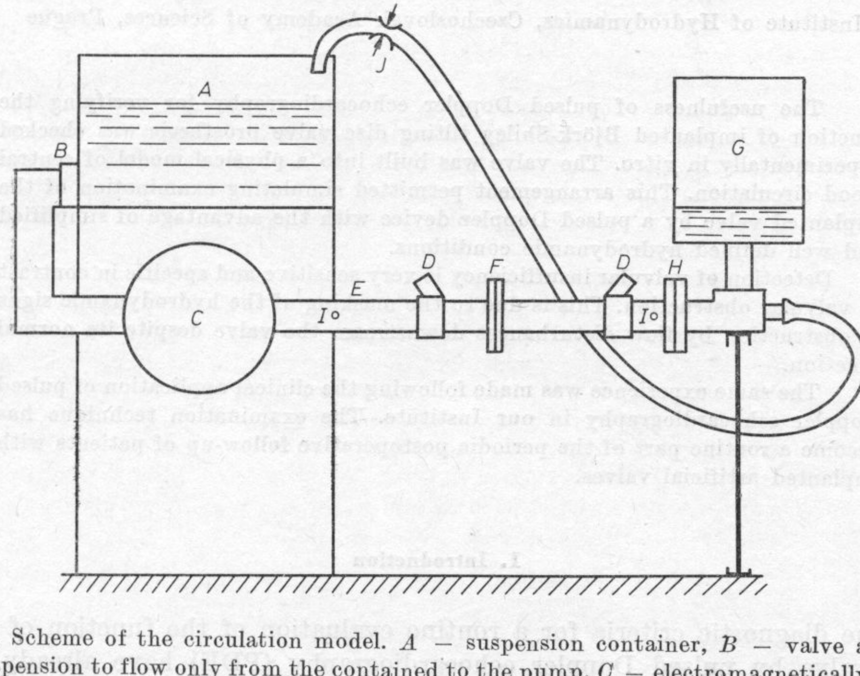

Fig. 1. Scheme of the circulation model. A – suspension container, B – valve allowing the suspension to flow only from the contained to the pump, C – electromagnetically driven piston pump, D – ultrasonic probe holders (movable along the tube E and rotatable around it), E – tube 23 mm *i.d.*, F – tested B – S valve, G – windkessel substituting the compliance (capacity) of the arterial system, H – probe of the electromagnetic flowmeter, I – fittings for pressure transducers, J – clamp for the control of peripheral resistance

For the PDE examination we used the module 500 *A* (Advanced Technology Lab., USA) together with the standard Echocardiovisor (Organon Teknika, Holland).

3. Results

Normal valve function

Local flow was sensed by placing the ultrasonic sample volume (SV) at various sites close to the B – S valve (up to 25 mm down – as well as upstream with respect to the valve disc).

In general, the flow downstream the valve is disturbed by the disc anb displays a turbulent character. The scheme in Fig. 2 explains the nomenclature used in further text. It also shows two basic (among many others used during the study) rotation angles β of the ultrasonic probe on the downstream side of the valve.

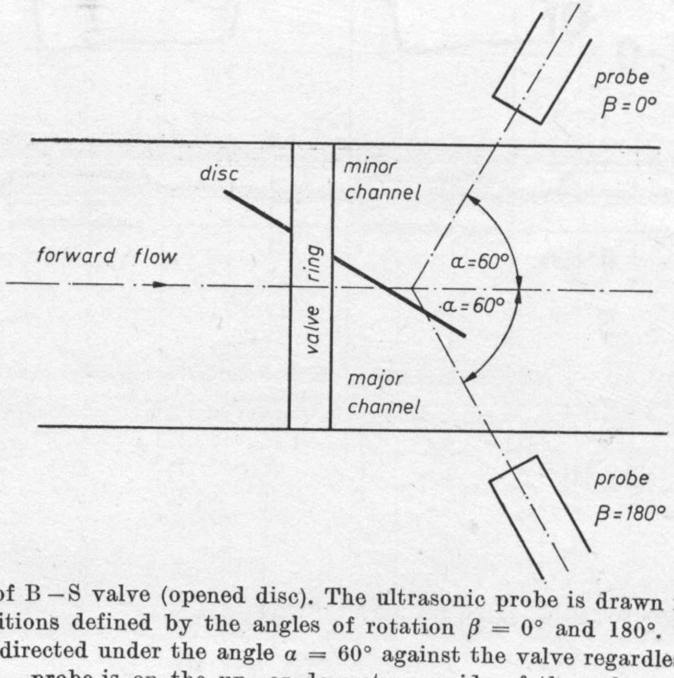

Fig. 2. Scheme of B – S valve (opened disc). The ultrasonic probe is drawn in two specific downstream positions defined by the angles of rotation $\beta = 0°$ and 180°. The ultrasonic beam is always directed under the angle $\alpha = 60°$ against the valve regardless whether the probe is on the up- or downstream side of the valve

Fig. 3 shows the experimental results with SV placed above the disc in the minor channel for $\beta = 0°$ (see the legend for curve identification). During the pump systole the flow was turbulent (abnormally scattered dots along the wave of the spatial average velocity). A negative wave during the first third of diastole mimicks regurgitation, which is, however, not confirmed by the elec-

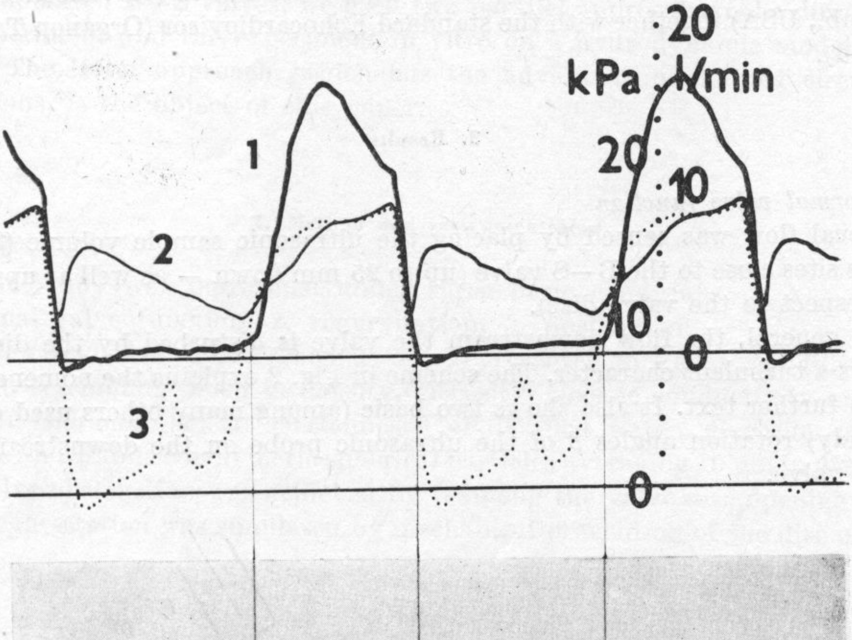

Fig. 3. Normal valve function. SV in the minor channel approximately 3 mm downstream the valve ring and 5 mm from the tube wall (i.e. $\beta = 0°$). 1 — flow sensed electromagnetically, 2 — "systemic" pressure, i.e. downstream the valve, 3 — pressure in the pump ventricle, i.e. upstream the valve, 4 — *M*-mode record of the valve disc action (with numerous reverberations), 5 — pump control pulses, 6 — local flow velocity sensed by the PDE system (solid line = wave of spatial average velocity within SV, dots: their scattering gives a qualitative knowledge about the width of Doppler signal frequency spectrum — this facilitates identification of the turbulence induced spectral broadening), 7 — instantaneous power of the Doppler signal (used mostly only for optimal setting of the pulsed Doppler device)

tromagnetic flowmeter. This phenomenon may be explained by flow reflection due to disc closure.

A recirculation zone with zero forward net velocity was found close to the disc [5] (Fig. 4).

In contrast to Figs. 3 and 4, Fig. 5 illustrates the situation when the ultrasonic beam was directed almost parallel to the stream in the major channel

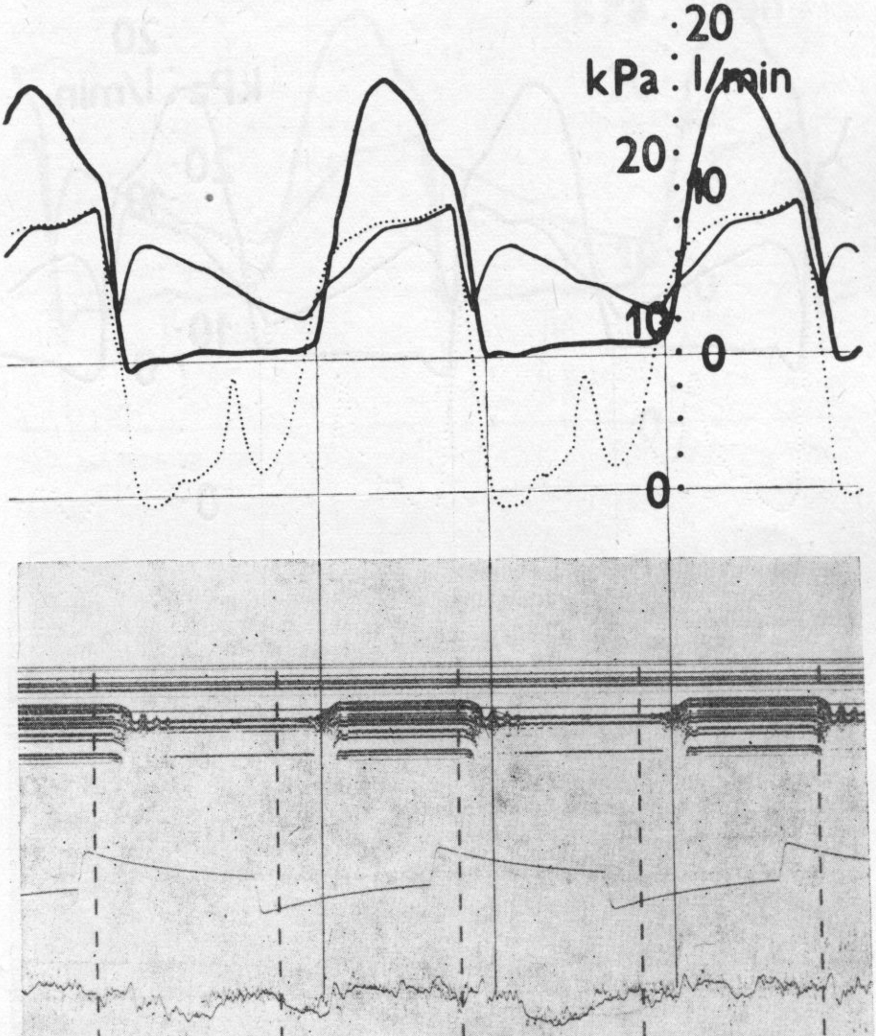

Fig. 4. Normal valve function. SV in the recirculation zone — above and close to the disc ($\beta = 0°$)

($\beta = 180°$). SV was located beneath the disc. The Doppler shift exceeded the Nyquist limit with respect to the repetition frequency of ultrasonic bursts so that higher Doppler frequencies could not be unambiguously detected. Consequently, the average velocity wave changes sharply its polarity.

Further downstream, approximately 100 mm from the valve ring, flow disturbances fade out and the flow profile becomes axisymmetrical and rather flat.

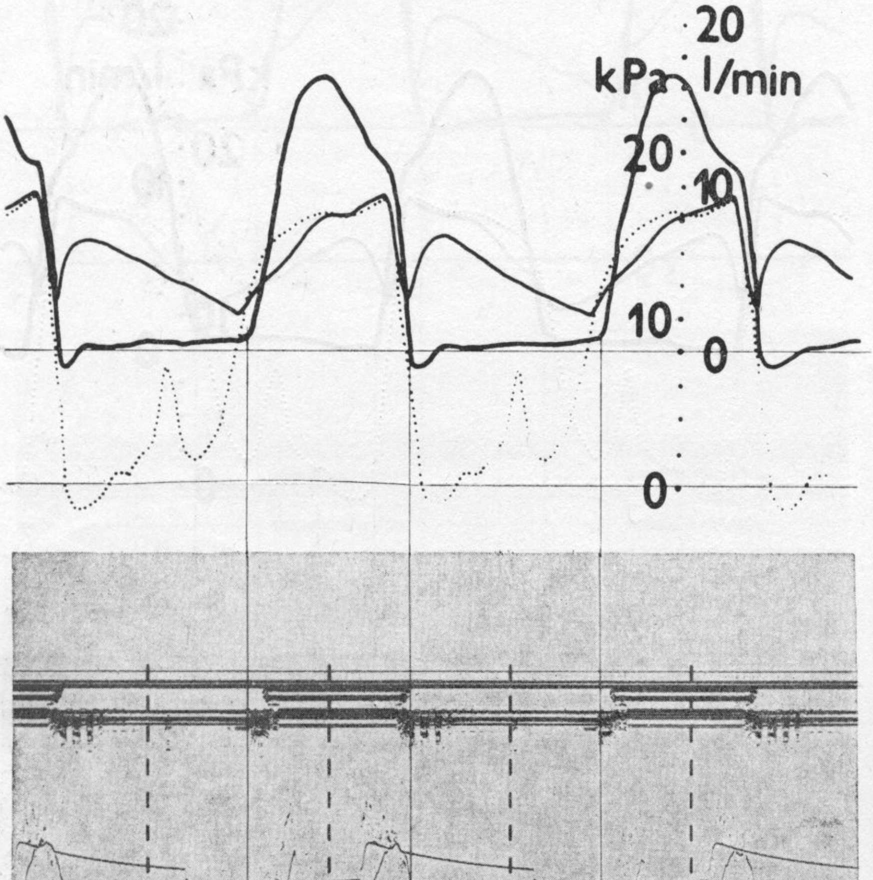

Fig. 5. Normal valve function. SV in the major channel beneath the disc ($\beta = 180°$). Nyquist limit is exceeded

As expected, the flow on the upstream side of the valve is laminar.

Obstruction

The presence of distal flow disturbances seen on examination of natural valves is a reliable sign of valvular stenosis. However, this criterion does not hold for the B–S valve because, as shown above, turbulence in the distal

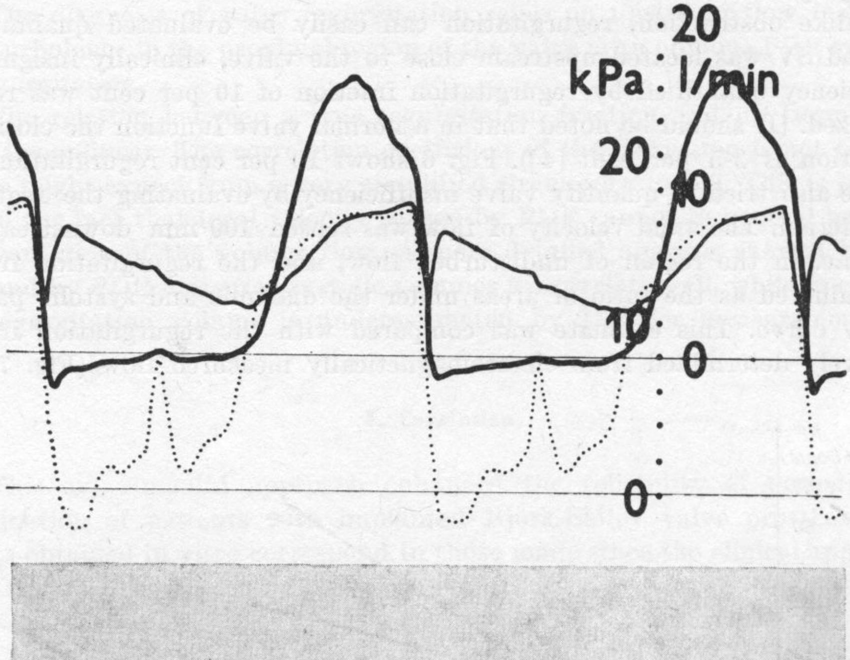

Fig. 6. Regurgitation (10 per cent). SV is placed in the near vicinity of the valve on its upstream side. Regurgitation is objectivized by electromagnetic flowmeter and also shown on velocity record by PDE

vicinity of the valve is normal. Therefore, SV should be placed further downstream where the valve disc no longer affects flow. On the other hand, the thus located SV fails to reflect sensitively and reliably even a meaningfull valve obstruction — for instance, a mean pressure gradient of 5.3 kPa in our experiment.

Regurgitation

Unlike obstruction, regurgitation can easily be evaluated qualitatively. Provided SV was located upstream close to the valve, clinically insignificant insufficiency quantified by regurgitation fraction of 10 per cent was reliably recognized. (It should be noted that in a normal valve function the closing regurgitation is 3-5 per cent [4]). Fig. 6 shows 10 per cent regurgitation.

We also tried to quantify valve insufficiency by evaluating the regurgitation fraction. The axial velocity of flow was sensed 100 mm downstream the valve, i.e. in the region of undisturbed flow, and the regurgitation fraction was evaluated as the ratio of areas under the diastolic and systolic parts of velocity curve. This estimate was compared with the regurgitation fraction objectively determined from electromagnetically measured flow (Fig. 7).

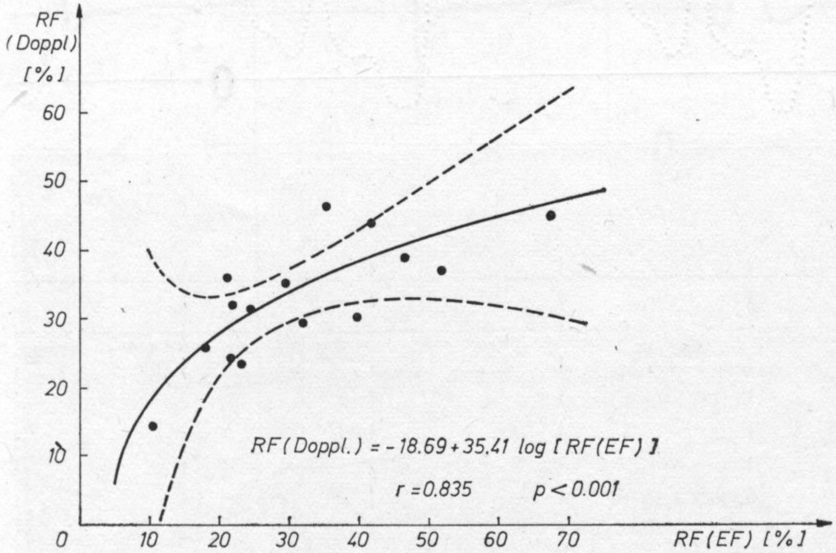

Fig. 7. Comparison of the regurgitation fraction estimated by PDE and objectively evaluated from electromagnetically measured flow

4. Discussion

Our findings related to the near downstream region correspond to the results of Yoganathan [5], who performed a complex flow measurement using a laser-Doppler anemometer. The valve disc induces major flow disturbances which may thus mask obstruction. Moreover, PDE flow patterns strictly depend on SV location and ultrasonic beam direction. In clinical praxis, these topological relations cannot, however, be reliably defined, especially because of the unknown position of the valve disc plane with respect to the chest surface. On the other hand, in a more distal region, where the hydrodynamic situation becomes clear, the sensitivity of PDE to valve obstruction decreases.

The diagnosis of valve regurgitation relies on upstream flow inspection. Any turbulence in the proximal region of the valve is an obvious PDE symptom of regurgitation.

The relation between a true regurgitation fraction and its Doppler estimate is nonlinear. The correlation coefficient of the regression is not too high, as one might expect from a very simplified circulatory model. This is probably due to the fact that local velocity sensed by PDE cannot in general be a good representation of the volume flow. A more detailed analysis showed both the true and by PDE measured systolic volumes to correlate well, while in contrast, the regurgitation volume is underestimated by Doppler measurement.

5. Conclusion

This experimental approach enhanced the reliability of periodic PDE examination of patients with implanted Björk-Shiley valve prostheses. Our results obtained in vitro correspond to those made since the clinical application of PDE.

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