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Citation for published version (APA):
Arts, M. G. J., & Reneman, R. S. (1977). Analysis of intramyocardial pressure (IMP) : a model study. *Bibliotheca anatomica*, *15*, 103-107.

Document status and date:
Published: 01/01/1977

Document Version:
Publisher’s PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

• A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
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Download date: 26. Mar. 2023

9th Europ. Conf. Microcirculation, Antwerp 1976. Bibl. anat., No. 15, pp. 103–107 (Karger, Basel 1977)

Analysis of Intramyocardial Pressure (IMP)

A Model Study

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Introduction

During the cardiac cycle myocardial perfusion is influenced by the mechanical stresses in the structures surrounding the coronary vasculature. Many investigators have tried to measure these stresses (defined as IMP) using various techniques (e.g. v.d. MEER et al,. 1970). In most of these studies during systole higher pressures were found in the subendocardial than in the subepicardial layers of the left ventricular wall. Several investigators reported higher systolic IMP's in the subendocardial layers of the left ventricular wall than in the left ventricular cavity. These results, however, are difficult to interpret since one can not describe the complex state of mechanical loading by one simple stress, i.e. IMP. In the present study a dynamic computer model of the mechanical action of the heart was designed to describe the state mechanical loading of the myocardial material and the role of IMP in this concept, allowing a more proper analysis of the different methods for measuring IMP and of the results obtained with these techniques.

Definition of the state of mechanical loading

Normally the state of mechanical loading is described by 6 independent stresses (3 normal and 3 shear stresses). In the myocardium the number of independent stresses can be reduced to three normal stresses by taking one coordinate parallel to the muscle fibers, a second one perpendicular to the former two. Since in papillary muscle experiments the stress-strain relation is measured in only one direction, assumptions have to be made about muscle material properties to obtain the additional stresses.

A computer simultation of the mechanical action of the heart

In a computer simulation of the mechanical action of the heart two different hypotheses concerning the myocardial muscle material properties were evaluated. The muscle material was considered to consist of either isotropic (rubber-like) contractile material with a prestrain in the direction of the muscle filaments or an anisotropic contractile filament structure embedded in a fluid-like weak material.

In the model the myocardium was assumed to consist of a thick-walled cylinder, composed of 8 concentric cylinders of muscle material with a fiber orientation according to the findings of STREETER et al., (1969), a force-length-time relation derived from the findings of BRUTSAERT (1974) and POLLACK (1975) and a depolarisation pattern according to the findings of DURRER (1968). The haemodynamic loading, i.e. the aortic input impedance is simplified to a resistance in series with a capacitance, which is in parallel with the peripheral resistance.

In the simulation with isotropic muscle material the instantaneous left ventricular pressure and aortic blood flow tracings showed, after a normal systolic rise, a rapid fall during mid-systole, which was associated with a very low ejection fraction (Figure 1A). In this condition the energy, which is supplied by the contractile mechanism, is largely absorbed by deformation of the cross-section of the muscle fibers, causing a lack of energy, which is necessary for the ejection of blood from the ventricle during the whole ejection period.

In the simulation with anisotropic muscle material, however, the instantaneous left ventricular pressure and aortic blood flow tracings compared favourably with the tracings obtained in animal experiments under comparable circumstances, as far as the end-diastolic left ventricular and aortic pressures and the input impedance of the ascending aorta are concerned (Figure 1A). The delayed rise time of the instantaneous ascending aortic flow curve in the animal experiment results from the position of the electromagnetic flow probe distal to the aortic orifice and the electronic delay in the flowmeter system. This simulation indicates that the muscle material can be regarded as an anisotropic contractile filament structure embedded in a fluid-like weak material. With this material properties the mechanical state of loading is determined by two entities:

- the stress in the contractile filament structure (actine and myosine filaments), and
- the pressure in the surrounding weak material, viz. cells, cell membranes and interstitial fluid (= IMP).

By calculating the stress in the filament structure from the stress-strain relation as determined in experiments on isolated papillary muscle (BRUTSAERT, 1974, POLLACK, 1975) the following results were obtained. During systole a negative IMP gradient was found from the subendocardial to the subepicardial layers of the left ventricular wall. The systolic IMP in the subendocardial layer was equal to the systolic left ventricular cavity pressure and reached atmospheric pressure in the subepicardial layer. During systole IMP never exceeded left ventricular cavity pressure (Figure 1B). These findings could be expected because during systole the stress in each contractile filament is positive and the curvature of each filament is directed concave to the endocardium. According to La Place's law each contractile filament contributes positively to the IMP at its endocardial side. The equality of the endocardial IMP to the left ventricular cavity pressure is a boundary condition. Therefore, it is likely that the overestimation of systolic IMP by many investigators has to be ascribed to measuring errors.

Analysis of the techniques for measuring IMP

Various methods have been used to measure IMP. In all methods the pressure is measured directly or indirectly in a fluid filled cavity surrounded by the tissue. The pressure in this cavity does not necessarily equal the IMP. By cutting the contractile filament structure, for instance, the fluid filled cavity tends to enlarge, giving rise to a cavity-pressure lower than the local IMP (Figure 2A). Since stresses in the filament structure are normally much higher than the IMP, even negative pressures can be expected, when the filaments are cut. By disalignment of the filament structure (Figure 2B, C) the pressure in the fluid filled cavity tends to be higher than the local IMP as a consequence of La Place's law, which says that stresses in curved surfaces give rise to pressure gradients. The resulting overestimation is higher at more pronounced curving of the contractile filaments. Disturbance of the contractile filament structure causes that the pressure in the fluid filled cavity does not only depend on the IMP, but also on the stresses in the contractile filaments. This unwanted effect can be minimized by reducing the damage of the contractile filaments to a minimum and by avoiding curvatures in the contractile filaments around the fluid filled cavity in which the pressure is measured.

This analysis indicates that with most of the techniques used for measuring IMP damage and/or disalignment of the contractile filaments occur giving rise to errors: this holds for the open method (e.g. needle) the closed method (balloon or vessel segment occluded at one side) and the perfusion method (v.d. MEER et al., 1970). In the perfusion method a venous or arterial segment is implanted in the myocardium and the perfusion pressure measured at which flow through the segment starts (diastolic pressure) and becomes continuous (systolic pressure). With this technique higher IMP's were found, when small venous segments (v.d. MEER et al., 1970) instead of large arterial segments (BAIRD, 1968) were implanted. This finding seems paradoxical because of the expected minimal disturbance of the local structures with smaller segments. However, a small cavity often is associated with highly curved filaments (Figure 2C), giving rise to a rather high additional pressure. On the contrary larger, more longitudinal shaped cavities often cause only slight curving in

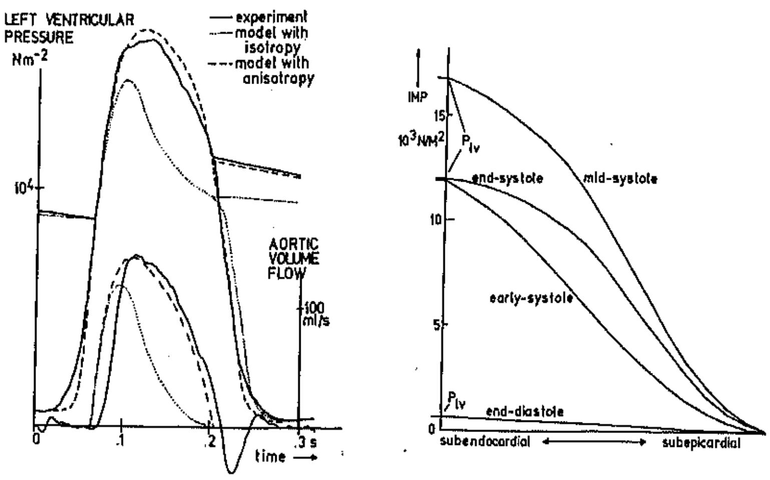

Figure 1: A. Comparison of the left ventricular pressure and aortic volume flow tracings obtained from an animal experiment and computer simulations with isotropic or anisotropic properties of myocardial tissue.
B: IMP as a function of the distance from the left ventricular cavity, as derived from the computer simulation.

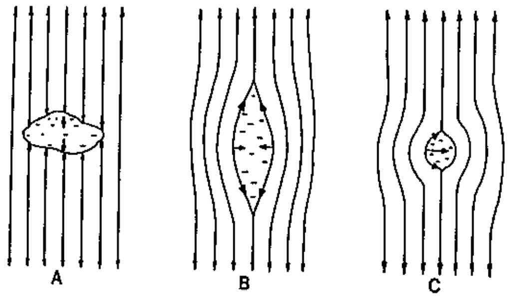

Figure 2: A. Cut filaments
B. Disalignment associated with slightly curved filaments
C. Disalignment associated with highly curved filaments

the filaments, resulting in a better correspondence between the pressure in the cavity and IMP. The wick (SCHOLANDER, 1968) and the capsule (GUYTON, 1963) technique are not intended to measure IMP, but the interstitial fluid pressure which is only a component of IMP and of less importance for the regulation of myocardial blood flow.

Conclusion

The present model study indicates that the myocardial tissue can be regarded as a contractile filament structure embedded in a weak material, consisting of cells, cell membranes and interstitial fluid; the endo to epicardial IMP gradient is negative; the systolic IMP never exceeds the systolic left ventricular cavity pressure; and none of the methods presently available is suitable to measure IMP reliably.

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