Regional Myocardial Stiffness Measured by a New Tactile Sensor System

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SUMMARY

Numerous investigators have attempted to measure regional wall stress directly. However, the measurement systems and devices employed have been too complex for accurate quantification in situ. We have developed a new tactile sensor system for measuring accurately myocardial stiffness in situ and validated its use for estimation of myocardial contractile function.

The tactile sensor was placed on the left ventricle of five mongrel dogs, (weighing 12–17 kg) and myocardial stiffness (g/mm²) was measured. Dobutamine (5.0 μg/kg/min) and propranolol (0.25 mg/kg) were sequentially administrated intravenously, and the change in myocardial stiffness was monitored.

Myocardial stiffness followed a time course similar to that of left ventricular pressure, indicating a close relationship with wall stress. Baseline end-systolic stiffness in 5 dogs was 2.38 ± 0.19 g/mm². After administration of dobutamine, end-systolic stiffness increased to 3.26 ± 0.32 g/mm² (p < 0.01). After the administration of propranolol, end-systolic stiffness decreased significantly to 1.83 ± 0.19 g/mm² (p < 0.01), compared with the baseline values.

Regional myocardial stiffness of a beating heart can be measured precisely using our new tactile sensor system. End-systolic stiffness is a useful index for accurate quantification of the regional myocardial contractile state. (Jpn Heart J 1997; 38: 709–715)

Key words: Tactile sensor, Myocardial stiffness, Regional wall stress, Myocardial contractile function

EVALUATION of regional contractile function is of clinical importance because various diseased states affect the myocardium heterogeneously. Therefore, many investigators have attempted to measure the regional wall
strain-stress relationship directly or estimate it by calculation based on a model.\textsuperscript{1,2)\textsuperscript{\textdagger}} However, clinical application of these methods is very limited due to difficulties encountered in the direct measurement of wall stress. An alternative approach for accurate evaluation of wall stress is to measure the stiffness of the myocardium. In 1987, Halperin and associates reported that transverse stiffness is linearly related to in-plane wall stress, and useful for accurately quantifying the regional contractile state.\textsuperscript{3)\textdagger}

We have introduced a tactile sensor for detecting small and invisible pulmonary nodules during thoracoscopic surgery.\textsuperscript{4)\textdagger} We have now developed a new tactile sensor and system designed to fit the ventricular wall, which is capable of measuring myocardial stiffness accurately in situ, and thus has potential for clinical use.

**METHODS**

**Tactile sensor system:** The principle of our tactile sensor has been described previously.\textsuperscript{4-7)\textdagger} Briefly, a vibrating finite lot has its own resonance frequency, and when the lot touches an object, a shift in resonance frequency is observed. Because this shift in frequency (delta f) depends on the stiffness of the object, we can

\begin{figure}[h]
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\includegraphics[width=0.7\textwidth]{tactile_sensor_diagram.png}
\caption{Tactile sensor structure. The sensor is 5.5 cm long, 7 mm in diameter, weighs 2.08 g, and is equipped with a small tip 3 mm in diameter connected to a piezoelectric transducer made of lead zirconate-barium titanate ceramic. The contact surface of the sensor is made of hard epoxy resin and forms a smooth curved surface to ensure that the contact area between the sensor and the myocardium is constant.}
\end{figure}
estimate the stiffness by monitoring delta f. The tactile sensor system comprises a sensor probe, an amplifier and a filter. Our new tactile sensor is designed for measurement of myocardial stiffness. The sensor probe is 5.5 cm long, 7 mm in diameter, weighs 2.08 g, and is equipped with a small round tip 3 mm in diameter that is connected acoustically to a piezo-electric transducer made of lead zirconate-barium titanate ceramic. The contact surface of the sensor is made of hard epoxy resin and smoothly curved (Figure 1). It is very important to keep the contact area of the sensor constant because the measurement of delta f is affected by a change in the area.5-7) Using this design, measurements were made to a depth of 10 mm, which was sufficient for measuring the stiffness of the canine left ventricular wall. When the sensor probe touches an object and the resonance frequency shifts, the vibration detector picks up the change in frequency and sends its signal to the amplifier that keeps the piezo-electric transducer vibrating at the new frequency (Figure 2). In our new system, this procedure can be performed 150 times per second by a frequency counter device (AX-CNT1001, Axiom Co., Ltd, Koriyama, Japan) and the delta-f value is processed sequentially by a personal computer (PC9821-Ne, NEC, Tokyo, Japan).

**Measurement and calibration of myocardial stiffness:** The sensor probe is inserted into a plastic tube 9 mm in diameter and 3 cm long, which is fixed to a
Figure 3. Strong correlation between stiffness and delta f was obtained using our tactile sensor ($R = 0.952$, $R^2 = 0.906$). The plots represent the stiffness and delta f derived from gelatin made from bovine skin.
myocardial stiffness, and left ventricular volume and pressure were measured. The relationship between myocardial stiffness and left ventricular volume was then studied. After measurement of baseline myocardial stiffness, dobutamine (5.0 μg/kg/min) was administrated intravenously. Myocardial stiffness and left ventricular volume and pressure were also measured during administration of a positive inotropic agent. One hour after the discontinuation of dobutamine infusion, propranolol (0.25 mg/kg) was administrated intravenously, and myocardial stiffness and left ventricular volume and pressure were measured. Myocardial stiffness under these two conditions was compared with the baseline stiffness at both end-systole and end-diastole.

**Statistical analysis:** All results are given as mean ± SD. The two-tailed paired Student’s t test was used to compare myocardial stiffness before and after administration of dobutamine and propranolol. Differences were regarded as statistically significant at p < 0.05.

**Results**

**Baseline myocardial stiffness:** Phasic changes in myocardial stiffness and left ventricular pressure are shown in Figure 4A. It is clear that the stiffness follows a time course similar to that of left ventricular pressure, indicating a close relationship with wall stress. In Figure 4B, we plotted the relationship between myocardial stiffness (S) and left ventricular volume (V) (S-V loop). Similar to the pres-

![Figure 4.](image)

**Figure 4.** A: Change in myocardial stiffness and left ventricular pressure wave. Solid line represents the change in stiffness and the dotted line represents pressure wave. B: Relationship between myocardial stiffness and left ventricular volume in a cardiac cycle (S-V loop).
Figure 5. The stiffness (S)-volume (V) loop under different contractile conditions.
A): S-V loop during administration of dobutamine.
B): baseline S-V loop.
C): S-V loop during administration of propranolol.

pressure-volume loop, the S-V loop was rectangular. Baseline end-systolic stiffness (left upper corner of the loop) was 2.38 ± 0.19 g/mm² (n = 5) and the end-diastolic stiffness (right lower corner of the loop) was 1.38 ± 0.12 g/mm² (n = 5).

Administration of dobutamine: The S-V loop was also rectangular in 5 dogs administered dobutamine (5.0 μg/kg/min) (Figure 5). The peak myocardial stiffness (reached at end-systole) was increased significantly compared to the baseline (3.26 ± 0.32 g/mm²: p < 0.01). The end-diastolic stiffness was 1.30 ± 0.19 g/mm² (not statistically significant from the baseline).

Administration of propranolol: After administration of propranolol (0.25 mg/kg), the S-V loop was also rectangular (Figure 5) and the end-systolic myocardial stiffness had decreased significantly in 5 dogs (1.83 ± 0.19 g/mm²: p < 0.01). End-diastolic stiffness was 1.40 ± 0.16 g/mm², (not statistically significant from the baseline).

DISCUSSION

Numerous investigators have attempted to measure ventricular wall stress directly for accurate evaluation of regional myocardial function. However, the measurement systems and devices employed have been so complex that their clinical application has not been successful. Since 1994 we have been using a new tactile sensor for detecting small and invisible pulmonary nodules during thoracoscopic surgery. Although we have found the sensor to be very useful for
this purpose, it was not readily applicable to the measurement of myocardial stiffness because of its slow dynamic response and the fact that it was unable to provide an absolute value of stiffness. Therefore, we developed a new tactile sensor system which is fast enough to follow the heart beat and also give us the absolute value of stiffness expressed as g/mm². In 1987, Halperin and associates reported that transverse stiffness is linearly related to in-plane wall stress. ³ Similarly, Omata et al. reported that in rat bladder, the stiffness in the filling phase measured by a tactile sensor correlated well with the wall tension (stress) calculated using the La Place formula. ⁷ These results support the idea that myocardial stiffness reflects ventricular wall stress. In the present study, we found that the stiffness (S)-volume (V) loop was rectangular and that the stiffness reached its maximum value at end-systole. Moreover, end-systolic myocardial stiffness increased significantly upon administration of a positive inotropic agent and decreased significantly with β-blockade. These results support that myocardial stiffness is related to the contractile state of the myocardium. Accordingly, we conclude that end-systolic myocardial stiffness can be a very useful index for accurately quantifying the myocardial contractile state. With further improvements of the tactile sensor probe, we are now attempting to use it clinically during cardiac surgery and cardiac catheterization to evaluate the regional changes in myocardial contractility that are often encountered in various heart diseases.

REFERENCES