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Evolving Technology

Microelectromechanical systems for endoscopic cardiac surgery

Gianluca Bonanomi, MD,[a] Keith Rebello, PhD,[a] Kyle Lebouitz, PhD,[a] Cameron Riviere, PhD,[b] Elena Di Martino, PhD,[c] David Vorp, PhD,[c] and Marco A. Zenati, MD,[a] Pittsburgh, Pa

A completely endoscopic approach has been achieved clinically in highly selected cases of coronary revascularization, mitral valve repair, and closure of atrial septal defect using telerobotic manipulation systems.[1] However, a major drawback of endoscopic surgery is the lack of sensory feedback and the complete reliance on visual information. Computer-assisted techniques and tools are needed to supply the lacking tactile information. For example, tissue hardness may be transformed into a numerical value that could be interpreted as an index of what the surgeon would have felt with his fingers in open surgery. Highly sensitive and accurate sensors that replace human discrimination capabilities and that can be introduced inside the chest through small ports may improve the safety and reproducibility of endoscopic procedures.

Microelectromechanical systems (MEMS) represent a recent technological advancement, sharing a fabrication process that enables the design and construction of integrated mechanical and electrical components that have dimensions in the range of micrometers.[2] The same concept that made microelectronics possible with the invention of the silicone-based integrated circuit can be adapted to produce small mechanical structures integrated with electrical components. The micromechanical component represents the interface for receiving information and for interacting with the physical world. MEMS technology might provide new opportunities for minimally invasive surgery because it enables the creation of miniaturized devices able to acquire and digitize information that can be integrated into endoscopic instruments. Moreover, MEMS have excellent mechanical resonance properties for manufacturing highly sensitive devices in which the measured quantity (eg, pressure, hardness, flow) is represented by a change in the resonant frequency of the sensor.[2,3] Current MEMS applications include pressure, chemical, and flow sensors; accelerometers; optical micromirrors; and fluid pumps that can be employed in strategic fields such as defense, environmental control, and the health sciences.[2] Although medical applications of MEMS technology are at an early stage, it is expected that the integration of sensors, actuators, and other microstructures with electronics will transform medicine and surgery.[3,4]

A MEMS sensor for differentiating between different levels of rigidity in tissues has been recently developed (H-Probe; Verimetra Inc, Pittsburgh, Pa). The H-Probe consists of 4 components: (1) the outer support tube, (2) miniature bellows, (3) the sensing rod, and (4) a piezoresistive MEMS pressure sensor (Figure 1). By applying a controlled displacement of the outer support tube, the sensing rod is brought into contact with the tissue to be characterized. Further displacement of the outer support creates a reaction force with a magnitude representative of the hardness of the anatomical matter. The reaction force causes the sense rod to compress the miniature bellows, thus creating a pressure change within the bellows that is detected by the MEMS pressure sensor as a voltage output representative of the hardness of the tissue.

We experimentally evaluated the H-Probe for its ability to discriminate different degrees of coronary arterial hardness. Six fresh porcine hearts were retrieved from 40- to 50-kg healthy adult pigs. The left anterior descending (LAD) coronary artery was left within its myocardial bed, removing a strip of ventricular tissue approximately 2 cm × 4 cm × wall thickness. Collateral vessels were ligated. Only the proximal and distal ends of the coronary artery were dissected free from the myocardium to allow cannulation and placement into a vessel loop system. A closed loop perfusion circuit was used to circulate sterile, oxygenated,

From the Division of Cardiothoracic Surgery, University of Pittsburgh[a]; Robotics Institute, Carnegie Mellon University[b]; and Vascular Biomechanics Research Laboratory, University of Pittsburgh,[c] Pittsburgh, Pa.

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Address for reprints: Gianluca Bonanomi, MD, Division of Cardiothoracic Surgery, University of Pittsburgh, 200 Lothrop St, Suite C-700, Pittsburgh, PA 15213 (E-mail: bonanomig@msx.upmc.edu).

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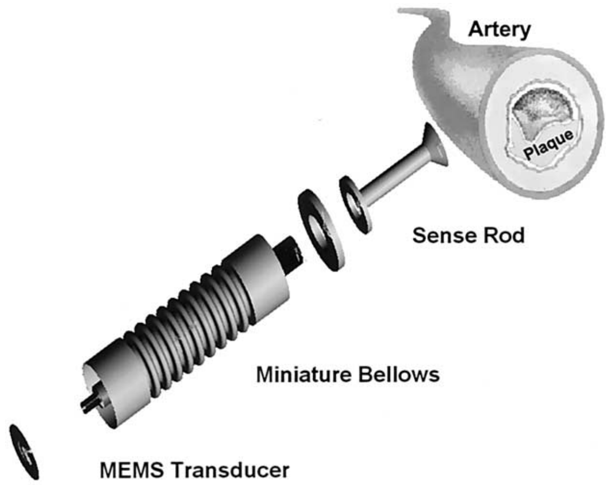

Figure 1. Exploded view of the H-probe to measure arterial wall hardness.

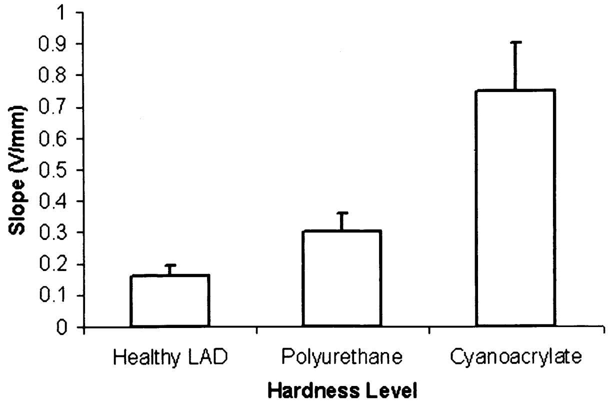

Figure 2. H-probe slope data for different tissue hardness levels (n = 6 for each group).

pH-adjusted lactated Ringer's solution maintained at 37°C at a mean pressure of 100 mm Hg and flow rate of 60 mL/min, as previously described.[5] The H-Probe was applied to the outer surface of the proximal LAD coronary artery.

Coronary artery hardness was classified according to 3 levels: (1) healthy artery representing low hardness; (2) artery covered with polyurethane to simulate medium hardness; (3) artery covered with cyanoacrylate to simulate severe hardness (calcification). Measurements were performed sequentially with the normal artery first and polyurethane- and cyanoacrylate-treated arteries afterward. When the probe came into contact with the artery, a reaction force caused pressure to increase inside the bellows. The voltage output of the H-probe increased linearly and was proportional to the pressure inside the bellows; the rate of this change in pressure was dependent on the hardness of the tissue being measured. A least squares fit was done to determine the slope of the plot. These plots were then repeated for each hardness level.

The H-probe was able to discriminate healthy coronary arteries from those coated with polyurethane and cyanoacrylate, which simulated increasing levels of hardness (Figure 2). Healthy coronary arteries were represented by a mean curve slope of 0.16 ± 0.03 (mean ± SD), range 0.12 to 0.2; polyurethane was responsible for a significant increase of the mean curve slope versus healthy coronary artery: 0.3 ± 0.06, range 0.26 to 0.45 (Wilcoxon test Z: −2.2, $P = .027$); cyanoacrylate was associated with a mean curve slope of 0.75 ± 0.15, range 0.6 to 0.95 (Wilcoxon test Z: −2.2, $P = .028$ versus healthy coronary arteries and polyurethane).

Although the H-probe represents an early product of MEMS technology, further refinement of the hardware engineering and the implementation of a dedicated software are expected to enhance the discriminatory capabilities of this technology and to provide real-time feedback information to the surgeon (eg, curve slope value displayed on a console). Furthermore, investigation is needed to validate the device on human tissues and to establish a relationship between the H-probe readings and different levels of tissue hardness to allow for a clinically useful application.

Incorporation of pressure and hardness sensors, strain gauges, or biochemical sensors into surgical devices might enable the fabrication of instruments capable of distinguishing different types of tissue and allow for enhanced precision and selectivity, thus minimizing tissue damage. Furthermore, miniaturization, batch fabrication, and potential integration with microelectronics are the characteristics of MEMS technology that make it particularly attractive in building small, low-cost, high-performance systems.

The introduction of MEMS-based "smart" devices in the clinical surgical arena might overcome some of the current limitations encountered in endoscopic telerobotic cardiac surgery.

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