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Short Communication

Wireless Implantable Sensors

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While physical and chemical measurements are useful for assessing health conditions of a person, limitations in technology are still making this seemingly simple task difficult. For example, many health factors cannot be remotely tracked with electromagnetic or acoustic energies. In fact, actual sensors need to be present in the human body for accurate measurement of parameters such as forces in organs or at joints, chemical concentrations in blood, etc. Essentially, a *Star Trek* type tricorder that can scan *all* health parameters by waving the device around the person is not yet available [1], or even feasible with today's technology (*Star Trek* inspired devices that can scan certain health indicators such as pulse rates and other vital signs [2] are available but they still cannot monitor internal parameters such as chemicals in blood).

The monitoring of many health parameters requires direct sensor access to the internal body. For examples, to measure chemical contents in blood, a blood sample has to be collected or a sensor probe has to be inserted to the blood vessel. This direct measurement method is acceptable if measurements are done infrequently. However, for long-term, continuous monitoring, the cost and risk of infections with direct measurement can be significantly high. Conversely, implantable sensor technologies are a good alternative to monitor parameters that require constant access to the internal body. Advantages of implantable sensors are that they can provide continuous measurements without constant breaching of the skin of a patient. The drawbacks of this type of sensors include issues with long-term biocompatibility, sensor degradation over time, and long-term power requirements.

Recently, studies were conducted by Ong at Michigan Technological University to examine the application of magnetically soft, magnetoelastic materials as implantable sensors [3-8]. Magnetoelastic materials are a class of magnetic materials that can convert magnetic to mechanical energies and *vice versa*. When under an excitation of a magnetic AC field, these materials generate a secondary magnetic flux that can be remotely monitored. In addition, these materials are also sensitive to stress, and change their magnetic signature in response with force or pressure loading. As a result, they have shown promise to be used as passive (battery-less), wireless implantable force and pressure sensors.

Magneto-harmonic implantable sensors were developed for real-time monitoring of pressure and strain in the human body by measuring the changes in the magnetic higher-order harmonic fields from a magnetoelastic strip [3-6]. The magnetic higher-order harmonic field was generated by exposing the material to a low frequency AC magnetic field, and capturing the returned field at higher frequencies. A permanent magnetic strip was placed next to the magnetoelastic strip. These sensors were specially designed so that when stress or pressure varied, the separation distance between the magnetoelastic strip and the permanent magnetic strip changed. This caused a shift in the pattern of the higher-order harmonic fields, allowing tracking of pressure or force. For pressure monitoring, the permanent magnet was placed on the membrane of an airtight chamber. As illustrated in (Figure 1), changes in the ambient pressure deflected the membrane, altering the separation distance between the two magnetic elements [3]. Similarly, the soft magnetic material and the permanent magnet were separated by a flexible substrate in the stress/strain sensor. Compressive and tensile forces flexed the substrate, changing the separation distance between the two elements and the higher-order harmonic fields [4].

Since the magnetoelastic material is also stress sensitive, pressure can be directly measured by monitoring the changes in the magnitude of the magnetic harmonic fields [7]. As shown in (Figure 2), the sensor has an almost linear response towards pressure. This sensor would be ideal for monitoring pressure in an abdominal aortic aneurysm stent.

The magnetoelastic sensor has also been used to remotely monitor constrictive/compressive forces, such as those generated by a tissue muscle. This type of sensors would be useful for monitoring constrictive pressure at the sphincter of Oddi, in real time and *in vivo*. Figure 3 shows a sensor embedded into a biliary stent model, which was designed to be implanted across the sphincter of Oddi. As illustrated in (Figure 4), the 2nd order harmonic response of the sensor increased with a compressive

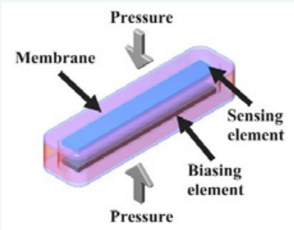

Figure 1 Design of the magneto-harmonic pressure sensor. The sensing element is a magnetoelastic strip and the biasing is a permanent magnetic strip.

load. The compressive force can be tracked by measuring the change in the maximum 2nd order harmonic response (the amplitude of the peak of each curve).

Magnetoelastic sensors have been arrayed to measure force loading on a surface [8], such as those on a knee replacement implant. There is a need to measure contact pressures at the femoral component of a knee replacement implant to determine the wear and tear of the polyethylene insert of the implant. Today, most pressure monitoring systems for knee implants are either limited for *in vitro* or intraoperative uses, or cannot measure contact pressures across the surfaces of the femoral component and tibia plate. Therefore, the magnetoelastic wireless sensor system, as illustrated in (Figure 5), can impact the long term care of patients who receive knee implantation.

As illustrated in (Figure 6), two magnetoelastic strips was placed on a flat substrate, and separated into four regions. Force loading at these regions cause different responses from both strips. As a result, the force loading at each region can be calculated by analyzing the responses from each region of the strip. Previous work [8] has shown this technique can be applied on a flat surface, and current work focuses on adapting this technology for a curved surface.

While the magnetoelastic sensors are promising for biomedical applications, many of them are not biocompatible since nickel and/or cobalt are present in most of them. As a result, Ong recently showed that applying a coating of Parylene-C could greatly increase the biocompatibility of these materials, making them suitable for medical applications [9].

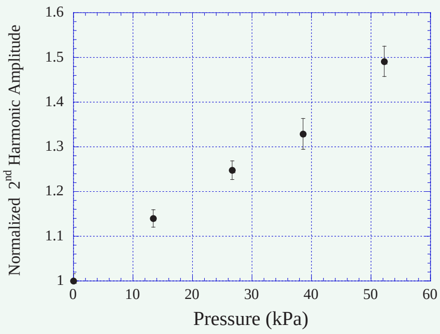

Figure 2 The change in 2nd harmonic amplitude is linear with ambient pressure.

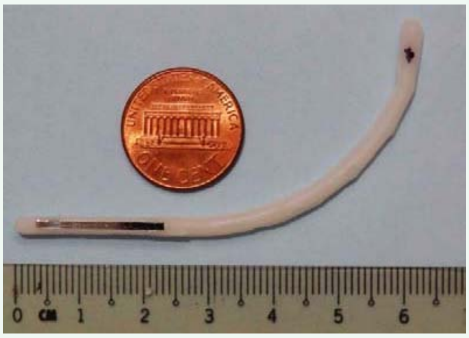

Figure 3 The magnetoelastic sensor embedded in a biliary stent model.

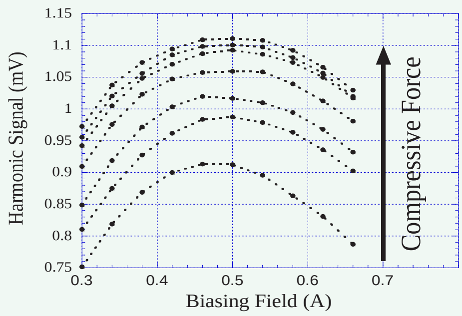

Figure 4 It was demonstrated that the higher-order harmonic response of the magnetoelastic-harmonic sensor correlated directly to the applied force.

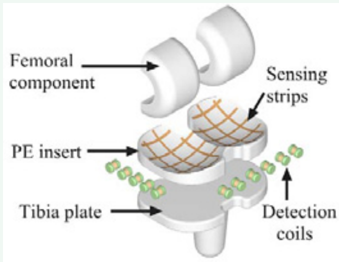

Figure 5 Illustration of the pressure-sensitive magnetoelastic strips embedded in the polyethylene insert (for illustration purposes the sensing strips are shown on the surface of the polyethylene insert). The detection coils are not part of the implant, instead will be worn externally by the user around the knee.

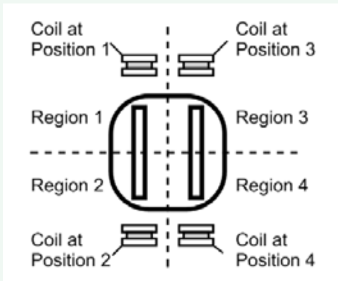

Figure 6 Illustration of the two-element magnetoelastic sensor array for measurement of force profile across a flat surface.

Many promising studies have been conducted to show the application of unique, magnetoelastic materials for biomedical sensing. Currently, Ong's laboratory is working on transforming these sensor technologies for clinical implementation. There is a strong effort to develop arrayed magnetoelastic pressure sensor for mapping pressure profiles at a higher resolution. In addition, animal models are being conducted to prove the efficacy and safety of these technologies, and work is being conducted to further enhance the biocompatibility of these materials.

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