I. INTRODUCTION

The elastic modulus of abnormal tissues such as breast tumors differs from surrounding normal tissues. Often the difference can be several folds. This difference provided the motivation to seek measurement technologies that can assess tumors or regions of tissues of abnormal stiffness mechanically. It would be desirable to be able to assess tissue abnormality in vivo. Typical soft-tissue mechanical property testers require specimens to be cut to a certain shape to fit in the tester and thus are unfit for in vivo measurements. To measure the elastic properties of soft tissues in vivo, one typically uses an indenter to depress the tissue and measures the depth of the indentation with a linear variable differential transducer or an ultrasound transducer, or using magnetic resonance imaging techniques. With these techniques, computations using inversion techniques are required to estimate the size, elastic modulus, and depth of the tumor. It will be beneficial to develop measurement techniques that can experimentally determine tumor elastic modulus, depth, and size noninvasively without relying on simulations or inversion techniques.

Recently, we have developed a piezoelectric cantilever sensor that has a driving piezoelectric layer for force application and a sensing piezoelectric layer for displacement determination for all-electrical palpationlike elastic modulus/shear modulus measurement, offering potential for in vivo elastic and shear modulus imaging applications. A schematic of a piezoelectric cantilever in indentation geometry for elastic modulus measurement is shown in Fig. 1. For shear modulus measurements, the cantilever would rotate 90° to be perpendicular to the sample surface. A piezoelectric cantilever has been demonstrated to be capable of imaging the elastic modulus differences between the tumor region and the surrounding tissues in excised breast tissues and between a hard inclusion and the soft matrix in model tissues. Using the width at half the peak elastic/shear modulus, the lateral size of the tumor or hard inclusion could be estimated. What remains unclear is the depth sensitivity limit under the indentation (or palpationlike) geometry of the piezoelectric cantilever. Preliminary results indicated that tumors or hard inclusions too deep underneath the surface were undetectable by a piezoelectric cantilever. This is understandable as the palpationlike or indentation measurement is a technique that only affects a limited region beneath the surface. If one can measure the depth sensitivity limit of a piezoelectric sensor, it will be possible to use piezoelectric cantilevers to measure the depth and the elastic/shear modulus of a tumor without relying on inversion simulations.

The purpose of this study is to experimentally investigate the depth sensitivity limit of a piezoelectric cantilever elastic modulus sensor and to explore the use of two piezoelectric cantilevers with different widths to simultaneously determine the elastic modulus and the depth of a tumor on model tissues consisting of bottom-supported modeling clay inclusions in a gelatin matrix. In the following, all inclusions are meant to be bottom-supported inclusions. The present modeling clay inclusions which mimic breast tumors had elastic moduli in the range of 40–150 kPa as similar to those of breast tumors. The gelatin matrix which mimics the surrounding breast tissue had an elastic modulus of a few kilopascal as analogous to those of normal breast tissues.
what follows, all experiments were done in the indentation
geometry for elastic modulus measurements. It should be
noted that the methodology discussed in this study for elastic
modulus measurements also applies to shear modulus
measurements. The rest of the paper is organized as follows.
Section 2 describes the fabrication and characterization of
the piezoelectric cantilevers, the all-electrical indentation
(palpationlike) tissue elastic modulus measurements, the
methodology of simultaneous determination of tumor depth
together with the sample.

II. EXPERIMENT PROCEDURE AND METHODS

A. Cantilever fabrication and characterization

Three piezoelectric cantilevers were used in this study.
Cantilever A was 3.8±0.2 mm wide, cantilever B was
6.1±0.2 mm wide, and cantilever C was 8.6±0.2 mm wide
as listed in Table I. All cantilevers had two 127 μm thick
lead zirconate titanate (PZT) layers (T105-H4E-602, Piezo
Systems Inc., Cambridge, MA) bonded to a 50 μm thick
stainless steel layer (Alfa Aesar, Ward Hill, MA), one on the
top side of the stainless steel for driving and the other on the
bottom side of the stainless steel for sensing as schematically
shown in Fig. 1, using a nonconductive epoxy (Henkel Loc-
tite Corporation, Industry, CA), followed by curing at room
temperature for one day and sanding of the edges for uniform-
ity. The driving PZT layers were 22±0.2, 24±0.2, and
25±0.2 mm long and sensing PZT layers were 11±0.2,
12±0.2, and 11±0.2 mm long for cantilevers A, B, and C,
respectively (see Table I). The stainless steel tip was fash-
ioned into a square loop at the free end with each side of the
square equal to the width of the cantilever to facilitate both
compression and shear measurements using one single can-
tilever. The cantilevers were clamped with a fixture made of
7.5 mm thick acrylic (McMaster-Carr, New Brunswick, NJ).
The PZT layers have a piezoelectric coefficient, 
\( d_{31}=\pm 320 \, \text{pC/N} \). Young’s modulus of the stainless steel
and that of the PZT layers were 200 and 62 GPa, respectively.
The capacitance and the loss factor of a PZT layer were
measured using an Agilent 4294A Impedance Analyzer (Agil-
ent, Palo Alto, CA).

In an indentation measurement, as the square stainless
steel tip cross section was much smaller than the sample
surface, it was the square stainless steel tip cross section that
defined the area of indentation. The contact areas were
14±1, 37±3, and 74±4 mm², the square of the widths of
cantilevers A, B, and C, respectively (see Table I).

For cantilever tip displacement measurements, Keyence
cantilever configuration laser displacement meter with a 0.5 μm
resolution was used. The effective spring constants of cantilevers A, B, and C were
143, 187, and 215 N/m as determined using the earlier
published procedure. In what follows, we conduct on a Newport optical table
(RS1000, Newport Corporation, Irvine, CA) to minimize low-frequency
background vibrations. The applied voltage across the driving
PZT layer and the induced voltage across the sensing
PZT layer were recorded on an Agilent Infinium S4832D
digital oscilloscope (Agilent, Palo Alto, CA). The dc power
source and the oscilloscope were connected to a personal
computer (PC). All voltage measurements, real-time elastic
modulus computations, and data acquisitions were controlled
from a PC by LABVIEW (National Instrument, Austin, TX)
programming.

B. Induced voltage measurements

When a dc voltage is applied across the driving PZT
layer, a measurable piezoelectric voltage is induced across
the sensing PZT layer. As an example, the induced voltage
versus time of cantilever A at various applied voltages is
shown in Fig. 2(a). As can be seen, the induced voltage in-
creased sharply initially to a maximum then decayed expo-
entially with time due to the finite resistance of the PZT. In
Fig. 2(b), we show the peak induced piezoelectric voltage
versus the cantilever tip displacement. Figure 2(b) shows that
the peak induced voltage was proportional to the cantilever
tip displacement. With the spring constant of the
cantilever, \( K=143 \, \text{N/m} \), the cantilever tip displacement
shown in the x axis of Fig. 2(b) can also be translated into a
force, \( F=Kd \), exerted on the cantilever tip, where \( d \) repre-
sents the cantilever tip displacement. The equivalent force
associated with a tip displacement \( d \) is labeled on the top x
axis of Fig. 2(b). Figure 2(b) clearly illustrates that the peak
induced piezoelectric voltage can be used to monitor the can-
tilever tip displacement as well as the equivalent force at the
cantilever tip. This is the basis of the cantilever’s all-
electrical elastic modulus measurements. In what follows, we
will refer to the peak induced piezoelectric voltage simply as
the induced voltage \( V_{in} \).

![Figure 1](https://example.com/figure1.png)

**FIG. 1.** A schematic of an all-electrical piezoelectric cantilever performing a compression test. The cantilever has a top PZT layer for driving, a bottom PZT layer for sensing, and a stainless steel tip that has a square contact area with the sample.

**TABLE I.** Dimensions of cantilevers A, B, and C.

<table>
<thead>
<tr>
<th>Cantilever</th>
<th>Driving PZT (mm)</th>
<th>Sensing PZT (mm)</th>
<th>Width (mm)</th>
<th>Probe area ((\text{mm}^2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>22±0.2</td>
<td>11±0.2</td>
<td>3.8±0.2</td>
<td>14±1</td>
</tr>
<tr>
<td>B</td>
<td>24±0.2</td>
<td>12±0.2</td>
<td>6.1±0.2</td>
<td>37±3</td>
</tr>
<tr>
<td>C</td>
<td>25±0.2</td>
<td>11±0.2</td>
<td>8.6±0.2</td>
<td>74±4</td>
</tr>
</tbody>
</table>
C. All-electrical indentation elastic modulus measurements

Since the induced voltage across the sensing electrode is linear to the displacement and the force at the cantilever tip, one can calibrate the corresponding force and displacement with the induced voltage and express the displacement, force, and elastic moduli in terms of the induced voltage.21,22

First, the induced voltages of the cantilevers at various applied voltages $V_a$ were measured without and with a sample underneath the cantilever tip. As an example, we plot $V_{in}$ vs $V_a$ of cantilever A without and with a gelatin sample in Fig. 3a. The concentration of the gelatin was 0.07 g/ml prepared by mixing 19.25 g of gelatin in 275 ml of water at 80 °C on a hot plate for 5 min, cooled at 5 °C for 1 h to solidify, and then equilibrated at room temperature for 1 h prior to measurements. The gelatin obtained as described above was the gelatin matrix for the model tissues we used in this study. With $V_{in,0}$ denoting the induced voltage without a sample under the indentation geometry, the elastic modulus $E$ of the gelatin sample could be deduced as21,22

$$X = \frac{1}{2} \left( \frac{\pi}{A} \right)^{1/2} (1 - \nu^2) K (V_{in,0} - V_{in}),$$

where $\nu=0.5$ being Poisson’s ratio of the gelatin sample,21,22 $A$ the contact area of the cantilever stainless steel tip, and $K$ the effective spring constant of the cantilever. Therefore, once the induced voltages without and with the sample were measured, the elastic modulus of the sample can be readily obtained from the slope of $X$ vs $V_{in}$. Note that in the present study, $X$ vs $V_{in}$ was linear with little hysteresis between the up sweep and down sweep. The reason for this lack of hysteresis is that the strains in these studies are very small, less than 0.1%. If larger strains are involved, generally, $X$ vs $V_{in}$ may not be linear and the elastic modulus should be deduced from the down sweep near the maximum $V_{in}$.23 Measurement of $V_{in}$, computation of $X$, plotting of $X$ vs $V_{in}$, and real-time extraction of the elastic modulus from the slope of $X$ vs $V_{in}$ were all carried out through LABVIEW. Note that Eqs. (1) and (2) are for a circular indentation area. Approximating the current square contact area as circular was justified as the error of using a circular indenter formula for the present square contact area was only 1.2%,23 which was smaller than the present experimental error. From Fig. 3(b), one could deduce the elastic modulus of the gelatin matrix from the

FIG. 2. (Color online) (a) Induced piezoelectric voltage vs time at the sensing PZT when a voltage was applied to the driving PZT layer and (b) peak induced voltage vs tip displacement (force on top) of cantilever A.

FIG. 3. (Color online) (a) $V_{in}$ vs $V_a$ of cantilever A without (open circles) and with (open squares) the gelatin sample and (b) $X$ vs $V_{in}$ where $X$ is as defined in the text. The slope of $X$ vs $V_{in}$ gave the elastic modulus of the gelatin sample.
therefore determined as the depth of the inclusion gelatin matrix. The depth sensitivity limit of a cantilever was face, the effective modulus would converge to that of the top and the modeling clay inclusion at the bottom. Con-


TABLE II. The summary of the known depth and modulus of the inclusions used in models I and II.

<table>
<thead>
<tr>
<th>Inclusion No.</th>
<th>Known depth (mm)</th>
<th>Known elastic modulus (kPa)</th>
<th>Known depth (mm)</th>
<th>Known elastic modulus (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1±0.3</td>
<td>145±10</td>
<td>2±0.3</td>
<td>145±10</td>
</tr>
<tr>
<td>2</td>
<td>3±0.3</td>
<td>145±10</td>
<td>2±0.3</td>
<td>92±9</td>
</tr>
<tr>
<td>3</td>
<td>5.5±0.3</td>
<td>145±10</td>
<td>2±0.3</td>
<td>54±12</td>
</tr>
<tr>
<td>4</td>
<td>6.5±0.3</td>
<td>145±10</td>
<td>4±0.3</td>
<td>145±10</td>
</tr>
<tr>
<td>5</td>
<td>9±0.3</td>
<td>145±10</td>
<td>4±0.3</td>
<td>92±9</td>
</tr>
<tr>
<td>6</td>
<td>11±0.3</td>
<td>145±10</td>
<td>4±0.3</td>
<td>54±12</td>
</tr>
<tr>
<td>7</td>
<td>13±0.3</td>
<td>145±10</td>
<td>6±0.3</td>
<td>145±10</td>
</tr>
<tr>
<td>8</td>
<td>15±0.3</td>
<td>145±10</td>
<td>6±0.3</td>
<td>92±9</td>
</tr>
<tr>
<td>9</td>
<td>16.5±0.3</td>
<td>145±10</td>
<td>6±0.3</td>
<td>54±12</td>
</tr>
</tbody>
</table>

slope as 3.8±0.5 kPa, which was consistent with the elastic modulus of gelatin of this concentration made with the above procedure. In what follows, all elastic modulus measurements were carried out using the indentation geometry, and the elastic modulus was deduced, as illustrated in Figs. 3(a) and 3(b) automatically through LABVIEW.

D. Depth sensitivity measurements

To examine the depth sensitivity limit of the cantilevers, a model consisting of a gelatin matrix (G7-500, Fisher Scientific, Fair Lawn, NJ) with red modeling clay (Modeling Clay, Crayola, Easton, PA) inclusions buried at various depths underneath the surface was prepared. Indentation tests were carried out at the center of the gelatin surface above the center of each inclusion to determine the effective elastic modulus of the model tissue which contained the gelatin on the top and the modeling clay inclusion at the bottom. Conceivably, as the inclusions became too deep below the surface, the effective modulus would converge to that of the gelatin matrix. The depth sensitivity limit of a cantilever was therefore determined as the depth of the inclusion (defined as the distance from the gelatin surface to the top surface of the inclusion) beyond which the measured elastic modulus of the model tissue was indistinguishable from that of the gelatin matrix. Nine inclusions, each with a 16×16 mm² top surface but a different height, were glued to the bottom of a container with 24 mm height (model I). The gelatin matrix had a concentration of 0.07 g/ml as prepared by mixing 19.25 g of gelatin in 275 ml of water at 80 °C on a hot plate for 5 min, poured over the model clay inclusions, and then cooled at 5 °C for 1 h to solidify. The sample was allowed to equilibrate at room temperature for 1 h prior to the measurements. The total height of the gelatin of model I was 24±0.3 mm. The depths of the nine inclusions in model I are listed in Table II.

E. Empirical determination of depth and elastic modulus of inclusions

To illustrate the empirical determination of the inclusion elastic modulus and inclusion depth, we embedded three different types of modeling clay inclusions of various depths (model II). Each type of modeling clay had a different stiffness. The elastic moduli of the three different types of modeling clay were independently measured using the procedures described in Sec. II C. The green modeling clay (Play-Doh, Hasbro Ltd., Newport, UK) was softer with an elastic modulus of 54±12 kPa. The blue modeling clay (Model Magic, Crayola, Easton, PA) was intermediate with an elastic modulus of 92±9 kPa, and the red modeling clay (Modeling Clay, Crayola, Easton, PA), which was also used in model I, was stiffer with an elastic modulus of 145±10 kPa. The gelatin matrix used had the same concentration and preparation procedure as described above. All the inclusions in model II were also bottom supported. The total height of the gelatin in model II was 20±0.3 mm. The “known” depths and elastic moduli of the nine inclusions in model II are also listed in Table II.

After the depth sensitivity limit of each cantilever was determined, as described in Sec. II D, it is possible to deduce both the elastic modulus of the inclusion \( E_i \) and the inclusion depth \( h_i \) (defined as the distance from the gelatin surface to the top surface of the inclusion) from the measurements of two cantilevers of different widths (cantilever 1 and cantilever 2). With the depth sensitivity limit of cantilever 1 and that of cantilever 2 designated as \( h_1 \) and \( h_2 \) and the effective modulus of the model tissue measured by cantilever 1 and cantilever 2 at the gelatin surface above the center of inclusion as \( E_1 \) and \( E_2 \)—and assuming the gelatin and the inclusion as two springs in series—the effective elastic moduli, \( E_1 \) and \( E_2 \), can then be expressed as

\[
\frac{h_1}{E_1} = \frac{h_i}{E_i} + \frac{(h_1-h_i)}{E_g},
\]

\[
\frac{h_2}{E_2} = \frac{h_i}{E_i} + \frac{(h_1-h_i)}{E_g}.
\]

A schematic of the “two-spring model” for the model tissue with an inclusion of elastic modulus \( E_i \) at a depth of \( h_i \) is shown in Fig. 4(a) the measurement of \( E_1 \) using cantilever 1 that has a depth sensitivity, \( h_1 \), and (b) the measurement of \( E_2 \) using cantilever 2 that has a depth sensitivity, \( h_2 \). As can be seen, there are two unknowns, \( h_i \) and \( E_i \), in Eqs. (3) and (4). All other quantities are measurable. Therefore, the two unknowns, \( h_i \) and \( E_i \), can be deduced by solving Eqs. (3) and (4) simultaneously using the input from measurements on the same model using two different cantilevers. Note that the implicit assumption of Eqs. (3) and (4) is that \( h_1 \) and \( h_2 \) are
larger than \( h_i \). If the inclusion is deeper than the depth sensitivities of the cantilevers, then the above analysis is not valid.

**III. RESULTS AND DISCUSSIONS**

**A. Depth sensitivity**

To experimentally determine the depth sensitivity of the cantilevers, indentation tests were carried out at the gelatin surface above the centers of the modeling clay inclusions in model I. In Fig. 5(a), we plot the measured elastic moduli of the model tissue above the center of the modeling clay inclusions versus the known depths of the inclusions for cantilevers A (white bars), B (cross-shaded bars), and C (line-shaded bars). Note that in deducing the effective elastic modulus of the model tissues, Poisson’s ratio of the inclusion was taken as 0.5, as validated in Ref. 22. As can be seen in Fig. 5(a), the measured effective elastic modulus decreased with an increasing depth and saturated at about 3.8±1 kPa, which was the elastic modulus of the gelatin matrix as shown in Fig. 3(b). The elastic modulus range of the gelatin matrix is marked by the two horizontal dashed lines in Fig. 5(a). We empirically defined a cantilever’s depth sensitivity limit as the largest depth at which the measured effective elastic modulus on the gelatin surface was larger than and experimentally distinguishable from that of the gelatin matrix. With this criterion, we obtained 8, 12, and 17 mm as the depth sensitivity limit for cantilevers A, B, and C, respectively. The dependence of the depth sensitivity limit on the cantilever width (the linear dimension of the indentation area) is summarized in Fig. 5(b), where we plot the depth sensitivity limit versus the cantilever width. As can be seen, the depth sensitivity limit was linear with cantilever width with a slope of about 2, indicating that for a given cantilever, the depth sensitivity limit was about twice its width. Therefore, the results shown in Figs. 5(a) and 5(b) indicate that in an indentation experiment, the depth affected by the indentation was roughly twice the linear dimension of the indentation area. Tissues below the depth sensitivity limit was unaffected by the indentation, thus insensitive to the measurements.

**B. Inclusion depth and elastic modulus measurement using two cantilevers**

With the depth sensitivity of each cantilever determined above, it is possible to determine the elastic modulus and depth of an unknown inclusion. In model II, we embedded nine inclusions out of three different kinds of modeling clays of various heights. As mentioned above, the elastic moduli of the green, blue, and red modeling clays were independently measured and determined to be 54±12, 92±9, and 145±10 kPa, respectively, using the indentation test as described in Sec II C. The known elastic moduli of the inclusions in model I and model II were also listed in Table II. As an example, we show the effective elastic modulus profiles of inclusion 2 in model II (see Table II), as measured using cantilever A (open circles) and cantilever B (open squares) in Fig. 6. From Fig. 6, one can see that at locations away from the center of the inclusion at \( x=0 \), the effective moduli measured by cantilever A were essentially the same as those measured by cantilever B. Moreover, the values of the effective elastic moduli at locations away from the inclusion, 4.1±0.4 kPa, matched that of the gelatin matrix independently obtained in Fig. 3(b), 3.8±0.5 kPa, as marked by the
horizonal dashed line in Fig. 6. Therefore, in the following analyses, for each of the nine inclusions in model II, two elastic modulus profiles were measured using two different cantilevers, cantilever A and cantilever B, as illustrated in Fig. 6. The elastic modulus of the gelatin matrix was then taken as values at locations away from the inclusion where the elastic moduli measured by the two cantilevers at the same location were the same. The elastic modulus and the depth of the inclusion were then deduced using the elastic modulus values obtained away from the inclusion (e.g., 4.1±0.4 kPa in Fig. 6) as input for the elastic modulus of the gelatin matrix for Eqs. (3) and (4). With \( h_1 = 8 \text{ mm} \) and \( h_2 = 12 \text{ mm} \) for cantilever A and cantilever B, respectively [as determined from Figs. 5(a) and 5(b) above] and \( E_1 = 14±2 \text{ kPa} \) and \( E_2 = 22±3 \text{ kPa} \), respectively (as determined by the peak effective elastic modulus values measured by cantilever A and cantilever B as shown in Fig. 6) as input, Eqs. (3) and (4) were then simultaneously solved for two unknowns, the inclusion depth \( h_i \) and the inclusion elastic modulus \( E_i \), using MAPLE 10 (Maplesoft, Ontario, Canada). The deduced \( h_i = 2±0.4 \text{ mm} \) and \( E_i = 82±18 \text{ kPa} \) were consistent with the known depth of \( 2±0.3 \text{ mm} \) and elastic modulus of \( 92±9 \text{ kPa} \) of inclusion 2 of model II, as shown in Table II. In Fig. 7, we summarize the deduced inclusion elastic modulus and inclusion depth in the two-dimensional (2D) elastic versus depth plot. The inset in Fig. 7 shows the photograph of model II which contained the nine inclusions of various moduli and various depths. Also plotted in Fig. 7 are the known values of the inclusion moduli and inclusion depths. As can be seen, for all nine inclusions, the deduced values and the known values were within each other’s experimental uncertainty in the 2D elastic modulus versus depth space, indicating that the present approach of using two cantilevers with different widths was indeed capable of determining the inclusion elastic modulus and inclusion depth simultaneously.

It should be noted that for the present method to work, the depth sensitivities of the cantilevers must be sufficiently larger than the depth of the inclusion as discussed above. Therefore, only when both cantilevers produce bell-shaped elastic modulus profiles such as the one shown in Fig. 6, Eqs. (3) and (4) can be used to deduce the inclusion elastic modulus and inclusion depth.

In addition, the inclusion elastic modulus, inclusion depth, and the lateral size of the inclusion, can also be deduced from the effective elastic profiles shown in Fig. 6. From the bell-shaped elastic modulus profile, the lateral size of the inclusion was estimated as the width at half the peak height. The lateral sizes of the inclusion as deduced from Fig. 6 were 16±1 and 15±1 mm as measured by cantilevers A and B, respectively, consistent with the known value of 16 mm. The location of the inclusion was marked by the shaded square in Fig. 6.

**ACKNOWLEDGMENTS**

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