

Measurement of Needle-Tip Bioimpedance to Facilitate Percutaneous Access of the Urinary and Biliary Systems

First Assessment of an Experimental System

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RATIONALE AND OBJECTIVES. Percutaneous access to the renal collecting system or biliary system is most frequently performed under image guidance. However, current techniques lack a feedback mechanism to help confirm successful access. A percutaneous needle system has been developed consisting of a modified 18-gauge percutaneous access needle that measures tissue impedance at its needle tip. Initial results in utilizing this novel system to determine successful access into dilated kidney and gall bladder specimens are reported.

METHODS. Impedance measurements were recorded as the needle was precisely advanced through ex vivo kidney and liver/gall bladder specimens. In an anesthetized porcine model, impedance values were recorded with laparoscopic visualization as the needle was advanced percutaneously through abdominal wall, liver, and into gall bladder.

RESULTS. A characteristic, reproducible drop in impedance was noted with successful entry into ex vivo distended kidney and gall bladder specimens. This feature was also noted during in vivo percutaneous cholecystostomy.

CONCLUSIONS. A measurable, characteristic drop in tissue impedance signifies successful entry into the urinary and biliary systems. This impedance needle system may facilitate cur-

rent percutaneous access techniques.

KEY WORDS. Electrical impedance; kidney; gall bladder; percutaneous nephrostomy; percutaneous cholecystostomy.

PERCUTANEOUS ACCESS to the renal collecting system and biliary system is often challenging even with current image guided techniques. The targeted renal calyx may be missed or overshot without feedback, thus necessitating multiple access attempts, particularly in nondilated systems.¹ Similarly, difficult biliary-access cases often require multiple needle punctures, which can result in hemobilia and other fistulous complications.^{2,3} An access needle capable of measuring impedance at its needle tip may facilitate access and reduce procedure time, blood loss, and trauma to the tissues.

Impedance (Z) is a measure of the total opposition to current flow in an alternating current (AC) circuit and is defined in terms of its three individual components: resistance (R), inductance (L), and capacitance (C).

$$Z = R + j(\omega L - 1/\omega C)$$

The angular frequency of the current is represented by ω , and j is the square root of (-1) . Impedance can best be understood as the AC correlate of resistance (R) in direct current (DC) circuits ($R = V/I$), and is likewise expressed in Ohms (Ω).

Schwan demonstrated that tissues and physiological fluids have characteristic ranges of impedance values.⁴ This principle has been used in select applications to distinguish tissues and confirm anatomic localization. In neurosurgery, bioimpedance measurement was first used to verify pene-

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Louis R. Kavoussi and Dan Stoianovici are coinventors of the Smart Needle system used in this study. Patent and trademark pending.

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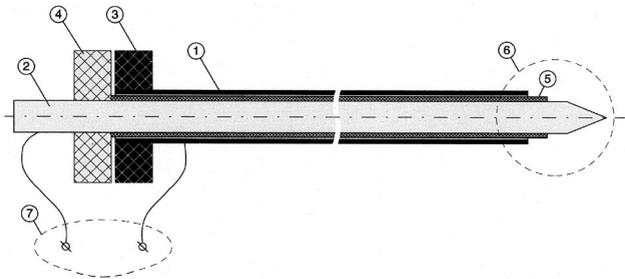


Figure 1. A schematic drawing of the impedance needle. The metal trocar¹ is insulated from the metal stylet² by an insulating coating.⁵ Both components are connected to an LCR meter.⁷ The needle tip⁶ measures impedance between the exposed stylet tip and the trocar tip. The plastic hubs of the trocar³ and the stylet⁴ are also shown.

tration of the spinal cord during percutaneous cervical cor-dotomy and has subsequently been applied to optimize characterization of brain tumors.^{5,6} In urology, it has been shown that regions of prostate cancer can be distinguished from normal prostate tissue based upon impedance characteristics.⁷ In this study, we report initial results on the feasibility of using a bioimpedance-sensing needle to confirm successful access to the renal collecting system and gall bladder.

Materials and Methods

Bioimpedance Apparatus

The needle system is a modified percutaneous access needle that measures electrical impedance at its tip every 200 milliseconds. The 18-gauge needle is composed of three parts: a metal outer tubular barrel, a metal inner stylet with a sharp needlepoint, and an insulating middle layer between the barrel and the stylet (Fig. 1). The electrical insulator leaves only the distal three millimeters uncovered such that the tip of the needle serves as a sensitive electrical probe. A robotic needle driver was used to insert the needle to precisely measured depths within the specimen.^{8,9} The experimental apparatus is shown in Figure 2.

A multifrequency inductance/capacitance/resistance (LCR) meter (Hewlett Packard 4275; Hewlett Packard, Palo Alto, CA, USA) connected to the needle tip measures impedance. This LCR meter applies a micro voltage sinusoidal signal of high frequency between the barrel and stylet at the needle tip and measures the amplitude and phase shift of the response signal. From this data, the individual components of impedance (Z): resistance (R), capacitance (C), and inductance (L) of the tissue surrounding the needle tip can be determined. The system was tested over a range of frequencies using an ideal circuit to identify a linear range between 400 and 2000 kHz. All tissue experiments were conducted using a frequency of 1000 kHz. Inductance and capacitance were found to be negligible at this frequency, thus the resistance was the principal component of impedance.

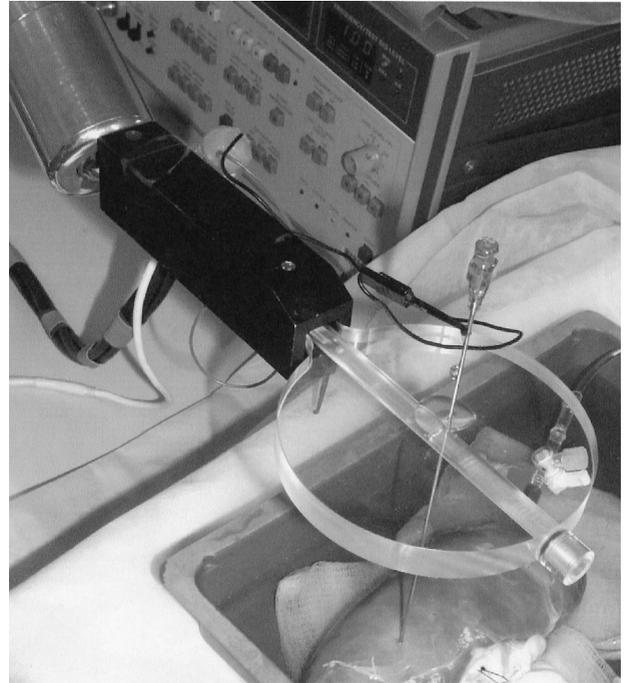


Figure 2. Overall setup of the impedance needle system during the ex vivo pig kidney experiments. The needle is supported in the robotic-needle driver and is seen piercing the kidney. Saline efflux from the top of the needle indicates successful entry into the collecting system. The LCR meter is seen in the background.

Real-time measurements of impedance, resistance (ohms), and depth were recorded for each experiment using the LCR meter and robotic needle driver, respectively. To facilitate comparison of data between trials utilizing different needles, results were reported as resistivity values (ohm meters). Resistivity is a measure of resistance adjusted by the needle calibration constant to correct for small physical differences between needles.

Experiments

Ex Vivo. A pig was killed and kidney and liver specimens with intact gall bladder were obtained. The kidney was distended by infusing saline from a height of 100 cm through a catheter inserted in an antegrade fashion into the collecting system. A purse-string suture was placed around the distal ureter providing a control for the degree of distension of the collecting system. The kidney was placed flat and the needle was advanced without image guidance in a linear fashion through the renal parenchyma. Impedance was measured continuously, and a robotic-linear needle driver allowed needle positioning at precisely measured depths within the parenchyma. Successful entry into the collecting system was confirmed by saline efflux once the stylet was removed.

The gall bladder remained distended after en bloc resection with the liver. In similar fashion, the needle was lin-



Figure 3. Impedance-needle system and robotic-positioning system during percutaneous cholecystostomy in a porcine model. Note the laparoscopic camera used to correlate needle-tip position with resistivity measurements.

early advanced into the gall bladder specimen with real-time measurement of impedance and needle tip depth. Successful entry into the gall bladder was confirmed by bile efflux when the stylet was removed.

In Vivo. After an approved protocol from the institutional animal care and use committee, a percutaneous cholecystostomy was performed in one anesthetized pig with laparoscopic visualization (Fig. 3). The impedance needle was linearly inserted through the abdominal wall, liver, and into

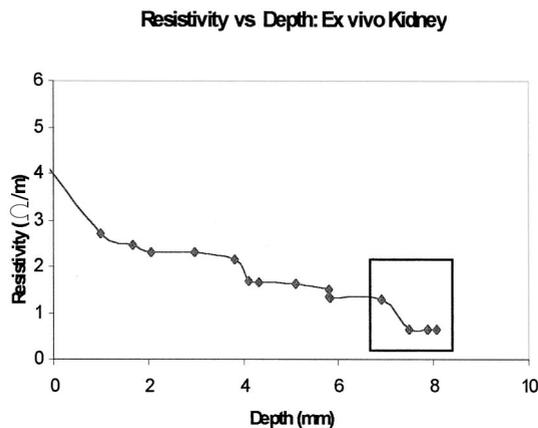


Figure 4. Resistivity versus depth during ex vivo pig kidney experiment. The characteristic drop in resistivity is outlined for emphasis.

Resistivity vs Depth: In Vivo Percutaneous Cholecystostomy

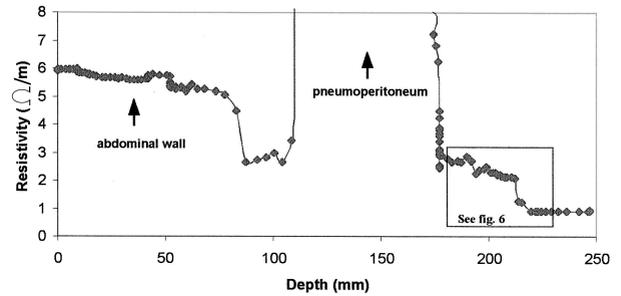


Figure 5. Resistivity versus depth during in vivo pig cholecystostomy. The left portion of the curve depicts the resistivity of the abdominal wall tissues. Upon entry into the pneumoperitoneum, the resistivity values were infinite.

gall bladder. A previously placed laparoscopic camera provided visualization of the insertions and allowed correlation of needle tip location with impedance measurements.

Results

A representative plot of resistivity versus depth is displayed for a successful ex vivo kidney access attempt (Fig. 4). Piercing of the renal-collecting system resulted in a sharp drop in resistivity from 1.5 Ω/m to 0.7 Ω/m in this specimen. A similar sharp drop in resistivity was noted in four additional punctures of this distended collecting system and in identical experiments on four other kidney specimens. Control punctures through renal parenchyma without entering the collecting system did not demonstrate a sharp drop in impedance and the resistivity values did not fall below 1.0 Ω/m. Similar results were obtained with access of the gall bladder in three ex vivo liver and gall-bladder specimens. A characteristic drop in resistivity from 2.0 Ω/m to 0.8 Ω/m was observed with passage of the needle tip from liver, through gall-bladder wall, and into gall bladder.

Resistivity vs Depth: In Vivo Percutaneous Cholecystostomy

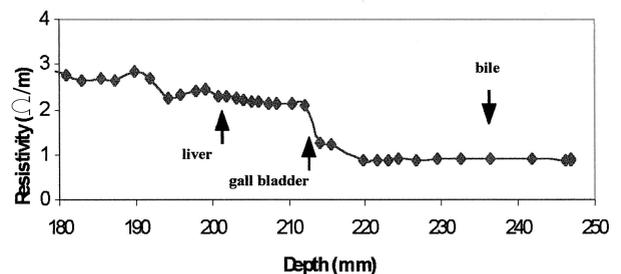


Figure 6. An enlargement of a portion of the in vivo percutaneous cholecystostomy plot shown in Figure 5. Resistivity values of liver range from 2.0 Ω/m to 3.8 Ω/m. A characteristic sharp drop in resistivity is noted during penetration of the gall bladder. The resistivity values plateau at 0.8 Ω/m representing needle immersion in bile within the gall bladder.

A representative resistivity versus depth plot is shown for in vivo percutaneous cholecystostomy access (Figs. 5 and 6). Arrows on the figure correspond to penetration of abdominal wall, entry into laparoscopic pneumoperitoneum, entry into liver, and entry into the distended gall bladder as observed with the laparoscopic camera.

Discussion

Resistivity is an intrinsic electrical property of tissues that can be measured and used to distinguish between different tissues. Schwan et al.¹⁰ published resistivity values, measured at 1000 kHz, of 4.2 Ω /m to 7.0 Ω /m for brain, 2.1 Ω /m to 4.2 Ω /m for liver, and 1.4 Ω /m to 2.5 Ω /m for kidney. The kidney and liver tissue resistivity values that we measured correlate well with the values obtained by Schwan et al.¹⁰ Furthermore, these feasibility trials demonstrate that successful entry into the collecting system or gall bladder can be confirmed by measuring tissue impedance (resistivity). A characteristic drop in resistivity (to values less than 1 Ω /m) is indicative of successful access of the collecting system or gall bladder.

The initial feasibility studies of this system are encouraging in that a reproducible characteristic drop in resistivity is seen upon entry into the distended renal collecting system or the gall bladder. Although the characteristic features of successful entry are as yet only discernible in a dilated renal collecting system or gall bladder, improvements in needle design may allow enhanced determination of entry into nondilated renal collecting systems and small intrahepatic bile ducts. For example, reducing the size of the needle and decreasing the spacing between the needle tip electrodes will likely improve the sensitivity of the system, thus allowing more precise discernment of changes in tissue properties. These improvements may allow detection of entry into smaller nondilated structures.

Currently, if the stylet is removed during an access attempt and then reinserted, fluid can accumulate between the inner stylet and the sheath leading to erroneous measurements. Redesign of the needle to incorporate precisely positioned ring electrodes along a nonconducting needle-tip stylet is currently underway. With additional research, and the rapid development of micro and nano scale devices, further refinements of this system may allow not only measurement of impedance and its components (resistance, capacitance, and inductance), but also other properties of tissues, such as optical characteristics and biochemical composition.

This impedance needle system is not limited to renal or biliary applications. It may prove useful for paracentesis, thoracentesis, lumbar puncture, placement of epidural catheters, and other procedures performed without image guidance. Additionally, it has been previously shown that electrical properties of distinct tissue types are significantly different.^{10,11} Therefore, this system may be useful to dis-

tinguish tissue types or to distinguish diseased from healthy tissue in medical renal disease or hepatic parenchymal disease. It has also been previously demonstrated that the electrical properties of cancerous tissues differ from normal tissues.^{7,12} Specifically, within the prostate, areas of prostate cancer were found to have higher impedances than areas of normal tissue.⁷ This capability to distinguish cancerous from normal tissues may be beneficial in the diagnosis and treatment of a wide range of malignancies.

In summary, we have designed a needle capable of precisely measuring tissue impedance. This initial feasibility study has reproducibly shown that a characteristic sharp drop in impedance signifies successful entry into the renal collecting system or gall bladder in ex vivo pig specimens. In vivo percutaneous cholecystostomy demonstrated similar impedance changes. The impedance-sensing function of the needle may prove to be of great assistance in minimally invasive percutaneous procedures.

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