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MEASUREMENT OF BIO-IMPEDANCE WITH A SMART NEEDLE TO CONFIRM PERCUTANEOUS KIDNEY ACCESS

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ABSTRACT

Purpose: The traditional method of percutaneous renal access requires freehand needle placement guided by C-arm fluoroscopy, ultrasonography, or computerized tomography. This approach provides limited objective means for verifying successful access. We developed an impedance based percutaneous Smart Needle system and successfully used it to confirm collecting system access in ex vivo porcine kidneys.

Materials and Methods: The Smart Needle consists of a modified 18 gauge percutaneous access needle with the inner stylet electrically insulated from the outer sheath. Impedance is measured between the exposed stylet tip and sheath using Model 4275 LCR meter (Hewlett-Packard, Sunnyvale, California). An ex vivo porcine kidney was distended by continuous gravity infusion of 100 cm. water saline from a catheter passed through the parenchyma into the collecting system. The Smart Needle was gradually inserted into the kidney to measure depth precisely using a robotic needle placement system, while impedance was measured continuously.

Results: The Smart Needle was inserted 4 times in each of 4 kidneys. When the needle penetrated the distended collecting system in 11 of 16 attempts, a characteristic sharp drop in resistivity was noted from 1.9 to 1.1 ohm m. Entry into the collecting system was confirmed by removing the stylet and observing fluid flow from the sheath. This characteristic impedance change was observed only at successful entry into the collecting system.

Conclusions: A characteristic sharp drop in impedance signifies successful entry into the collecting system. The Smart Needle system may prove useful for percutaneous kidney access.

KEY WORDS: kidney, swine, electric impedance, surgical instruments

Various minimally invasive urological procedures, including percutaneous nephrolithotomy and transitional cell carcinoma treatment, depend on image guided, percutaneous renal access. Successful rapid percutaneous access to the renal collecting system requires multidirectional imaging and significant operator experience. The targeted calix may be missed or overshot without feedback. To determine the actual location of the needle tip the surgeon must occasionally pause, remove the inner stylet and observe or aspirate urine. In this conventional system the surgeon has limited objective means of judging whether successful access has been attained. In addition, many complications of percutaneous nephrolethotomy are associated with initial needle placement. Using a Smart Needle to confirm access to the collecting system of the kidney may decrease the number of punctures necessary to attain access and, thus, reduce operative time, blood loss and kidney trauma.

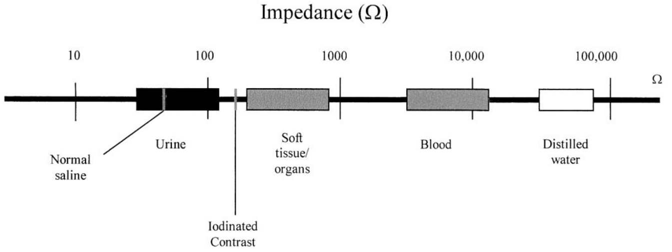

FIG. 1. Characteristic range of electrical impedance values for select tissues and fluids.

The Smart Needle consists of a modified percutaneous access needle that continuously measures electrical impedance at its tip. Impedance is a measure of the total opposition to current flow in an alternating current circuit. It is best understood as the alternating current correlate of resistance (R) in using the formula, $R = V/I$, for direct current circuits, where V represents voltage and I represents electrical current. It is also expressed in Ω. Previous studies have shown that tissues and physiological fluids have characteristic ranges of electrical impedance (fig. 1).[1] When modeling our system as an LRC circuit, impedance (Z) was defined in terms of its 3 individual components, including resistance, inductance (L) and capacitance (C), using the formula, $Z = R + j(\omega L - 1/\omega C)$, where ω represents the angular frequency of the current and j represents the square root of (-1). Initial experimentation demonstrated that inductance and capacitance are negligible in our system at the testable frequency of 1,000 kHz. and the resistive component is the principal factor when evaluating the constitution of the tissue at the needle tip.

The impedance properties of tissues have previously been measured in other medical fields to aid in distinguishing tissues. In 1969 neurosurgeons first used bio-impedance measurements to verify penetration of the spinal cord during percutaneous cervical cordotomy.[2] Others later applied bio-impedance to optimize the characterization of brain tumors.[3] More recently it has been shown that regions of prostate cancer may be distinguished from normal prostate tissue based on impedance characteristics.[4] Although bio-impedance has been applied in numerous investigations, to our knowledge our study is the first to investigate its usefulness for confirming percutaneous access to the renal collecting system. Considering the definite disparity in impedance

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of urine and the renal parenchyma this property is an attractive means on which to base a percutaneous access detection device.

MATERIALS AND METHODS

Bio-impedance apparatus. The Smart Needle is a modified percutaneous access needle that enables continuous measurement of electrical impedance at its tip. The 18 gauge device is composed of a metal outer tubular barrel, a metal inner stylet with a sharp needle point and an insulating middle layer between the barrel and stylet (fig. 2). The electrical insulator leaves only the distal 3 mm. uncovered, so that the tip of the needle serves as a sensitive electrical probe.

A multifrequency Model 4275 LCR meter connected to the needle tip measures impedance. This meter applies a low voltage sinusoidal signal of high frequency to the needle tip and measures the amplitude and phase shift of the response signal. From these data the individual components of impedance (resistance, capacitance and inductance) were determined. A percutaneous kidney access needle driver is coupled with a remote center of motion robotic system to orient and insert the needle to precisely measured depths within the kidney.[5, 6] Figure 3 shows the experimental apparatus.

Calibration. Individual needles were calibrated against known standards within the resistivity range of physiological solutions and calibration constants were determined. Although the manufacturing process is imperfect, all Smart Needles had similar calibration constants. The system was tested over a range of frequencies using an ideal RC circuit to identify a linear range of 400 to 2,000 kHz. All experiments were performed using a frequency of 1,000 kHz.

The critical factor in distinguishing among tissues or physiological fluids is the resistive component of impedance. Real-time measurement of overall impedance and resistance in Ω were recorded for each experiment using the LCR meter. To facilitate comparison of data between trials utilizing different needles, results were reported as resistivity values in Ω m. Resistivity is a measure of resistance adjusted by the needle calibration constant to correct for small physical differences among needles.

Porcine kidney specimens. Porcine kidneys were obtained from a local commercial slaughterhouse immediately after slaughter in accordance with all applicable guidelines. The kidneys were maintained frozen until the day of the experiments, when they were thawed and the ureters were carefully isolated. A wire was advanced in retrograde fashion into the collecting system of the kidney and manipulated into the upper pole before being advanced through the kidney parenchyma. A 22 gauge angiocatheter was advanced in antegrade fashion over the wire and into the collecting system. The wire was retracted and the catheter was sutured in place, securing access to the collecting system. Gravity irrigation was achieved by connecting the catheter to an intravenous bag of normal saline suspended 100 cm. above the specimen. A purse-string suture was placed around the distal ureter, providing control of the degree of collecting system distention.

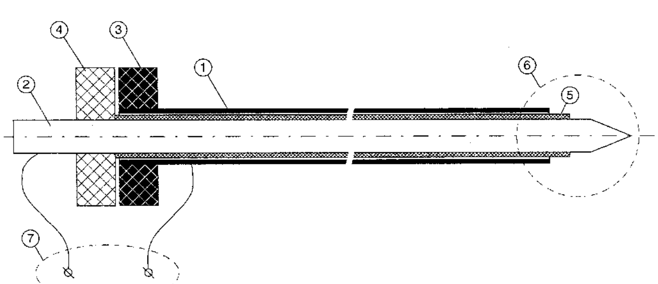

FIG. 2. Smart Needle. Metal trocar (*1*) is insulated from metal stylet (*2*) by insulating coating (*5*). Each component is connected to LCR meter (*7*). Needle tip (*6*) measures impedance between exposed stylet and trocar tips. Note plastic trocar (*3*) and stylet (*4*) hubs.

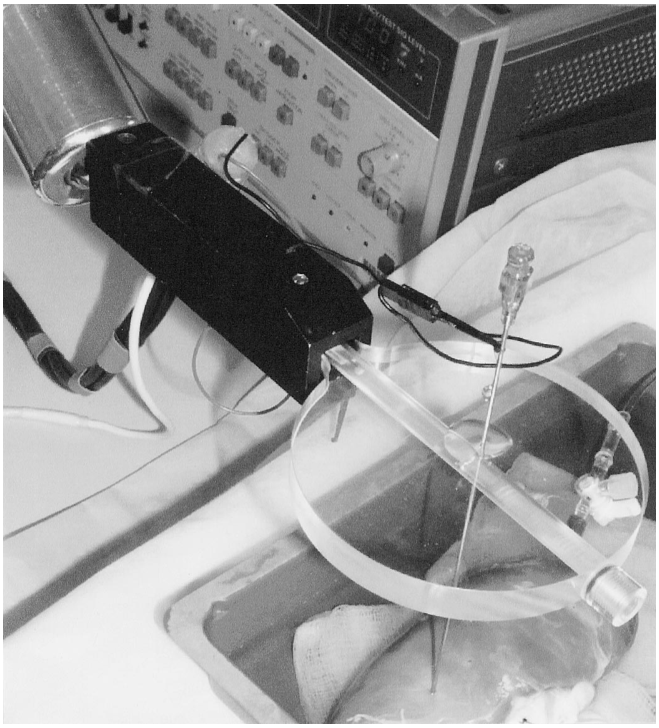

FIG. 3. Overall Smart Needle system setup during ex vivo porcine kidney experiments. Smart Needle supported in percutaneous kidney access remote center of motion robotic needle driver pierces kidney. Saline efflux visible at needle top indicated successful entry into collecting system. Note LCR meter in background.

The kidney was placed flat and the Smart Needle was advanced through the renal parenchyma in controlled fashion to puncture the collecting system. Continuous impedance and depth measurements were recorded and real-time graphs of these insertion attempts were generated. At the completion of each needle insertion the inner stylet was removed and successful entry into the collecting system was confirmed by saline efflux. After each access attempt the puncture site was sutured closed to allow multiple punctures per kidney.

RESULTS

We performed 16 percutaneous access attempts without imaging guidance in 4 ex vivo porcine kidneys. Figure 4 shows representative graph of the resistivity of the kidney tissue versus depth of penetration. Piercing the collecting system resulted in a sharp drop in resistivity from 1.9 to 1.1 Ω m. Successful collecting system access was confirmed by removing the inner stylet and visualizing saline efflux. This characteristic sharp decrease in resistivity was noted in all 11 insertion attempts in which the collecting system was successfully accessed.

Five needle insertion attempts did not result in needle entry into the collecting system. The graphs of resistivity versus depth for these trials also had characteristic features and were distinguishable from successful access attempts. During the unsuccessful access attempts resistivity did not decrease below 1.5 Ω m. (fig. 5). When the inner stylet was removed, saline efflux was not observed, confirming that the needle tip had not entered the collecting system.

DISCUSSION

Resistivity is an intrinsic electrical property of tissues that may be measured and used to distinguish different tissues.

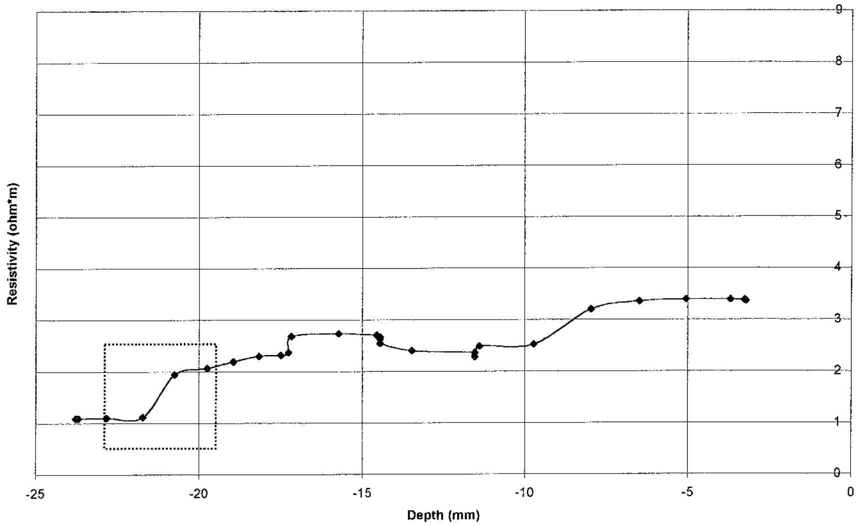

FIG. 4. Resistivity versus depth during successful ex vivo porcine kidney experiment. Box indicates characteristic drop in resistivity

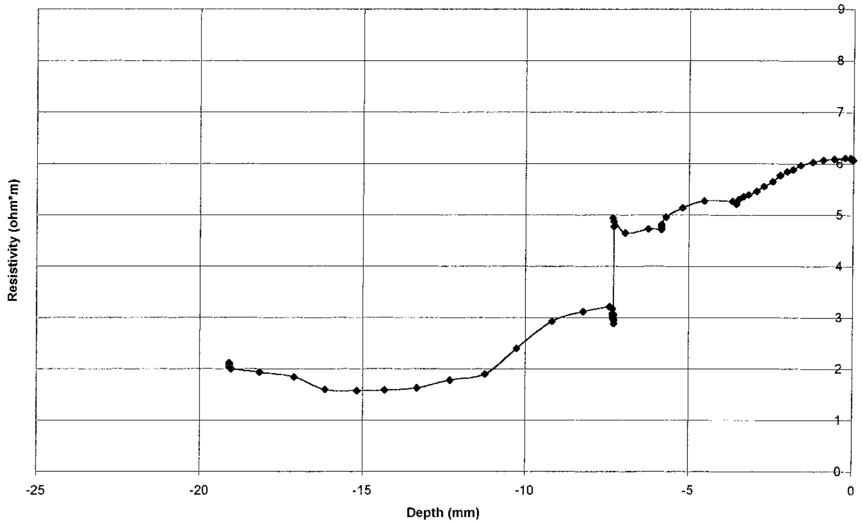

FIG. 5. Resistivity versus depth during unsuccessful ex vivo porcine kidney experiment showing artifact due to needle slippage in driver at −7 mm. deep.

Schwan et al reported resistivity values measured at 1,000 kHz. of 4.2 to 7, 2.1 to 4.2 and 1.4 to 2.5 Ω m. for brain, liver and kidney, respectively.[7] Kidney tissue resistivity values measured by the Smart Needle system correlated well with those noted by Schwan et al.

Furthermore, these experiments demonstrate that the Smart Needle system may confirm successful entry into the collecting system by measuring impedance (resistance) at the needle tip. A characteristic drop in resistivity from approximately 1.9 to approximately 1.1 Ω m. indicated successful collecting system access (fig. 6). This decrease in resistivity occurred over a 1 cm. distance and may reflect tenting of the collecting system tissue by the needle before complete puncture. Therefore, through-and-through puncture of the collecting system without an observed drop in resistivity is a theoretical concern, especially in nondilated collecting systems. However, this concern did not materialize in our ex vivo experiments, perhaps because of distention of the collecting system. Nevertheless, improved needles with more closely spaced electrodes (current spacing is 3 mm.) may provide a greater degree of resolution and, therefore, a resistivity decrease in a shorter distance.

These experiments were done using kidneys harvested from slaughtered animals. The kidneys were immediately frozen, later thawed to room temperature and distended with normal saline. Normal saline was chosen as a substitute for urine because it has a specific impedance value within the range of urinary impedance. Urinary impedance is inversely related to urine concentration. Using saline eliminated potential variations in urine concentration and, therefore, in impedance that may be present in different urine samples.

This ex vivo porcine model was limited by absent blood flow, respiratory variation and other physiological processes as well as by higher distention pressures (100 cm. water) than standard access procedures. Therefore, these resistivity values are not directly applicable to an in vivo situation. However, similar results have been obtained in preliminary clinical trials. In the operating room during percutaneous nephrolithotomy the resistance component of impedance was observed during needle advancement. The measured resistance of renal parenchyma was 180 to 135 Ω as the needle traversed the parenchyma. While entering the collecting system, a sharp drop in resistance plateaued at 73 Ω. The stylet was removed and urinary efflux was observed, confirming collecting system access. To compare access attempts using various needles resistance in Ω was converted to resistivity in Ω* m., a parameter that is independent of variation due to individual needle imperfections. The resistivity versus depth

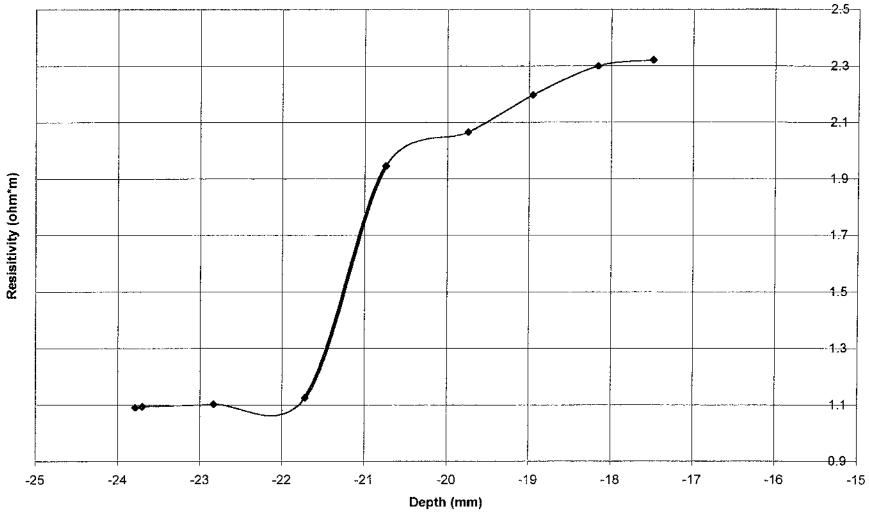

FIG. 6. Bold line indicates characteristic drop in resistivity at Smart Needle entry into collecting system

plot in this case showed the characteristic features of collecting system entry, similar to the curves in porcine kidneys (figs. 4 and 6). These initial data are encouraging, but further studies are needed to determine the impedance values of grossly bloody or pus filled urine and assess the usefulness of the Smart Needle system in these situations.

The impedance sensing function of the needle may be of great assistance in minimally invasive surgical procedures that require percutaneous renal access. Currently such access requires multidirectional fluoroscopic imaging and significant operator experience. The Smart Needle may enable a surgeon to confirm needle tip entry into the collecting system more rapidly and accurately, saving time and minimizing the potential for damage from multiple needle punctures.

However, confirmation of renal collecting system access is not the only application of our system. It has been previously shown that electrical properties of distinct tissue types are significantly different.[7, 8] The system may be used to distinguish tissue types or diseased from healthy tissue in medical renal disease. It has also been previously shown that the electrical properties of cancerous tissue differ from those of normal tissue.[4, 9] Specifically within the prostate areas of prostate cancer had higher impedance than areas of normal tissue.[4] Distinguishing cancerous from normal tissue using the Smart Needle system may be beneficial for diagnostic and therapeutic management of renal malignancy and malignancy in other organs. With further research and the rapid development of micro and nano scale devices further refinements of the Smart Needle may enable 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.

CONCLUSIONS

We designed a Smart Needle system to measure precisely tissue impedance. This study reproducibly showed that a characteristic sharp drop in impedance signified successful entry into the renal collecting system in ex vivo porcine specimens. Our Smart Needle system may improve the efficiency of current renal percutaneous access techniques.

C. R. Bard, Inc. provided the needle prototypes.

Dr. Stephen V. Jackman, co-inventor of the Smart Needle system, provided permission to use and modify the system.

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