A LAPAROSCOPIC HIFU PROBE FOR KIDNEY ABLATION PRIOR TO PARTIAL NEPHRECTOMY

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Abstract - In an effort to reduce the complications associated with nephrectomy, high intensity focused ultrasound (HIFU) has been used to selectively ablate renal tissue prior to partial nephrectomy. To this end, a hand-held HIFU laparoscopic probe (OD=11mm) was developed. The probe consists of two focused rectangular HIFU piezoceramic transducers for side and front firing configurations. The probe was fully characterized for electrical impedances, acoustic fields, and total acoustic power outputs for both side and front transducers. It was then tested in an *in vivo* animal experimental study in which 5 pigs were treated through a sterile HIFU open surgery procedure. A cross-sectional disk-shaped coagulative lesion was induced in the lower pole of the right kidney in each animal. The average treatment time for an ablated volume of 20cc was approximately 45 minutes. Histopathology results demonstrated contiguous well-delineated necrosed lesions extending from the kidney's pelvic system to the capsule. Moreover, the histology results suggested that the tissue ablation was obtained through both thermal and mechanical mechanisms. The overall results suggest that the cross-sectional necrosed tissue volume effectively reduces blood loss during partial nephrectomy.

I. INTRODUCTION

Renal cell carcinoma is the third most common cancer in urology and is by far the most common malignant tumor of the kidney. After detection of the tumor, if the features are suggestive of malignancy or if it is growing rapidly, the patient is treated surgically through either partial or total nephrectomy depending upon the size and location of the tumor and the preference of the physician. Since kidney is a highly vascularized organ, nephrectomy, as an invasive procedure, is usually associated with significant bleeding resulting in high morbidity.

Nowadays, there is an increasing interest in laparoscopic techniques as a minimally-invasive tool for performing different kinds of surgeries including nephrectomy. To this end, the urology surgery community is investigating several laparoscopic techniques among existing technologies. Notable examples are: cryoablation using extreme cold, radiofrequency ablation [1], and HIFU (high intensity focused ultrasound) ablation. HIFU technology has demonstrated promising results in treating benign and malignant diseases of prostate such as BPH (benign prostatic hyperplasia) and localized prostate cancer [2-4]. A notable example of HIFU clinical systems is the Sonablate^{TM} platform developed by Focus Surgery Inc., Indianapolis, IN (http://www.focus-surgery.com). The device makes use of a proprietary transrectal image-guided HIFU technology to treat prostate diseases.

Moreover, several recent studies have demonstrated the ability of HIFU to control bleeding and to induce hemostasis (partial or total) in different tissues and vessels [5-6]. Acoustic hemostasis, if appropriately applied, has been shown to provide a useful tool for cauterization not only on the surface of tissues, but also in deep regions. Two distinct effects of HIFU, i.e. thermal (through coagulation necrosis) and mechanical (through cavitation and acoustic streaming) have been shown to contribute to acoustic hemostasis.

In a previous feasibility study, we extended the application of the Sonablate^{TM} device to laparoscopic surgery of the kidney [7]. Results of an *in vivo* porcine study demonstrated the feasibly of laparoscopic HIFU to create well-delineated

contiguous necrosed lesions extending from the kidney's pelvic system to the capsule. Based on these encouraging results, in the current study, a hand-held HIFU probe suitable for laparoscopic surgery of renal carcinoma under video camera imaging has been developed. The new probe was characterized and evaluated through an *in vivo* open surgery porcine study in which a cross-sectional disk-shaped ablated tissue volume was induced in a lobe of the kidney. It is anticipated that using laparoscopic HIFU prior to partial nephrectomy will lead to significantly less bleeding and lower morbidity through the hemostasis properties of the HIFU lesions.

II. Materials and Methods

Laparoscopic HIFU probe

A hand-held HIFU probe was developed to meet the main features required for sterile laparoscopic surgery of kidney. The probe was built from a stainless steel tube with 11 mm outer diameter and 38 cm length (Fig. 1). The probe consists of two focused rectangular HIFU piezoelectric crystals for side and front firing configurations. The crystals were made from a special high-power piezoceramic material (KEZITE NOVA 3B) capable of providing the high acoustic power required in HIFU applications (KERAMOS Inc., Indianapolis, IN). The parameters of the crystals are:

Side firing crystal: Aperture=25×8mm, Focal length=20mm, Center frequency=4.0 MHz.

Front firing crystal: Aperture=10×7mm, Focal length=10mm, Center frequency=5.0 MHz.

During HIFU procedure, the transducers are covered by a latex sheath filled with circulating water and supported by a backing sleeve. The backing support sleeve (Fig. 1-b), made from brass, has two functions: (1) protection of the coupling latex sheath, and (2) providing acoustic windows to allow the latex sheath to distend in the desired planes only in front of the crystals, i.e. in direction of the HIFU beam propagation for both the side and front firing crystals.

The laparoscopic probe was fully characterized by measuring its electrical impedance, acoustic field, and total acoustic power output. The probe was able to generate acoustic power levels of up to 35W and 10W for the side and front transducers respectively.

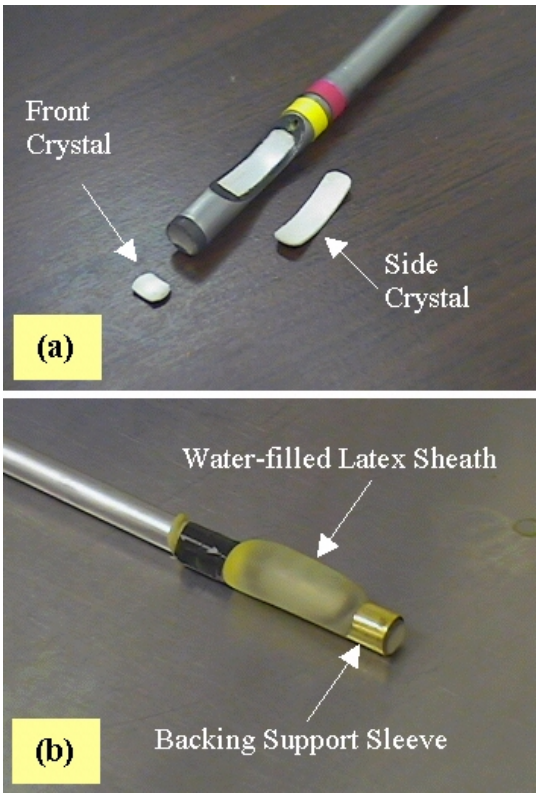

Fig. 1. (a) The hand-held laparoscopic HIFU probe and the piezoceramic crystals shown separately. (b) A close-up of the probe tip ready to operate.

These, in turn, correspond to maximum tissue focal intensities over 3000W/cm^2 and 5000W/cm^2 for the side and front transducers respectively. These intensity levels would be sufficient for tissue ablation through coagulation necrosis by rapid temperature rise (>90°C) and cavitation mechanisms.

Fig. 2 shows Schlieren images of the acoustic intensity field created by the side and front transducers in water.

Active pump/chiller system

An active pump/chiller system (SonaChill^{TM} 200, Focus Surgery Inc., Indianapolis, IN) was used in conjunction with the laparoscopic probe to ensure continuos circulation of cold water (~20°C) around the transducers. This led to application of high powers by increasing the efficiency of the transducer and lowering the risk of transducer overheating.

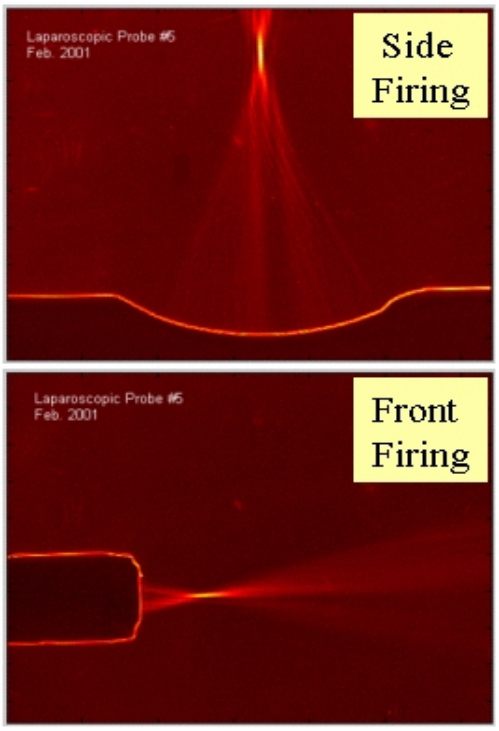

Fig. 2. Schlieren images of the acoustic intensity field created by the side and front transducers in water.

Animal model

5 female Yucatan pigs with weights ranging from 45 to 55 kg were used in this study under a protocol approved by the animal experimental usage committee. The lower pole of the right kidney was treated in all the pigs. The kidney size in these pigs approaches that of a human adult and is suitable for testing the laparoscopic HIFU probe.

III. *IN VIVO* EXPERIMENTAL PROCEDURE

5 pigs were used in a subacute (4 days survival) study. All pigs were treated through a sterile open surgery procedure. Prior to surgery the animal received 1 g intravenous Cefazolin to prevent infection. The Pig was anaesthetized with IM injection of Ketamine (100 mg/ml) and Xylazine (20 mg/ml) for induction followed by Sodium Pentothal (2.5% solution, 0.5 ml/lb) intubated and placed on isoflurane gas anesthesia throughout procedure.

An open surgical approach for HIFU partial renal ablation was utilized in which a subcostal incision was made in the abdominal wall to expose the right kidney. The kidney was then completely mobilized while the ureter and vessels were kept intact. The mobilization of the kidney allowed optimal positioning of the hand-held HIFU laparoscopic probe to create a circumferential disk-shape lesion about 1 cm wide through the entire thickness of the kidney. The lesion was induced at the junction of the middle and the lower renal pole with adequate tissue coagulation confirmed by direct inspection.

The treatment was mainly performed using the probe's side transducer. The exposure settings for the side transducer were: TAP= 28 W, Tissue Focal Intensity= 2400 W/cm^2, HIFU On/Off Times= 2/2 s, and No. of Shots per Site= 5.

After completion of the treatment, the incision in the abdominal wall was closed with sutures and the pig was returned to the cage and was initially monitored every 30 minutes until the animal recovered from anesthesia and was moving normally around in the cage. The incision site was monitored for any abnormalities and a consulting veterinarian would be contacted if any complications arise. The animal was kept on pain medications for 4 days using butorphenol tartate (0.1-0.3 mg/kg) and on antibiotics-TMP/SMX suspension (48 mg/kg) for 3 days.

All animals were sacrified 4 days after the treatment. As a part of the sacrifice procedure the kidney was perfused with a fixative solution (2.5% glutaraldehyde in 0.1M sodium cacodylate, PH= 7.4, 400 mOsm). Once the perfusion was complete the kidney was removed and transferred into fresh fixative solution and stored at a temperature of 4°C for further histopathology studies.

IV. RESULTS

Immediately after the treatment a coagulated area appeared as a whitish circumferential rim about 1 cm wide on the surface of the kidney (Fig. 3-a). A drastic change in color of the lower pole was also observed within the circumferential HIFU lesion. This is believed to be due to the depletion of arterial blood supply resulting in gangrene of the lower pole. On autopsy, a significant area in the lower pole was dark (almost black) in color. This indeed supports the hypothesis that the HIFU-induced lesion acts as hemostasis barrier which significantly blocks the blood flow to the lobe of the kidney. Both gross pathology and histology results revealed contiguous well-delineated necrotic disk-shape lesion extending from the kidney's pelvic system to the capsule (Fig.

3-b). The average treatment time for a lesion of 20cc was approximately 45 minutes.

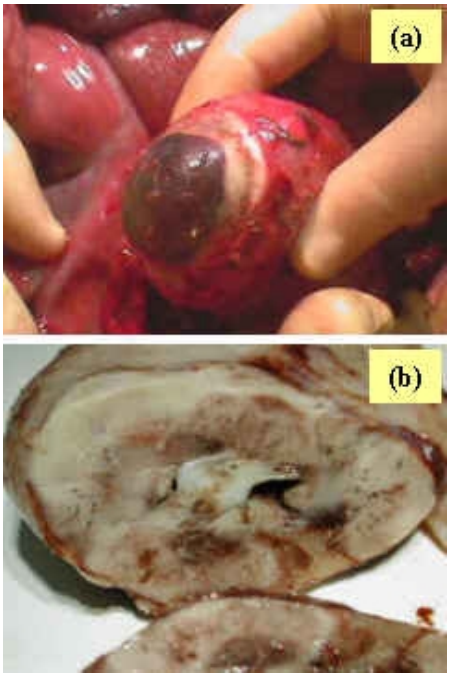

Fig. 3. (a) A view of the circumferential HIFU lesion created in the kidney's lower pole. (b) Cut section of the kidney through the lesion to show the uniformity of the lesion extending from the pelvic system to the capsule.

V. CONCLUSIONS

This study showed the feasibility of laparoscopic HIFU to create repeatable well-delineated lesions in a highly perfused organ such as the kidney. Contiguous necrotic lesions were created in the lower pole of the kidney extending from the pelvic system to the capsule. The focal intensity used in this study as well as the histopathology results of the lesions suggest that the tissue ablation was obtained through both thermal (coagulation necrosis) and mechanical (cavitation) mechanisms. A previous similar study [7] showed the appearance of hyperechoic regions in the real-time ultrasound B-mode images of the target region. This further supports that cavitation may also have a role in this mode of tissue ablation. These preliminary studies suggest that laparoscopic HIFU can be used to create a cross-sectional necrotic tissue volume as a hemostasis barrier in a lobe of the kidney prior to partial nephrectomy. It is anticipated that this necrotic tissue volume will significantly reduce bleeding during partial nephrectomy. Work is under progress to quantify the degree of hemostasis achieved by this method. The next step will be the verification of the technique in laparoscopic kidney surgery under video imaging guidance.

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