Paper:

Technologizing and Digitalizing Medical Professional Skills for a Non-Invasive Ultrasound Theragnostic System – Technologizing and Digitalizing Kidney Stone Extraction Skills –

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We have been studying the technologizing and digitalizing skills of the medical professionals in the medical diagnostics and therapeutics. The concept of technologizing and digitalizing medical skills involves extracting functions in medical professional skills and reconstructing and implementing these extracted functions in the mechanisms, controllers, and image-processing algorithms of the medical support system. In this paper, we focus on the kidney stone extraction skills of medical professionals by utilizing robot vision technology, and discuss a methodology for technologizing and digitalizing medical diagnostic and therapeutic skills for a non-invasive ultrasound theragnostic system.

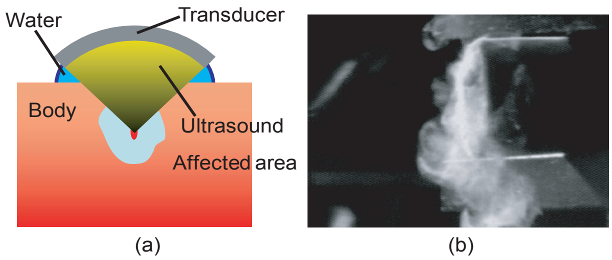


Fig. 1. (a) High-intensity focused ultrasound (HIFU). (b) Destruction of kidney stone by HIFU.

1. Introduction

Information and Robot Technology (IRT) is drawing increasing attention in the technologizing and digitalizing of medical professional skills. In fields such as manufacturing, high-precision tasks, not possible with human, skills have been already realized by industrial robots. The medical field is thus expected to advance with progress in the development of medical robots able to provide diagnosis and therapy that are much more precise than those of conventional medical professionals.

This paper focuses on robot vision technology for technologizing and digitalizing medical diagnostic and therapeutic skills for the Non-Invasive Ultrasound Theragnostic System (NIUTS) that compensates for movement by tracking and following the area to be treated by stereo ultrasound imaging while irradiating the affected area with High Intensity Focused Ultrasound (HIFU).

In HIFU, ultrasound beams are generated and focused onto the small region by utilizing the spherical transducers. It thus becomes possible to concentrate the energy onto a small region in the body to treat an affected area in focal volume without damaging surrounding or overlying tissues. HIFU, as a non-invasive technique, is an attractive alternative to current abdominal and endoscopic surgery (**Fig. 1(a)**).

Areas can be selectively diagnosed and treated non-invasively using HIFU using the same principle as in conventional ultrasound. Ultrasound propagates harmlessly through living tissue. However, if an ultrasound beam is focused too tightly, the energy in the focal volume may cause local heating [1].

Our proposed system uses focused ultrasound to destroy tumors and stones without damaging healthy tissue.

"Theragnostics," a compound "therapeutics" and "diagnostics," is achieved by tracking and following the affected area – kidney stones in the present study – in order to compensate for movement due to the patient's respiration and other causes.

A number of studies have been conducted since Lynn et al. first demonstrated the potential of HIFU for use in medical applications [1, 2]. One example of a medical application of HIFU is the non-invasive destruction of kidney stones (**Fig. 1(b)**) by using the energy generated by cavitation. HIFU irradiation has an advantage in that any debris produced from such stones is small enough to prevent complications with adjacent organs [3].

The JC HIFU® system is widely used in clinical practice [4, 5]. A total of 19 devices for clinical use were used to treat 1,050 patients who had a variety of tumors [6, 7]. There was no compensation, however, for the movement of organs in the affected area, which is primarily caused by respiration. Preventing such movement while irradiating an affected area with focused ultrasound is generally difficult for both the physician and the patient.

Related to research on technologizing and digitalizing skills, the concepts of artificial skill [8], hyper human [9], and digital human [10] have been proposed, and studies related to technologizing and digitalizing of skills are increasing. In the medical field, Mayer [11] and Zong [12] studied automatic suturing aiming at technology transfer. We have developed the Remote Ultrasound Diagnostic System (RUDS) based on technologizing and digitalizing technology [13, 14].

This paper is organized as follows: the concept of technologizing and digitalizing medical skills is proposed in Section 2.1. The project roadmap of technologizing and digitalizing medical skills for a NIUTS is also illustrated in this section.

Functional requirements are determined in Section 2.2. In Section 2.3, a framework for the NIUTS is constructed based on the functional requirements described in Section 2.2. In Section 2.4, we discuss the required servoing precision and clarify problems in visual motion tracking of the target kidney stone in the body by ultrasound images in the proposed NIUTS.

In Section 3, we propose a method to technologize and digitalize the stone extraction skill of the target kidney stone by utilizing the following two features: (i) the stone's acoustic impedance higher than that of surrounding tissues. (ii) The acoustic shadow generated by the stone.

In Section 4, we conduct experiments in which the phantom/swine kidney stone is extracted to confirm the effectiveness of the proposed method. We conclude the present work in Section 5.

2. Concept of Technologizing and Digitalizing Medical Skills and System Construction Methodology

2.1. Concept of Technologizing and Digitalizing Medical Skills

The concept proposing technologizing and digitalizing of medical skills involves 3 steps: (i) extracting medical diagnostic and therapeutic primitive functions, (ii) decomposing and reconstructing (structuring) these extracted primitive functions considering implementation, and (iii) implementing reconstructed functions in mechanisms, controllers, and image processing algorithms as functions, as shown in **Fig. 2**.

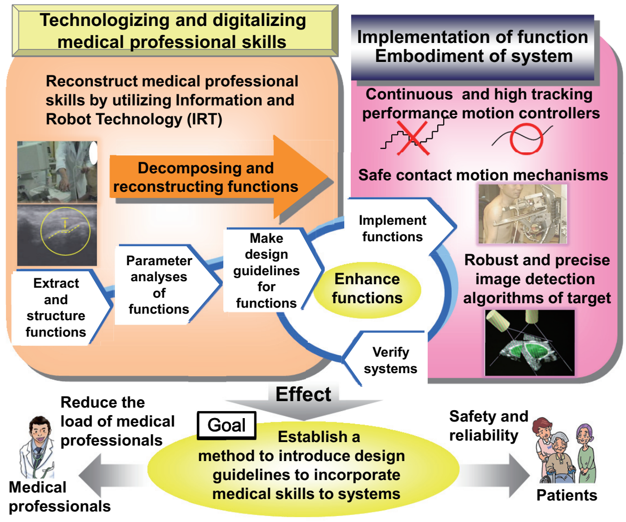


Fig. 2. Concept of technologizing and digitalizing of medical skills.

Figure 3 shows an overview of the project roadmap for technologizing and digitalizing medical skills for a NIUTS. Among the steps in **Fig. 3**, we focus on the kidney stone extraction skills of medical professionals. Steps and basic technologies related to this paper are highlighted by red frames in **Fig. 3**.

It is important both to imitate medical professional skills and to take novel approaches as needed to add and implement functions enhancing the quality of medicine, e.g., high-speed and high-precision motion should be realized by highly rigid mechanisms.

To do so requires five basic technologies: (a) safe contact motion technology with the body, (b) mechanism design technology, (c) extracting and restructuring technology for skill, (d) switching control technology based on medical diagnostics and therapeutics, (e) robot vision technology for theragnostics. This paper focuses on this fifth technology in the NIUTS.

2.2. Structuring Functional Requirements

Clarification of functional requirements is important in order to realize an efficient system. **Fig. 4** shows an overview of the structuring – decomposition and reconstruction – of functional requirements. The functions required for a NIUTS are categorized as

(FR-1) diagnostic functions or

(FR-2) therapeutic functions.

Diagnostic functions (FR-1) are further categorized into the following five subcategories:

(FR-1.1) moving the probe to the affected area,

(FR-1.2) extracting the affected area,

(FR-1.3) focusing the HIFU focus onto the appointed position in the affected area,

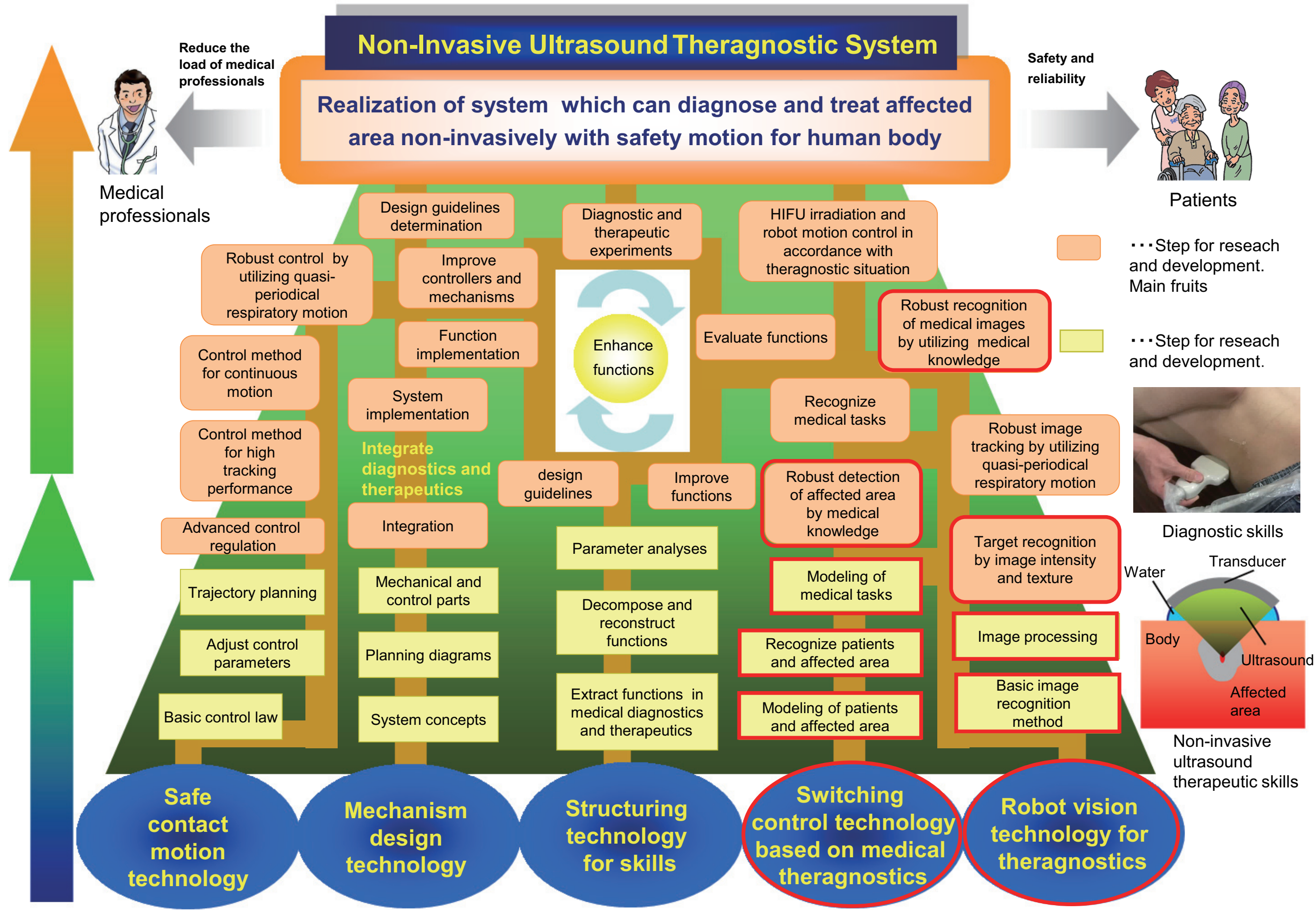


Fig. 3. Project roadmap of technologizing and digitalizing medical skills for an NIUTS.

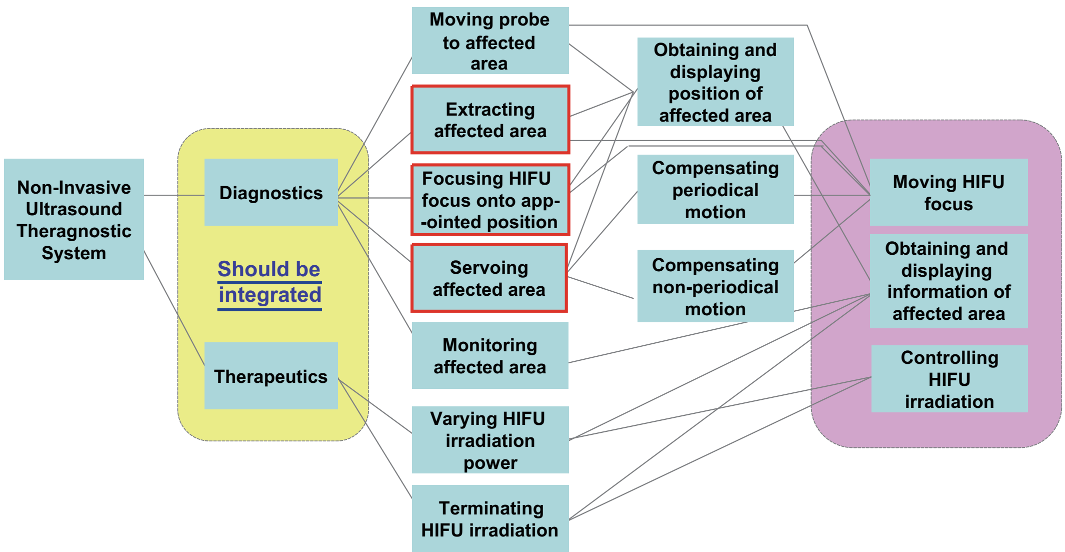


Fig. 4. Required structuring functions for an NIUTS.

(FR-1.4) tracking and following the affected area,

(FR-1.5) monitoring the affected area.

Therapeutic functions (FR-2) are further categorized into the following two subcategories:

(FR-2.1) varying the HIFU irradiation power,

(FR-2.2) terminating HIFU irradiation.

Tracking and following the affected area (FR-1.4) is further categorized into the following two subcategories:

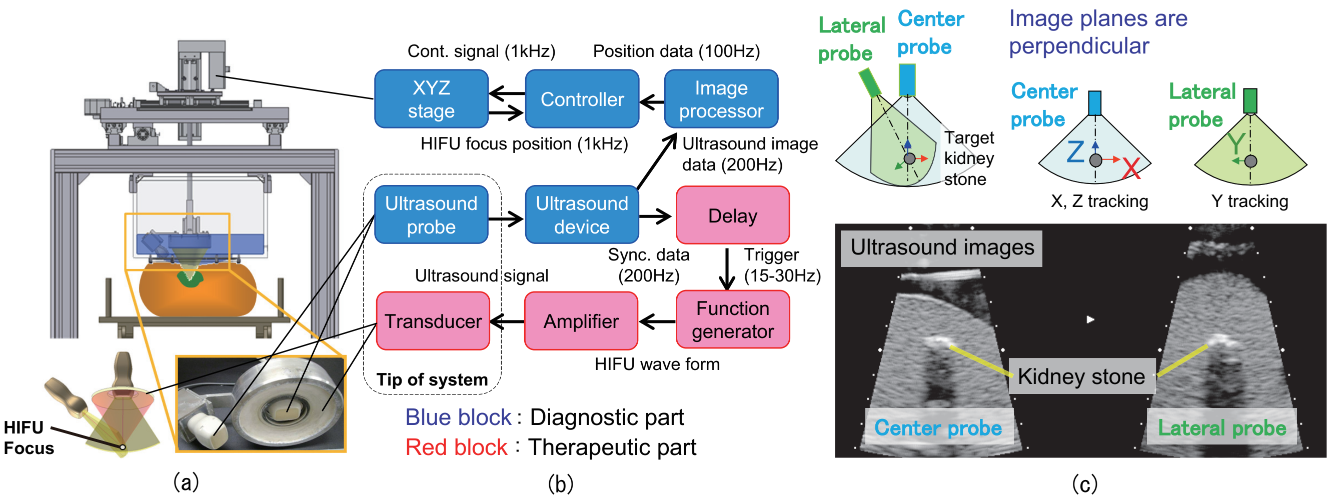


Fig. 5. System configuration of an NIUTS. (a) Overview of system configuration. (b) Block diagram of system. (c) Probe configuration and acquired ultrasound images for kidney stone model in ultrasound kidney phantom model.

(FR-1.4.1) compensating for periodic motion of the kidney stone,

(FR-1.4.2) compensating for non-periodic motion of the kidney stone.

Next, functional requirements should be achieved by considering how the system will be implemented. As a result, decomposed functions are reconstructed to obtain the following three functions:

(R-FR-1) moving the position of HIFU focus,

(R-FR-2) obtaining the state of the affected area and displaying this information to the medical professional,

(R-FR-3) controlling HIFU irradiation.

In the present paper, we propose a technologizing and digitalizing technology of medical diagnostic skills related to (FR-1.2)–(FR-1.4) in the following sections.

2.3. Implemented System Configuration

An NIUTS was constructed (**Fig. 5**) based on required functions as described in Section 2.2. The overview and the block diagram of the system is shown in **Figs. 5(a)** and **(b)**. Stereo diagnostic images are acquired using two diagnostic probes. These images are then used to determine a 3D positioning data of the affected area and the focus position of the HIFU. In control, the focus point tracks the kidney stone using 3D positioning data. HIFU irradiates the kidney stone using a function generator, an amplifier, and a transducer. HIFU irradiation parameters are given in Reference [3].

The robot has a spherical piezoelectric transducer and two ultrasound probes (**Figs. 5(a)** and **(c)**), one of which is located in the center of the piezoelectric transducer and the other of which is located on the lateral side of the piezoelectric transducer. These two probes satisfy the following two requirements:

(i) The focus of the HIFU, which is irradiated by piezoelectric transducers, is located on the image planes of both probes (**Fig. 5(a)**).

(ii) The image planes of probes are mutually perpendicular (**Fig. 5(c)**).

The two ultrasound image planes are shown in **Fig. 5(c)**. The stone appears as bright regions in the ultrasound images at left and right. The ultrasound image on the left is acquired by the probe in the center of the piezoelectric transducer, and the ultrasound image on the right is acquired by the probe on the lateral side of the piezoelectric transducer.

To acquire the proper diagnostic images of the affected area and irradiate HIFU onto target kidney stones, it is important to ensure stable contact status between the tip of the theragnostic system and the affected area. To do so, we implemented a water tank with a silicon membrane between the tip of the theragnostic system and the affected area.

The kidney stone is tracked by imaging the left and right ultrasound images based on the Matrox Imaging Library (MIL 8.0) processing cycle, which involves the following three steps: 1) grabbing ultrasound images, 2) processing grabbed images to enhance image quality for tracking the kidney stone, and 3) detecting the 3D location of the stone.

The target position is obtained by the ultrasound system at a limited sampling rate of 100 Hz. In contrast, the *XYZ*-stage is controlled at a rate of 1 kHz at a positioning resolution of 5 nm. The specifications of the controller are reported in reference [15].

2.4. Required Servoing Precision and Problems with Visual Motion Tracking Using Ultrasound Images

In this section, we discuss the required servoing precision, together with problems with visual motion track-

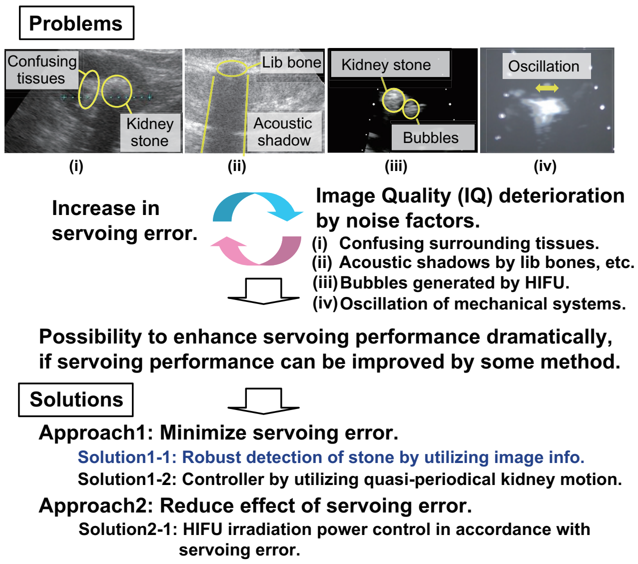


Fig. 6. Problems and solutions with visual motion tracking using ultrasound images.

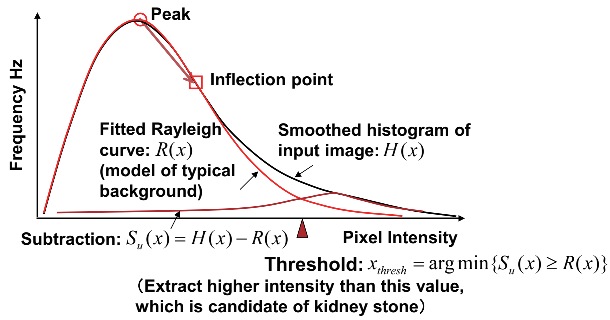


Fig. 7. Automatic thresholding of intensity to extract model kidney stone.

ing using ultrasound images in the special theragnostic system. We first discuss the required servoing precision, which should be smaller than the radius of the irradiated object:

$$E_d < k_r \bar{r}_{stone} \quad \ldots\ldots\ldots\ldots \quad (1)$$

where $\bar{r}_{stone}$ is the average radius of the irradiated object, and k_r is a proportionality constant. The irradiated object is a kidney stone model [16] having a diameter of approximately 10 mm. The target tracking precision is therefore set to 1 mm ($k_r = 10$). The HIFU irradiated region (lesion) is ellipsoidal, with a long axis of approximately 10 mm and a short axis of approximately 1 mm. The resolution of the ultrasound diagnostic image is approximately 0.3 mm when a 3-MHz probe is applied.

We now discuss the problems and solutions associated with visual motion tracking of the target kidney stone by using ultrasound images (**Fig. 6**). Servoing error increases when Image Quality (IQ), for visual servoing of the target kidney stone, is decreased. Noise factors that deteriorate IQ are four factors, as follows: (i) surrounding tissues, which have high acoustic impedance, (ii) acoustic shadows, which are generated by high acoustic impedance tissues such as lib bones. (iii) Bubbles, which are generated by HIFU irradiation, and (iv) blur noise by oscillation in mechanical systems. Servoing error causes an image to change, which in turn increases servoing error. This negative spiral causes servoing performance to become increasingly worse. This, however, also increases the possibility of dramatically enhancing servoing performance if performance can be improved by some method that will result in a positive spiral.

In order to solve this problem, we consider two approaches. The first approach is to minimize servoing error. This approach attempts to enhance both the efficiency of therapy and the safety of the patient. The second approach is to reduce the effect of servoing error. This approach primarily contributes to safety enhancement by avoiding injuring healthy tissues surrounding the affected area.

With respect to the first approach, we developed two solutions, not only to enhance the servoing performance in order to realize efficient therapy but also to enhance the safety of the patient [15, 17]. The first solution is robust detection of the target kidney stone position based on information in the ultrasound image [17]. The second solution is a controller that compensates for periodic respiratory motion of the affected area [15]. Here, we propose a robust kidney detection method by utilizing the following two features: (i) the higher acoustic impedance of the target kidney stone, which exceeds that of surrounding tissues, (ii) the acoustic shadow that is generated by the kidney stone. Medical professionals utilize the above information on the target kidney stone.

With respect to the second approach, we developed a solution to control HIFU irradiation power in accordance with servoing error in order to enhance patient safety [17].

3. Technologizing and Digitalizing of Kidney Stone Extraction Skill

3.1. Semiautomatic Thresholding of Intensity to Extract Kidney Stone Model

In this section, we propose a semiautomatic thresholding method of pixel intensity to extract the kidney stone model (**Fig. 7**). We first calculate smoothed histogram $H(x)$ from the input ultrasound image, which incorporates the kidney stone. We then introduce the Generalized Rayleigh curve $R(x)$ as a model of the typical background of the target kidney stone in the ultrasound image. Specifically, the Generalized Rayleigh curve is defined as follows:

$$R(x|\sigma, S_c, x_0) = S_c \frac{x - x_0}{\sigma^2} \exp\left(\frac{-(x - x_0)^2}{2\sigma^2}\right). \quad (2)$$

Here, σ is a parameter to adjust curve width, S_c is a scale parameter, and x_0 is a translation parameter. The Generalized Rayleigh curve is a typical background model of the ultrasound image and fitted to the histogram of the input ultrasound image based on the peak and the inflection

Table 1. Acoustic impedance.

medium	blood	fat	muscle	kidney	renal calculi
$Z(\mathrm{kg/m^2 s}) \times 10^6$	1.62	1.38	1.7	1.62	3.18 to 6.51

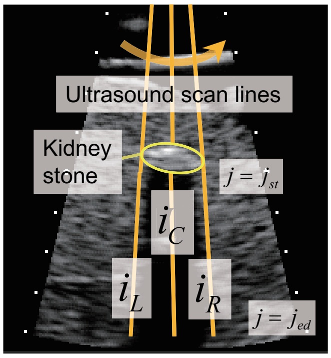


Fig. 8. Kidney stone decision by acoustic shadow.

point.

We then calculate subtraction $S_u(x)$.

$$S_u(x) = H(x) - R(x) \quad \ldots\ldots\ldots\ldots \quad (3)$$

We obtain threshold candidate value x_{thresh} to extract the kidney stone.

$$x_{thresh} = \arg\min\{S_u(x) \geq R(x)\} \quad \ldots\ldots \quad (4)$$

Practically, we apply (and adjust by trial and error, if required) the abovementioned threshold candidate value x_{thresh} as an initial value to extract the model kidney stone.

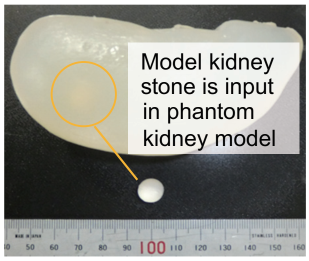
3.2. Determination of Kidney Stone by Acoustic Shadow

Kidney stones are very hard tissues and have relatively high acoustic impedance, as stated in **Table 1** [18]. Most incident ultrasound therefore cannot pass through the kidney stone. This makes an acoustic shadow behind the kidney stone. In this section, we propose a method to determine from an acoustic shadow whether the extracted region is actually the stone (**Fig. 8**).

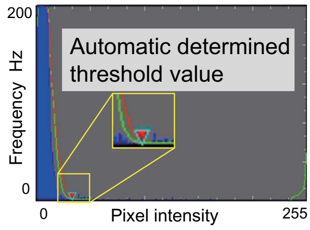
In advance, a scan line that passes through the kidney stone candidate and two scan lines that pass on either side of the candidate are obtained. Acoustic shadow factor f_{shadow} is defined by the intensity of the scan lines' portion posterior to the candidate.

$$f_{shadow} = \frac{\sum_{j=j_{st}}^{j=j_{ed}} I(i_C, j)}{\sum_{j=j_{st}}^{j=j_{ed}} 0.5(I(i_L, j) + I(i_R, j))} \quad \ldots\ldots \quad (5)$$

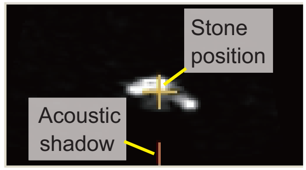
Here, $I(i_C, j)$ is the intensity of the j-th datum on the i_C-th scan line, which passes through the center of the two tangential scan lines – i_L-th scan line passing on the left, and i_R-th scan line passing on the right, which pass on both sides of the candidate.



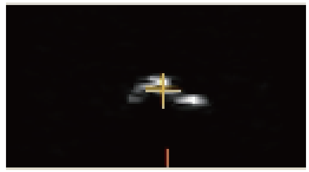
(a) Phantom kidney model



(b) Automatic thresholding result of pixel intensity



(c) Extraction result of center probe image



(d) Extraction result of lateral probe image

Fig. 9. Extraction result of model kidney stone in the phantom kidney model.

4. Experiments

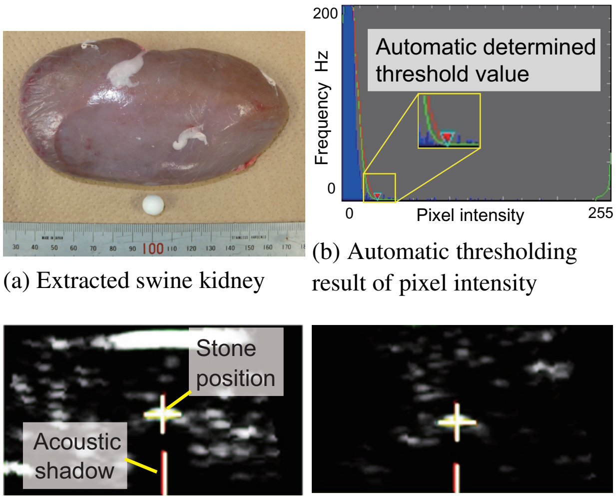
4.1. Phantom Experiments

Here, we explain the results of kidney stone model extraction experiments in the ultrasound kidney phantom model (**Fig. 9(a)**). The purpose is to confirm the effectiveness of the proposed stone extraction method. Specifically, we input the kidney stone model into the kidney phantom model and confirm whether we can extract the model kidney stone or not. **Fig. 9(b)** shows that the threshold value is automatically determined properly to extract the target kidney stone model. **Figs. 9(c)** and **(d)** show that stone positions in ultrasound images from the center and lateral ultrasound probes are detected properly by the proposed method. The recognized acoustic shadow is also shown in **Figs. 9(c)** and **(d)**.

4.2. Ex-Vivo Experiments

Here, we explain the results of kidney stone model extraction experiments using an extracted swine kidney (**Figs. 10(a)–(d)**). The purpose is to confirm the effectiveness of the proposed stone extraction method. Specifically we input the kidney stone model into the swine kidney and confirm whether we can extract the kidney stone model or not.

It is also confirmed that the position of the kidney stone model is identified properly by the proposed method. It is confirmed that ultrasound images are more noisy in the extracted kidney than in the phantom kidney model. Specifically, surrounding tissues, which have high acous-



(a) Extracted swine kidney

(b) Automatic thresholding result of pixel intensity

(c) Extraction result of center probe image

(d) Extraction result of lateral probe image

Fig. 10. Extraction result of model kidney stone in the extracted swine kidney model.

tic impedance, mainly make ultrasound images noisy, compared with the phantom kidney model.

Although ultrasound images are noisy, we could extract the model kidney stone alone in the swine kidney, which has confusing surrounding tissues. We conducted the same experiments with 3 extracted swine kidneys and confirmed that we could extract the kidney stone model properly with the proposed extraction method.

5. Conclusions

We have presented the concept of technologizing and digitalizing medical skills. We have shown a roadmap of technologizing and digitalizing medical skills for an NI-UTS. The structuring of required functions has been discussed and problems encountered in servoing the target kidney stone clarified.

We have proposed a method to technologize and digitalize the extraction skill of the target kidney stone by utilizing the following two features: (i) the higher acoustic impedance of the target kidney stones which exceeds that of surrounding tissues and (ii) the acoustic shadow generated by the kidney stone.

Medical professionals utilize these features of the target kidney stone in their works. We have conducted kidney stone model extraction experiments using phantom and swine kidneys and confirmed the effectiveness of the proposed kidney stone extraction method.

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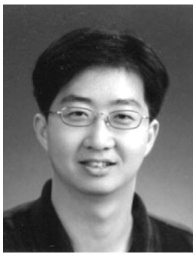
• The Japan Society for Precision Engineering (JSPE)
• The Robotics Society of Japan (RSJ)
• The Acoustic Society of Japan (ASJ)
• The Institute of Electrical and Electronic Engineers (IEEE) Robotics and Automation Society



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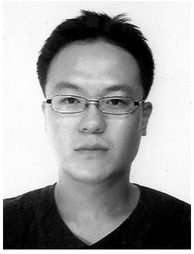
Main Works:
• physiological motion compensation for HIFU therapy
• visual servo system

Membership in Academic Societies:
• The Korean Society of Mechanical Engineers
• Korean Society for Precision Engineering



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2002-2003 Visiting Researcher, Stanford University, USA
2004 Received M.S. degree in Mechanical Engineering and Aeronautics from Seoul National University, Korea
2004-2008 Software Engineer, INUS Technology, Korea
2008-2011 Received Ph.D. in Mechanical Engineering from The University of Tokyo
2012- Research Staff Member, Samsung Advanced Institute of Technology, Korea

Main Works:
• therapeutic/diagnostic ultrasound, computer guided minimal/non-invasive robotic surgery system

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Brief Biographical History:
2010 Received B.E. degree in Mechanical Engineering from Tohoku University
2012 Received M.E. degree in Mechanical Engineering from The University of Tokyo

Main Works:
• robustness enhancement for noninvasive ultrasound theragnostic systems

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Brief Biographical History:
2002 Received M.D. degree from Kyoto Prefectural University of Medicine
2004 Completed urology residency in National Medical Center, the Graduate School of Medicine, The University of Tokyo

Main Works:
• fusion of engineering and medical science, non-invasive ultrasound diagnosis and treatment of urologic and renal disease

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Brief Biographical History:

1987 Completed medical education, Hamamatsu Univ. School of Med. (HUSM)
1987- Started surgical and urological fellowship, HUSM and its affiliated hospitals
1993-2000 Instructor, HUSM
2000-2004 Head, Dept. of Urol, Yaizu Municipal General Hosp.
2004-2007 Assistant Professor, the specialty of urology, The Univ. of Tokyo Hosp.
2007- Head, Division of Total Renal Care, Graduate School of Med., The Univ. of Tokyo

Main Works:

• renal replacement therapy, HIFU treatment for urological diseases, fusion of engineering and medical science, less-invasive diagnostic and therapeutic methods

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Researcher, National Institute of Advanced Industrial Science and Technology (AIST)

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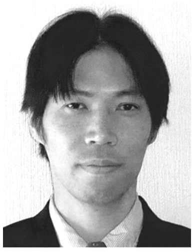
Brief Biographical History:

2002 Received Ph.D. degree from Faculty of Engineering, Kyoto University
2002- Researcher, Surgical Assist Technology Group in Institute of Human Science and Biomedical Engineering, AIST
2007-2010 Senior Lecturer, Graduate School of Bioengineering, The University of Tokyo
2010- Researcher, Surgical Assist Technology Group in Human Technology Research Institute, AIST (concurrently)

Main Works:

• navigation and control for internal medical instruments, magnet resonance compatibility for surgical tools and microbubble enhanced ultrasound in a human body



Name:
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Brief Biographical History:

1996 Received the Master's degree of Mechanical Engineering from The University of Tokyo
1996-2003 Worked for NEC Corporation
2003- Research Associate, The University of Tokyo
2005 Received the Doctoral degree of Engineering in Mechanical Engineering from The University of Tokyo
2007- Associate Professor, The University of Tokyo

Main Works:

• machining of biomaterials, robot-assisted surgical systems and intelligent manufacturing systems

Name:
Yoichiro Matsumoto

Affiliation:
Professor, The University of Tokyo

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Brief Biographical History:

1977 Received Ph.D. degrees from Mechanical Engineering, The University of Tokyo
1977- Lecturer, Mechanical Engineering, The University of Tokyo
1978- Associate Professor, The University of Tokyo
1992- Full Professor, The University of Tokyo

Main Works:

• fluids engineering, molecular dynamics, rarefied gas dynamics, bubble dynamics, multi-phase flows, medical application of fluids engineering, development of living matter simulator and knowledge structuring

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Professor, Graduate School of Medicine, The University of Tokyo

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Brief Biographical History:

1978 Completed Medical education, The University of Tokyo
1978- Started surgical and urological Fellowship, The University Hospital and subsequently its affiliated hospitals
1987-2003 Associate Professor, the specialty of lower urinary tract dysfunctions, The University Hospital
2003- Director, the Department of Urology, Japan Red Cross Medical Center
2008- Chairmanship, the Department of Urology, Graduate School of Medicine, The University of Tokyo

Main Works:

• oncology, chemoprevention of bladder cancer recurrence

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Brief Biographical History:

1979 Received the B.S. degree in Physics Engineering from The University of Tokyo
1981 Received the B.E. degree in Mechanical Engineering from The University of Tokyo
1983 Received the M.E. degrees in Mechanical Engineering from The University of Tokyo
1986 Received the Ph.D. degree in Mechanical Engineering from The University of Tokyo
1987-1988 Visiting Research Scientist, the Institut fuer Productionstechnik und Automatisierung (IPA), Stuttgart, Germany
1987-1989 Lecturer, The University of Tokyo
1989-1999 Associate Professor, The University of Tokyo
1999- Full Professor, The University of Tokyo

Main Works:

• computer integrated surgery systems, intelligent manufacturing systems, nanomicromanufacturing, and nanobiointegration

Membership in Academic Societies:

• The Institute of Electrical and Electronic Engineers (IEEE) Robotics and Automation Society
• College International pour la Recherche en Productique (CIRP)
• The American Society of Precision Engineering (ASPE)
• The Japan Society of Mechanical Engineers (JSME)
• The Japan Society for Precision Engineering (JSPE)
• The Society of Instrument and Control Engineers (SICE)
• The Robotics Society of Japan (RSJ)
• The Information Processing Society of Japan (IPSJ)