A Computer-Controlled Ultrasound Pulser-Receiver System for Transskull Fluid Detection using a Shear Wave Transmission Technique

Sai Chun Tang, *Member, IEEE*, Gregory T. Clement, and Kullervo Hynynen

Abstract—**The purpose of this study was to evaluate the performance of a computer-controlled ultrasound pulser-receiver system incorporating a shear mode technique for transskull fluid detection. The presence of fluid in the sinuses of an *ex vivo* human skull was examined using a pulse-echo method by transmitting an ultrasound beam through the maxilla bone toward the back wall on the other side of the sinus cavity. The pulser was programmed to generate bipolar pulse trains with 5 cycles at a frequency of 1 MHz, repetition frequency of about 20 Hz, and amplitude of 100 V to drive a 1-MHz piezoelectric transducer. Shear and longitudinal waves in the maxilla bone were produced by adjusting the bone surface incident angle to 45° and 0°, respectively. Computer tomography (CT) scans of the skull were performed to verify the ultrasound experiment. Using the shear mode technique, the echo waveform clearly distinguishes the presence of fluid, and the estimated distance of the ultrasound traveled in the sinus is consistent with the measurement from the CT images. Contrarily, using the longitudinal mode, no detectable back wall echo was observed under the same conditions. As a conclusion, this study demonstrated that the proposed pulser-receiver system with the shear mode technique is promising for transskull fluid detecting, such as mucus in a sinus.**

I. Introduction

Sinusitis, or sinus infection, which can be caused by a number of conditions, is one of the most common healthcare problems in the U.S., accounting for more than $5.8 billion in direct health care expenditures [1]–[4]. Acute bacterial infection occurs when bacteria colonize and overgrow in trapped fluid in the sinuses, [5]–[7] generally indicating the need for treatment with antibiotics. However, up to 98% of sinusitis cases are viral, and can generally be treated with over-the-counter medications. Despite this, primary care physicians prescribe antibiotics for 85 to 98% of patients suspected of having rhinosinusitis [3].

To differentiate between viral and bacterial infection, the presence of an air-fluid level in the maxillary sinus [8], [9], as assessed by puncture or imaging, provides a standard for evaluating the diagnostic reliability of physical symptoms. The absence of these findings is highly significant for ruling out bacterial infection. Therefore, plain x-ray radiographs or computed tomography (CT) is used to evaluate the presence of fluid. Unfortunately, the cost and inconvenience of both approaches have been obstacles to their routine use for diagnosis.

The potential for ultrasonic pulse-echo A-scan to detect transskull fluid, such as mucus in a sinus, has been realized for more than three decades [10]–[15]. In ultrasound diagnosis of sinusitis, a high-amplitude acoustic pulse is transmitted through the maxilla bone toward the back wall of the sinus cavity on the other side of the bone. The air in a normal sinus prevents the ultrasound propagation; only one echo from the front wall of the sinus is produced. On the other hand, if the sinus is infected, the sinus will be filled with fluid that conducts the ultrasound, and a second echo from the back wall will be generated [16].

Unfortunately, significant variability in the method results from strong ultrasound scattering and attenuation caused by the skull. In previous ultrasonic sinus fluid detection studies [17], [18], the ultrasound transducer was placed parallel to the maxilla bone, and the incident angle was approximately zero degree. The problem of using such a configuration is twofold. First, the ultrasound propagation inside the bone is primarily in longitudinal mode [19], [20]. The speed ($\sim$2820 ms^{-1}) of longitudinal sound propagation inside skull bone is almost twice that of the sound speed in soft tissues and water ($\sim$1500 ms^{-1}). The large discrepancy in sound speed causes significant impedance mismatch; most of the ultrasound energy is reflected at the boundary between the media. As a result, the ultrasound energy transmitted through the bone is greatly reduced. In practice, a very high-amplitude acoustic pulse from the transducer is required to compensate for the reflection loss. Second, as the transducer is oriented parallel to the bone, multiple reflections between the bone and the transducer may occur. These multiple echoes deteriorate the signal-to-noise ratio (SNR) of the desired back wall echo signal, and therefore decrease the accuracy of the detection.

Yet, a reliable ultrasound method would have clear advantages over existing standard methods for sinusitis diagnosis, such as sinus puncture and x-ray CT. Ultrasound represents a very compact, low-cost method that is noninvasive and does not involve ionizing radiation [17], [21]. It is envisaged that a portable, single-channel ultrasound

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The authors are with the Department of Radiology, Brigham and Women's Hospital, Harvard Medical School, Boston, MA (e-mail: sct@bwh.harvard.edu).

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modality would provide a convenient and cost-effective clinical procedure for sinusitis diagnosis, and follow-up of treatment results.

The present work examines an improved method for propagating into the sinuses using a shear mode conversion. Recently, it was demonstrated that the use of shear wave propagation, instead of the longitudinal mode, inside the skull bone can improve ultrasound transmission substantially [19], [20]. The shear wave in skull bone can be produced by adjusting the incident angle greater than the longitudinal critical angle. Unlike that of the longitudinal mode, the sound speed of shear wave ($\sim$1400 ms^{-1}) in skull bone is close to that of soft tissues. The similarity in speed of sound improves the acoustic impedance matching considerably, and thus increases the transmitted ultrasound energy through the bone. The enhanced ultrasound transmission reduces the required acoustic pressure and also the energy consumption of the pulser system. Furthermore, when the shear mode method is used, the transducer is oriented at an angle ($> 30°$) with respect to the maxilla bone; the multiple-reflection issue is naturally relieved as a significant portion of the echo from the maxilla bone reflects away from the transducer.

In this study, we developed a compact and economical computer-controlled pulser-receiver system and demonstrated the operation of the system incorporating a shear mode technique derived in our prior studies [19], [20]. The purpose of this study was to investigate the performance of the system using the shear mode method and to compare it with its traditional counterpart, longitudinal mode, for transcranial fluid detection using an *ex vivo* human skull.

II. Pulser-Receiver System Design

A block diagram of the proposed ultrasonic pulser-receiver system is shown in Fig. 1. Both transmitting ultrasound pulses and receiving echo signal are accomplished by the same transducer. The transducer is driven by a pulse train generator, which delivers a high-voltage bipolar pulse train. Bipolar voltage pulse is employed because it has lower unwanted dc and a low-frequency component that may increase the leakage current compared to its unipolar counterpart. Another advantage of using bipolar pulse is that the peak-to-peak pulse voltage can be twice the voltage rating of the coaxial cable connecting the pulser and the transducer. As a result, the size and cost of the cable can be substantially reduced, especially in the case where a multi-element transducer array is used.

The amplitude of the pulse train is determined by the output voltage of the high-voltage dc supply, which steps up battery voltage (e.g., 12 V) to ±60–180 Vdc. The amplitude and the SNR of the received echo signal can be improved by increasing the pulse train amplitude and driving the transducer at its resonance frequency. The frequency of the pulse train can be generated either by a computer through a digital I/O interface or from an external signal source such as a function generator or an oscillator. In the prototype design, the pulse train was generated by a digital I/O card (PCI6534, National Instruments, Austin, TX). The pulse frequency and number of pulses were programmed by a personal computer with a program implemented by LabVIEW (National Instruments).

On the receiving side, the echo ultrasonic signal is converted to an electrical signal by the same transducer, and amplified by a high-gain amplifier. High-pass filters are integrated into the echo amplifier to eliminate the low-repetition frequency, which might saturate the high-gain amplifier. The amplified echo signal is then converted to digital format by a high-speed analog-to-digital converter (ADC). These digitized echo data are temporarily stored in the on-board memory and then transferred to the personal computer that stores and analyzes the signal.

A. High-Voltage dc Supply

A high-voltage pulse train for driving the transducer is desired to produce large-amplitude ultrasound and improve the SNR of the echo signal. The bipolar pulse train amplitude at the pulse generator output follows the output voltages (±HV) of the high-voltage dc power supply. Fig. 2 shows the circuit diagram of the dual high-voltage power supply. The positive and negative output voltages designated as +HV and −HV, respectively, are variable from ±60 to ±180 V. High voltage is accomplished by employing a high-turns-ratio step-up transformer (Tr_1). The power converter is connected in flyback topology. The output voltage and power are controlled by the duty ratio of the metal-oxide-semiconductor field effect transistor (MOSFET) Q_1. When Q_1 is turned on, current flows into the primary of Tr_1. Diodes D_1 and D_2 are reverse-biased, so secondary windings are open-circuited. At this state, magnetic energy is stored in the transformer core, and no energy transfers to the secondary side. When Q_1 is turned off, back electromotive force (EMF) is induced at the secondary windings, and magnetic energy stored in the transformer is released to the secondary side. At this state, D_1 and D_2 are forward-biased. Capacitors C_1 and C_2 are being charged toward the desired voltage level, which is controlled by a MOSFET controller LM3478 (National Semiconductor Corp., Santa Clara, CA). This controller uses a current mode control scheme to limit the MOSFET (Q_1) and output currents by feeding the voltage across the current-sensing resistor (R_S) into the current-sensing pin I_{sen}. The output voltage is sensed through a feedback resistor divider network (R_1, R_2, and VR_1) and fed into the feedback pin (FB) of the controller. The positive output voltages, +HV, can be controlled between 60 and 180 V by adjusting the position of potentiometer VR_2. The lower and upper voltage limits are determined by the values of resistors R_1 and R_2. With the information of the feedback voltage and current, driving signal for Q_1 with appropriate duty cycle can be generated by the controller. By transforming the feedback resistor divider network to its equivalent circuit as shown in Fig. 3, the output voltage is giving by [22]

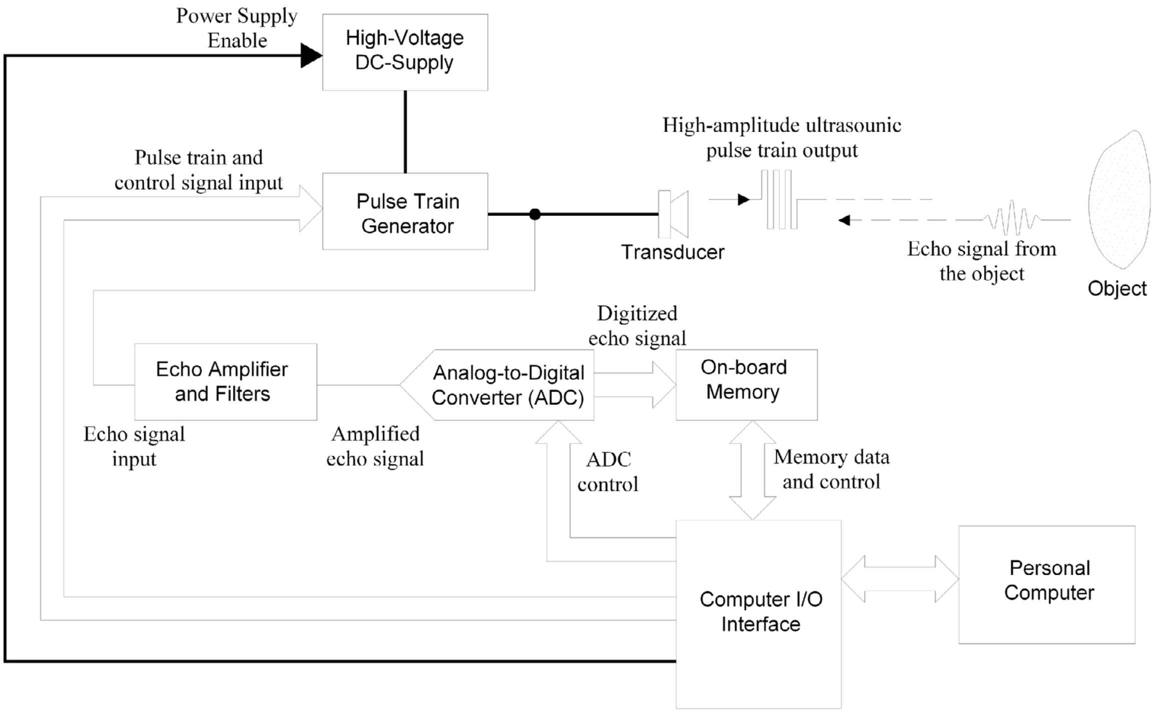

Fig. 1. A block diagram of the computer-controlled ultrasonic pulser-receiver system.

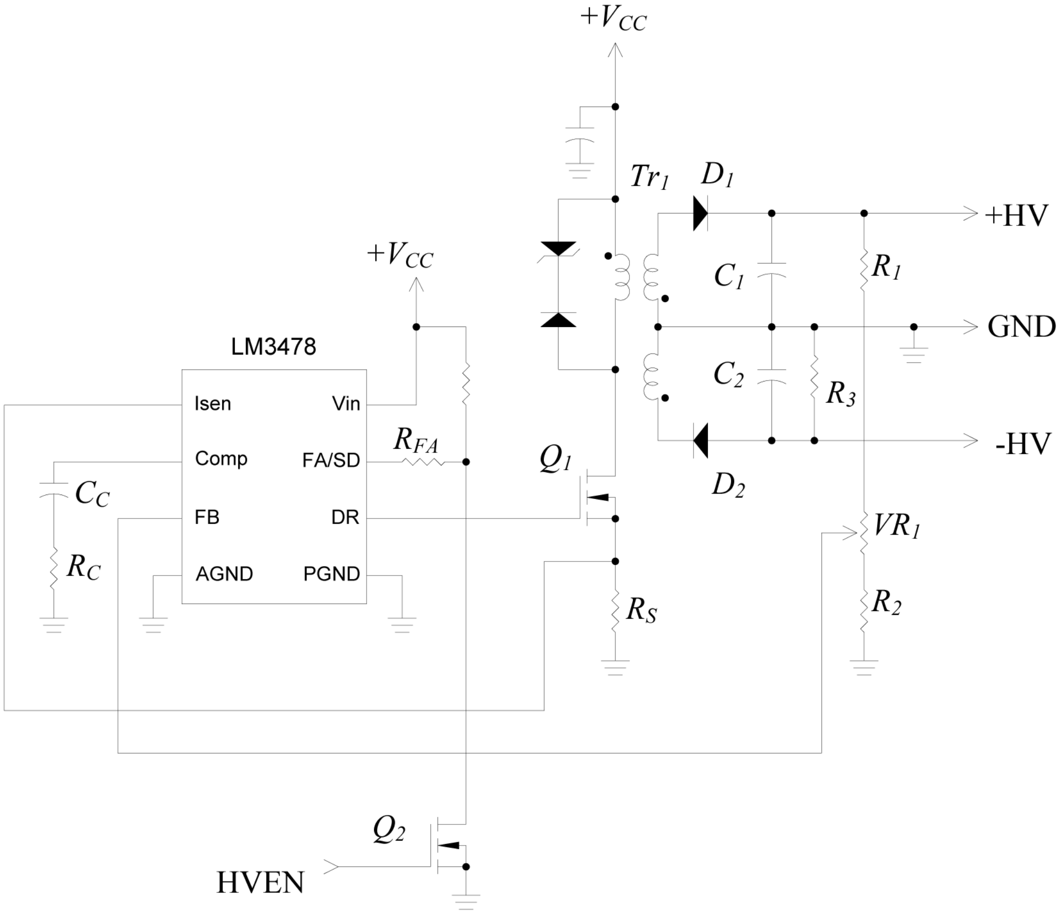

Fig. 2. Circuit schematic of the high-voltage power supply.

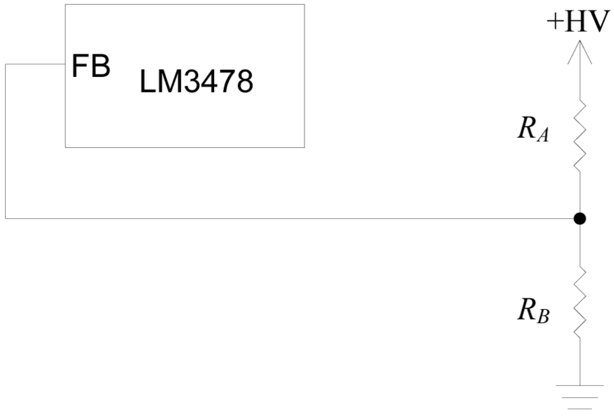

Fig. 3. Equivalent feedback resistor divider network for the high-voltage power supply.

$$+HV = 1.26\left(1 + \frac{R_A}{R_B}\right).$$

Because the pulse generator loads the positive and negative outputs symmetrically, the negative voltage amplitude follows the positive voltage level, and therefore both voltages can be regulated using the same controller. The resistor, R_3, connected to the negative output terminals is used to discharge the high voltage across C_2 when the circuit is turned off for the sake of safety. It also balances the load at the positive and negative outputs in order to keep the dual voltage amplitude symmetric.

The high-voltage dc supply operates as a switching mode power converter that could be a significant source of electromagnetic interference (EMI) to the very sensitive high-gain echo amplifier. For this reason, the high-voltage power supply is shut down temporarily at the period between sending the pulse train and waiting for the echo signal by applying a logic low-level signal to the high-voltage-enable (HVEN) input. During this period, the output capacitors C_1 and C_2 supply energy to the pulse generator. In the circuit prototype, ripple voltage of less than 0.1% of the output voltage was measured when both C_1 and C_2 are 1 μF and the idle time is 100 μs.

B. Pulse Generator

Similar to that of the high-voltage supply, the design of the pulse train generator was configured to operate at switching mode so as to minimize the power consumption and heat dissipation. Without the requirement of cooling, the cost, size, and weight of the pulse train generator are significantly reduced. Moreover, reliability and accuracy can be considerably improved as there is no excessive heat generated from the circuit. The driving circuit for the transducer, as shown in Fig. 4, is made of a half-bridge switching converter. The dual voltage supply ±HV determines the amplitude of the bipolar pulse train, which is generated by switching on and off the N-channel power MOSFETs Q_3 and Q_4 complementarily. In the positive half-cycle, Q_3 is on and Q_4 is off, and the generator output voltage is equal to +HV. On the contrary, during the negative half-cycle, Q_3 is off and Q_4 is on, and the output voltage becomes −HV.

In the design of a practical pulse generator, parasitic capacitors associated with the MOSFETs and the coaxial cable connecting to the transducer have to be considered. These capacitors keep the pulse generator output at high voltage for a long period that could saturate the high-gain echo amplifier and also increase the leakage current that may create safety issues. Thus, at the end of each pulse train, discharging the parasitic capacitors to zero potential is essential. The purpose of solid-state switch S_1 is to discharge the parasitic capacitors when both Q_3 and Q_4 are in the off state. Fig. 5 illustrates the solid-state switch that discharges the parasitic capacitor, via MOSFETs Q_5 and Q_6. The operating principle of this solid-state switch is detailed in [23].

The gating signals for Q_3, Q_4, and S_1 are generated by the computer I/O interface with software control, although we have verified they can be achieved by standalone digital circuitry. Because the source terminals of both Q_3 and Q_4 are not connected to the ground, isolated gate drive circuits for the MOSFETs are required. In this prototype, isolation is achieved by using a signal transformer Tr_2 with two secondary windings and turns ratio of 10:15:15.

C. Echo Amplifier

In practical situations, the received echo signal intensity can be less than 1% of that sent out from the transducer. A high-gain amplifier is required to amplify the echo signal received from the transducer. The echo amplifier being used consists of four stages of low-noise operational amplifiers, OA_1 to OA_4, as shown in Fig. 6. Each stage provides a voltage gain of 10 times, and 10^4 times in total. Two first-order high-pass filters (HPFs) are integrated into the amplifier circuit to eliminate the low-repetition frequency, which may cause the amplifier to become saturated. The coarse and fine gain adjustments of the amplifier are accomplished by potentiometers VR_2 and VR_3, respectively. Because the echo amplifier input is connected directly to the pulse generator output that delivers the high-voltage pulse train, a protection scheme is necessary to prevent the echo amplifier from being damaging by the high voltage. At the echo amplifier input, the non-inverting input of OA_1 is limited to less than one volt by using two inexpensive small signal diodes (D_4 and D_5) in anti-parallel connection.

D. Analog-to-Digital Converter and Memory

The amplified echo signal is converted to digital format by a high-speed analog-to-digital converter (AD9215, Analog Devices, Inc., Norwood, MA) as shown in Fig. 7. The sampling frequency of data conversion is set to 66.67 Megasamples per second (MSPS). In order to achieve optimum signal conversion performance, the single-ended amplified echo signal is converted to differential format by a signal transformer Tr_4, and filtered by a pair of RC low-pass net-

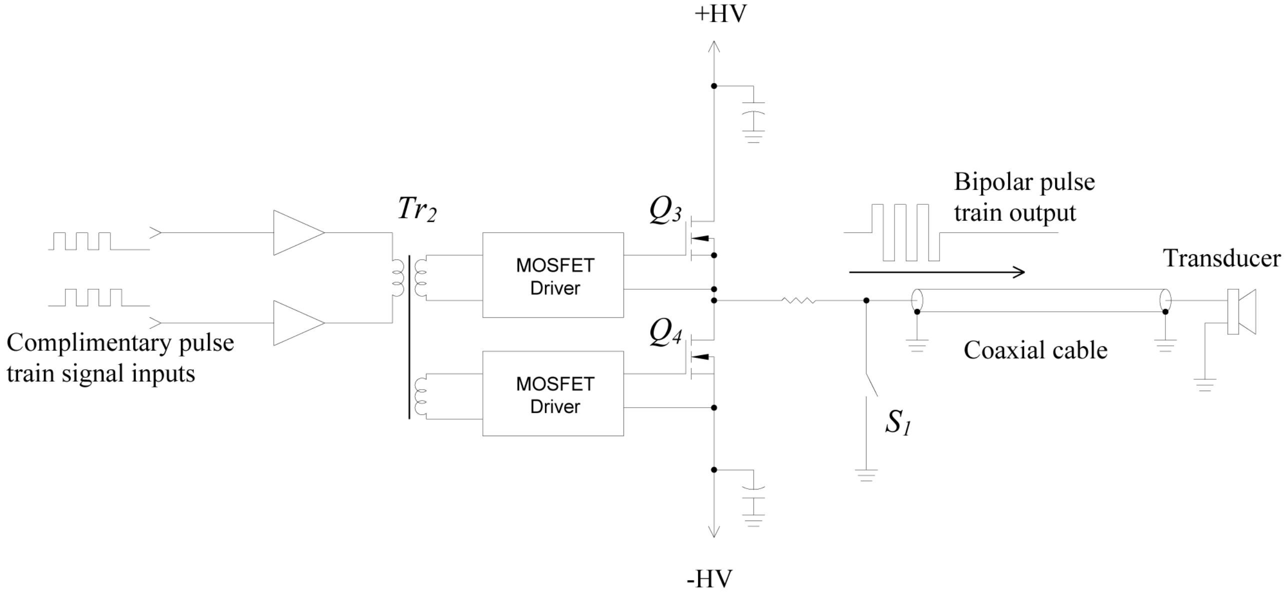

Fig. 4. Circuit schematic of the pulse generator.

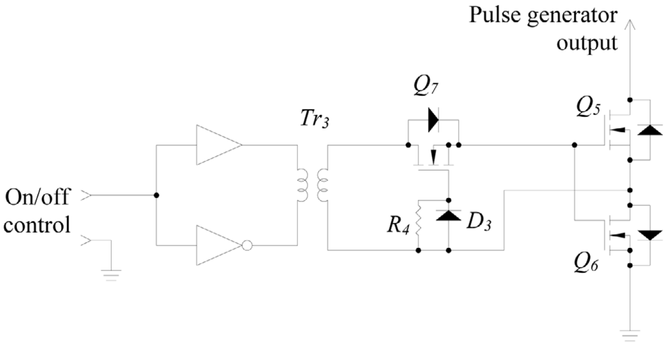

Fig. 5. Circuit schematic of the solid-state switch, S_1.

works [24]. The digital output from the ADC is connected to the data I/O pins (D_0–D_9) of the memory via an array of switches S_2, which controls the data flow from the ADC to the memory. The switches turn on only when the echo signal is being recorded to the memory.

Because of the high sampling rate of the data conversion, a high-speed static random-access memory (SRAM) (K6R1016V1D, Samsung Semiconductor, Inc., San Jose, CA) is employed to cache the digitized echo signal. This SRAM is a 64-kB, 16-bit, high-speed memory module with up to 8 ns access time. After a whole frame of analog echo signal is digitized and cached in the SRAM, the data in the SRAM will be transferred to a PC through the digital I/O card PCI6534 for storage and analysis. The memory addressing of the SRAM is controlled by a high-speed 16-bit counter. The triggering of the data conversion, the data flow direction, and the memory address counting are controlled by the LabVIEW program through the same digital I/O card.

III. Experiment

A. Sinus Fluid Detection Setup

The use of the ultrasonic pulser-receiver system for the detection of fluid in sinus cavities is illustrated in Fig. 8. The presence of fluid in the maxillary sinuses of an *ex vivo* human skull was being detected. An ultrasound simulation study was conducted with a previously described transskull ultrasound propagation algorithm, using magnetic resonance imaging (MRI) sinus images of a volunteer in order to determine the optimal transducer frequency, diameter, and radius of curvature. In this study, ultrasound was propagated first as a longitudinal signal that was then separated into both a longitudinal and a shear mode in the bone. Both modes then transferred back to two longitudinal signals in the fluid-filled sinus. This signal was reflected off the back wall of the sinus, where the mode conversion occurred again as the signal exited the head. Based on this study, a 1-MHz-resonance PZT crystal (EBL Products, Inc., East Hartford, CT) was selected, with a 20-mm diameter, and a 40-mm radius of curvature. The crystal was backed with 25% tungsten-epoxy composite material for acoustic damping, and mounted so that the ultrasound was directed at an angle of approximately 45° relative to the skull surface. The beam width at the point of contact with the mandible was elongated due to the angle of incidence, entering with an approximately 10×7 mm footprint on the mandible surface.

For the study, a human skull was reconstituted after full desiccation by submersing it in deionized water and degassing the specimen in a bell jar. Afterward, the skull was stored in a 10% buffered formaldehyde solution. A previous study has shown that human skulls undergoing this dehydration-reconstitution process have sound speeds closely matching that of fresh bone tissues [25].

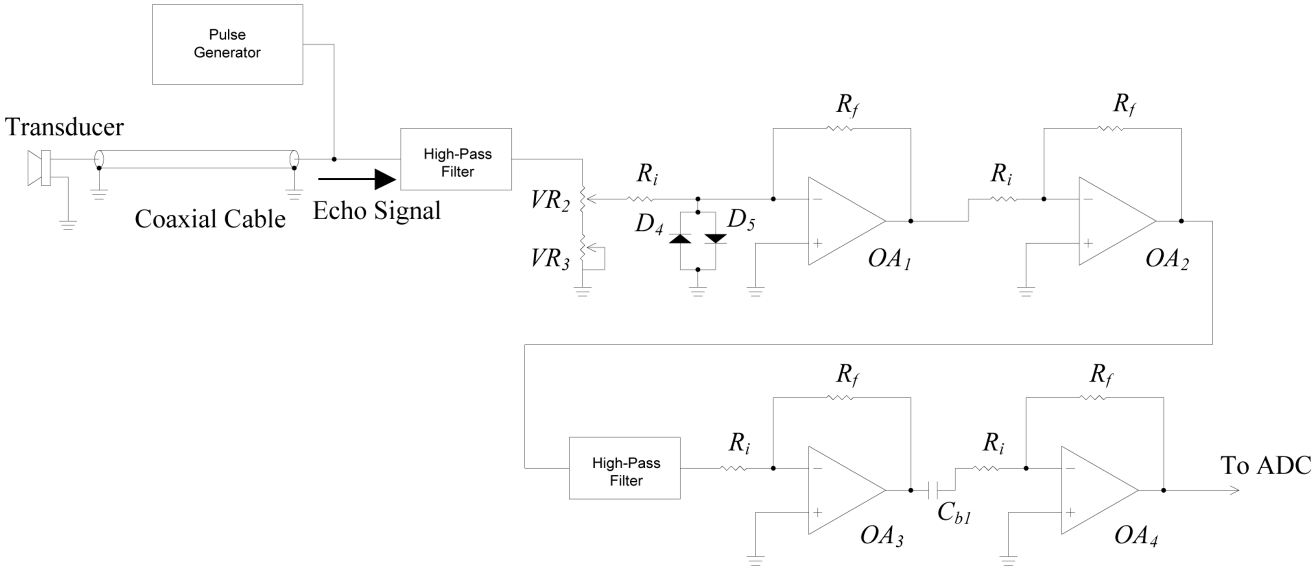

Fig. 6. Circuit schematic of the echo amplifier.b

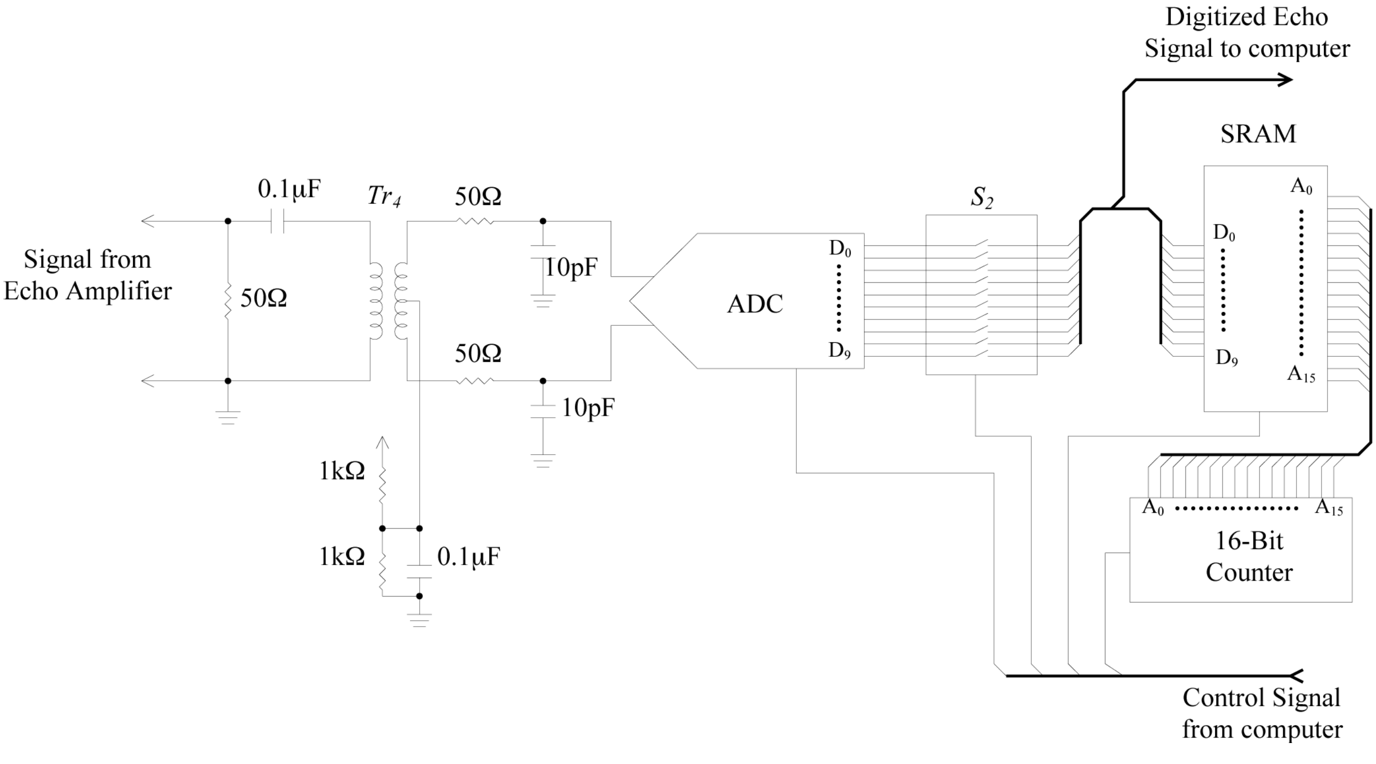

Fig. 7. Circuit schematic of the analog-to-digital converter and memory.

The transducer and human skull were immersed in degassed deionized water in a tank filled with padded rubber to reduce reflections from the tank walls. The detections of fluid in both left and right maxilla sinus cavities were performed. For the experiments of sinus fluid detection, the sinus cavity was first completely filled with water. Control experiments were conducted by inserting a tube into the sinus cavity and injecting air by means of a syringe attached to the other end of the tube. The skull was oriented with the face horizontal in order to trap the air in the sinus for the control experiments.

The effects of shear and longitudinal propagation through the maxilla bone were examined by orienting the transducer at different angles, as shown in Fig. 9. For the measurement of the echo signal with shear mode propagation through the maxilla bone, the incident angle was adjusted to approximately 45°, which is greater than the longitudinal critical angle of about 30° [19]. It is noted that both the transmitted and received waves were longitudinal. The propagation involved a mode conversion from longitudinal in the skin into a shear wave in the bone, and then back into longitudinal in the sinus fluid, if present. If

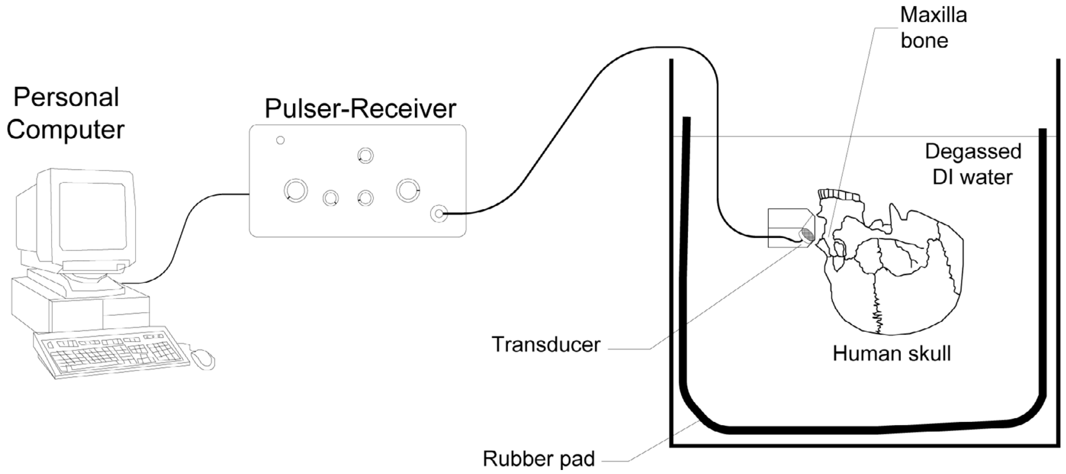

Fig. 8. Experimental setup for detecting the presence of fluid in the maxillary sinuses.

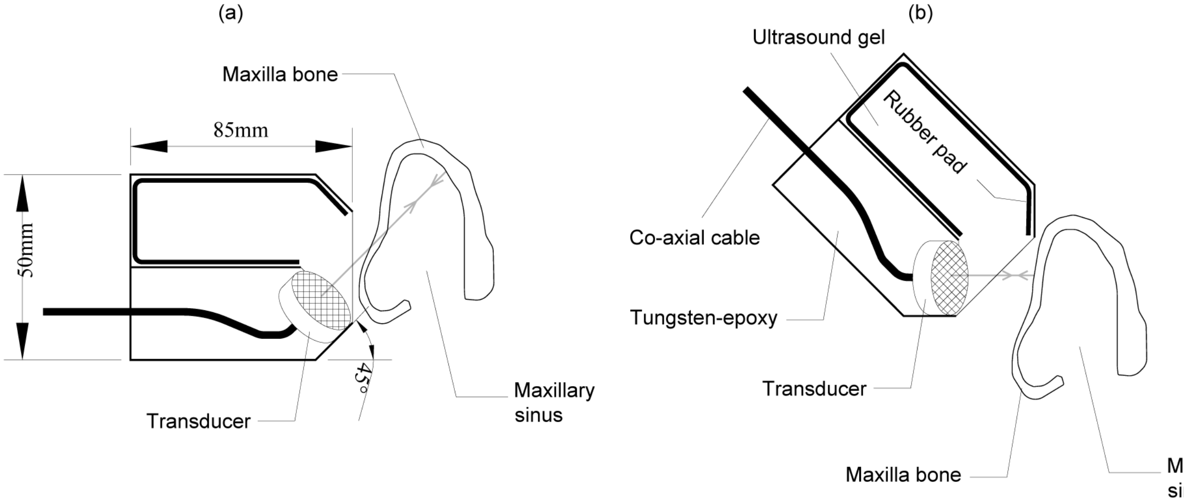

Fig. 9. Orientations of the transducer for the echo measurements with (a) shear and (b) longitudinal propagations. Sagittal view of the maxilla bone is shown; the skull was upside down.

the cavity was fluid-filled, the reverse process took place where echoes off of the back of the sinus cavity were again converted to shear waves in the bone and then back to longitudinal before reaching the transducer. For the echo measurement associated with longitudinal propagation in bone, the transducer is positioned approximately parallel to the maxilla bone, so that the incident angle (∼0°) is smaller than the longitudinal critical angle.

B. Pulser-Receiver System

The computer-controlled ultrasonic pulser-receiver system described in the previous section was constructed in-house. The pulser-receiver system was used to transmit a high-voltage pulse train to and receive echo signal from the same transducer. The transducer was connected to the pulser-receiver through a Belden 8216 RG174U 50Ω coaxial cable of length about 1 m. A bipolar pulse train with amplitude regulated at ±100 V was adopted to excite the transducer. The pulse train frequency of 1 MHz and five pulse cycles in each pulse train were set through a software interface, implemented in LabVIEW code, as shown in Fig. 10. At the end of each pulse train, the pulser output was shorted to ground for 10 μs to discharge the undesired stray capacitor formed by the pulser output MOSFETs, the coaxial cable, and the transducer.

Both pulse train transmission and echo receiving were controlled using the same software interface. The voltage across the transducer terminals was sensed, recorded, and transmitted to the computer in real time. Data recording started when the pulse train was transmitted, and the record duration was set to 100 μs. The sensed transducer voltage was converted to 10-bit digital offset binary format, buffered in a static RAM, and then transmitted to a PC at a rate of 20 Mbytes/s. Signal processing for the received transducer voltage was handled by a sixth-order software Butterworth low-pass-filter implemented in LabVIEW code in order to filter out high- frequency noise. The cut-off frequency was set to 3.4 MHz. The repetition frequency of the pulse train and data conversion/recording

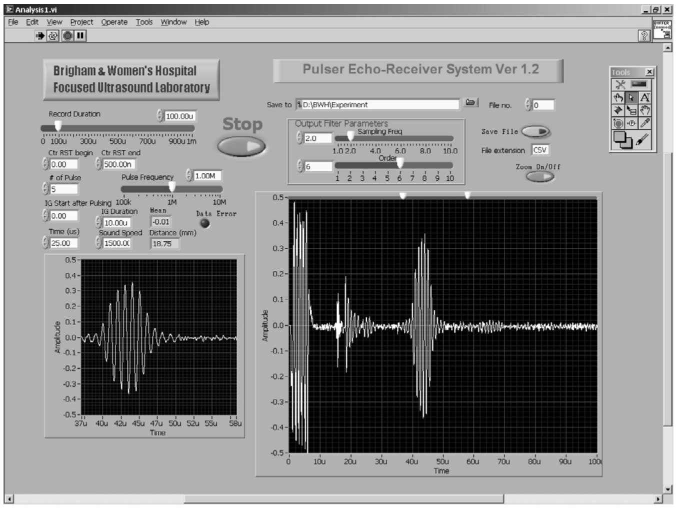

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Fig. 10. Software front panel for the pulser-receiver system.

cycle was approximately 20 Hz. Real-time transducer voltage waveform was displayed on the software interface for the measurements of time-of-fight, and hence the distance between the objects that the ultrasound beam traveled. The echo waveforms for the experiments were saved in the computer hard disk for further analysis.

C. Sinus Imaging

Structure and dimensions of the maxilla bone of the *ex vivo* human skull used in the sinus fluid detection experiment were obtained from CT images (Somatom Sensation 64, Siemens, Erlangen, Germany). The skull was preserved in formalin and scanned under water. Two hundred CT slides in coronal view were taken at 1-mm intervals using a 279 × 279-mm field of view with resolution of 512 × 512 pixels (0.54 mm^2 pixels). Image data for each slide were saved to an individual file in binary format. Axial and sagittal views of the skull were reconstructed (Fig. 11) from the coronal view image files using a program (written in-house) implemented by LabVIEW code with embedded MATLAB (The MathWorks, Inc., Natick, MA) script.

IV. Results

The transducer signals recorded by the pulser-receiver system for sinus fluid detection are shown in Figs. 12 and 13. First, it should be noted that a high-amplitude voltage swing with a duration of a few microseconds at the beginning of every recorded signal was caused by the coupling from the high-voltage pulse train originating from the pulse generator. Second, a short period of voltage swing appearing at around 15–16 μs was caused by the transducer transient when the solid-state switch connecting the transducer and the ground was opened. Thus, the receiver began to receive echo signal after the settling of the transducer transient at around 16 μs.

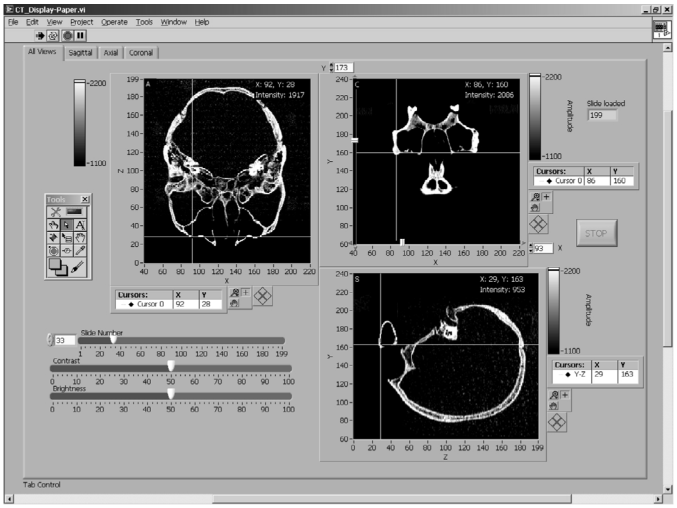

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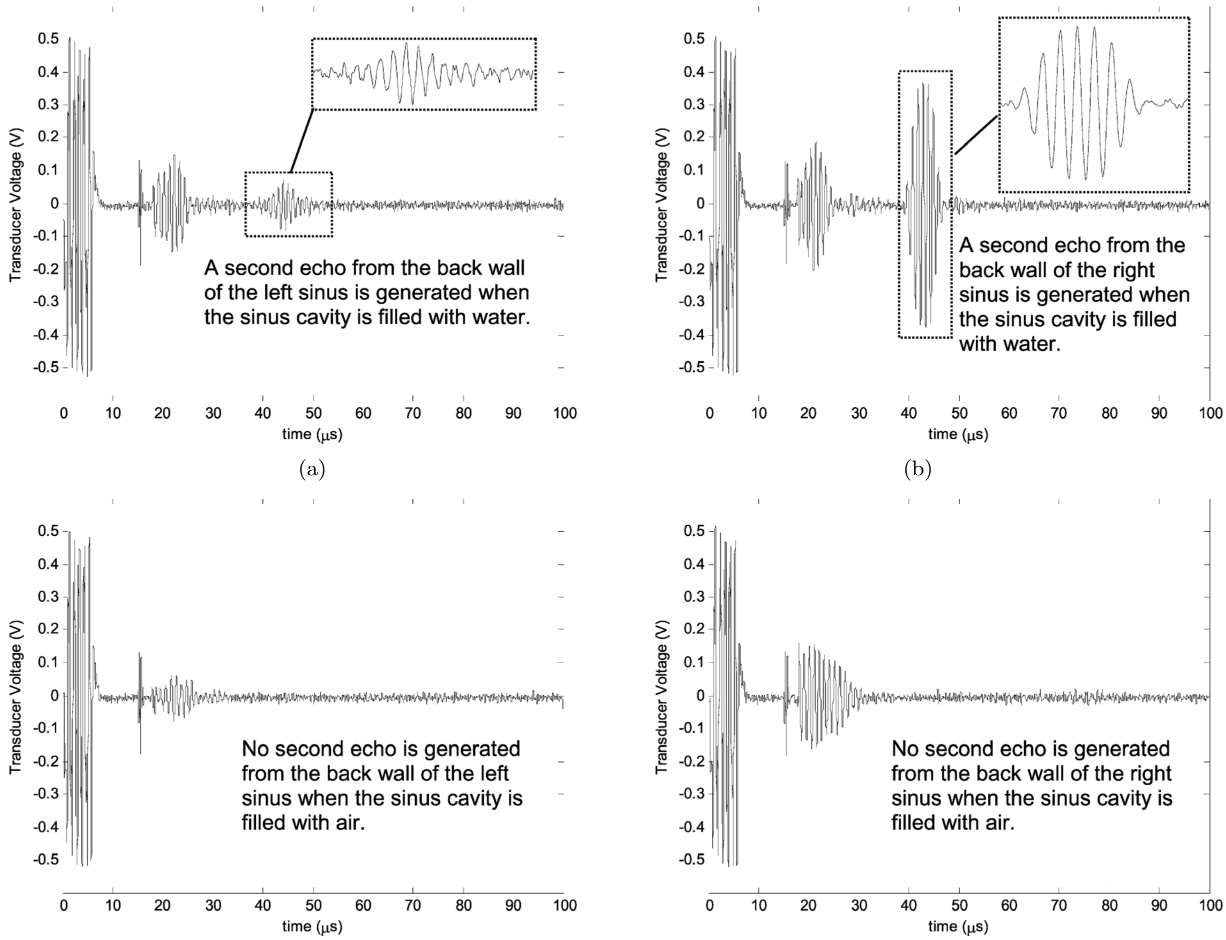
Fig. 11. Software front panel showing the axial, sagittal, and coronal views of the human skull used in the fluid detection experiment.

The sagittal views of the CT scans for the *ex vivo* human skull in upside-down orientation, showing the left and right maxillary sinuses, are displayed in Fig. 14(a) and (b), respectively. The positions of the transducer for the shear mode experiment are indicated on the figures. For the case of shear wave propagation, the transducer voltage signals from the left and right sinuses filled with air and water are shown on Fig. 12(a)–(d), respectively. In this case, the ultrasound beam first hit the outer surface of the maxilla bone (indicated as point 1), as illustrated in Fig. 14(a) and (b). This echo propagated back to the transducer surface at about 18 μs after transmitting the pulse train as shown in Fig. 12. When the sinus cavity was filled with water, the ultrasound beam then transmitted through the sinus and hit the back wall of the maxilla bone, indicated as point 2 in Fig. 14(a) and (b). The second echo propagated back to the transducer surface at around 40 μs, as shown in Fig. 12(a) and (b). Conversely, when the sinus was filled with air, the ultrasound beam was reflected back at the first hit and could not transmit through the air sinus due to impedance mismatch. Fig. 12(c) and (d) reveal that the received transducer signal had only one echo for the air-filled sinus.

As indicated on the CT images in Fig. 14, the shapes of the left and right maxilla bones are not identical. Echo signal measurements, in Fig. 12(a) and (b), also show that the echo amplitudes from the second reflection on the left and right maxilla bones are not the same. The ratio between the second echo and the noise amplitudes on the left and right sides are 3.3 and 13.9, respectively. However, the echo times are approximately the same on both sides. Based on the measured echo time, the distance between points 1 and 2 in both sinuses are approximately 16.5 mm, with the assumption that the sound speeds in water and the bone in shear mode [19] are both 1500 ms^{-1}. The distance estimation is found to be consistent with the measurement from the CT scan, as illustrated in Fig. 14.



(a) (b)

(c) (d)

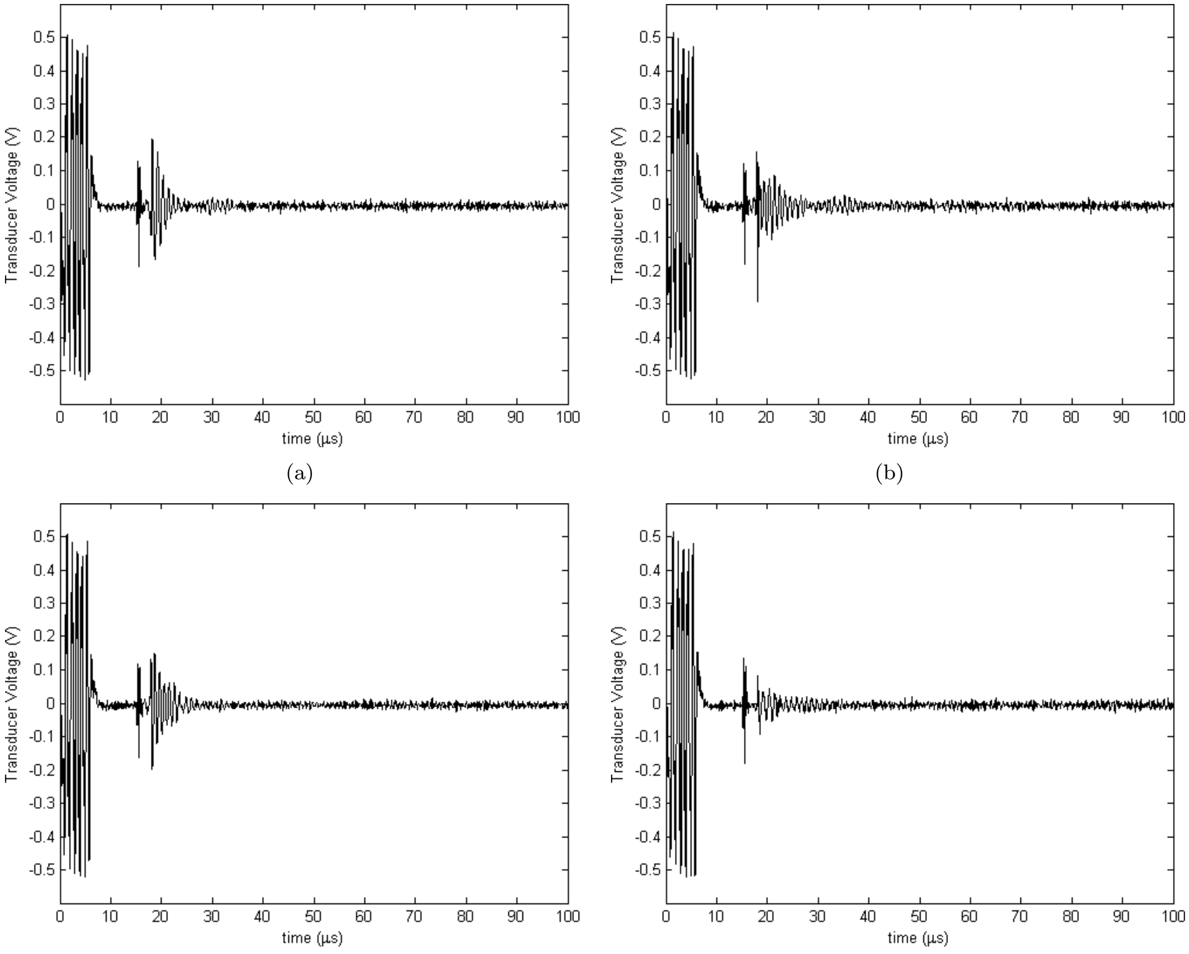
Fig. 12. Measured transducer voltage for shear propagation in bone: (a) left sinus filled with water, (b) right sinus filled with water, (c) left sinus filled with air, and (d) right sinus filled with air.

The effect of longitudinal wave propagation in bone was examined by orienting the transducer in parallel to the maxilla bone. In this case, the incident angle was approximately zero degree and smaller than the longitudinal critical angle of the skull [19]. The transducer voltage waveforms for longitudinal propagation measured on both left and right maxillary sinuses filled with water and air are displayed in Fig. 13. For all of these cases, only one echo from the maxilla bone was received at 18 μs.

V. Discussion

This study confirms our previous investigations on transskull ultrasound transmission enhancement using shear mode conversion, in which the transmitted ultrasound intensity is increased and the distortion is reduced by improved acoustic impedance matching. In this study, we developed a self-contained clinical prototype of ultrasonic pulser-receiver system with computer control for transskull fluid detection. Incorporating the shear mode technique, we demonstrated that the system could be used to distinguish the presence of fluid in sinus cavities in an *ex vivo* human skull, while the traditional longitudinal method cannot detect at the same pulse voltage.

The pulser-receiver system, built in-house, generates a multi-cycle pulse train, instead of a single negative pulse used in traditional pulsers, for transducer excitation that delivers higher transmitted ultrasound energy, thus increasing the echo signal level for SNR improvement. The pulse train frequency was selected to match the transducer resonant frequency at which the transducer efficiency is optimized. The lower limit of the number of cycles is determined by the transducer time response when the ultrasound amplitude generated reaches its steady-state value, while the upper limit is limited by the distance between the transducer and the first object hit by the ultrasound beam. Although the pulser can generate pulse amplitude up to 180 V, we found that a pulse train with 5 cycles and 100 V pulse amplitude was enough to obtain a back wall echo with sufficiently high amplitude that the presence of fluid in an *ex vivo* human sinus could be distinguished using the shear mode method. The number of pulse cycles and the pulse amplitude values were not optimized in this study; they can be further reduced by increasing the gain of the echo amplifier and optimizing the filter parameters. The frequency of the pulse train used in the experiment was 1 MHz; that is within the appropriate frequency range for ultrasonic transskull diagnostic imaging [26]. A frequency



(a) (b)

(c) (d)

Fig. 13. Measured transducer voltage for longitudinal propagation in bone: (a) left sinus filled with water, (b) right sinus filled with water, (c) left sinus filled with air, and (d) right sinus filled with air.

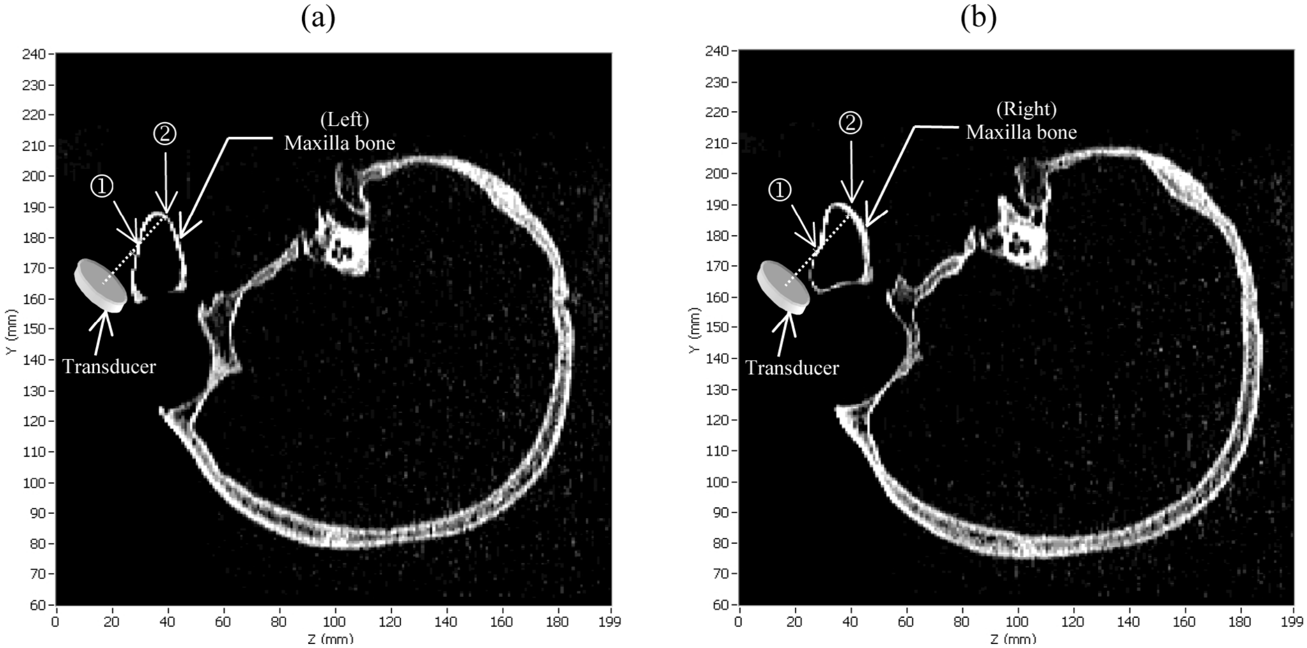


Fig. 14. Sagittal CT images of the skull (upside down), with indication of the transducer position for shear propagation, showing the (a) left and (b) right maxillary sinuses of the *ex vivo* human skull used in the sinus fluid detection experiment.

lower than 1 MHz can be used to reduce the attenuation in bone at the expense of lower spatial resolution. In this study, the echo signal was digitized by a high sampling rate (66.67 MSPS) and high resolution (10-bit) ADC and stored in spreadsheet format for clinician's analysis.

In the pulser-receiver system design, both the high voltage power supply and the pulse generator operate in switching mode, which generally results in higher energy efficiency, smaller size, and lighter weight, compared to those parameters for linear mode circuits. The issues due to the parasitic capacitor at the pulser output, the transducer, and the coaxial cable connected between them were considered. For reasons of safety, a solid-state switch was used to discharge the high potential across the capacitor after sending pulses. The pulser-receiver system does not generate high temperature; it does not require cooling means, such as heat sink and cooling fan, and works stably throughout our experiments.

From the experimental results of fluid detection using the shear mode technique, the right sinus gave a higher back wall echo amplitude than the left, though the system parameters, including pulse amplitude and gain of the echo amplifier, were the same. This result was expected and can be explained by the CT images that the left and right sinuses are not symmetric. The area of the right sinus back wall hit by the ultrasound beam and parallel to the transducer surface is larger than the left. Thus, the amount of ultrasound energy reflected back to the transducer from the right back wall is higher than that from the left, at which a significant portion of ultrasound reflects away from the transducer; however, in reality the ultrasound transmission is more complicated than the beam illustrated in the principle diagram in Fig. 9, due to refraction, geometry, and dispersion of the ultrasonic beam, as well as scattered reflection from curved surfaces. In these experiments, the transducer angles for the left and right measurements were approximately the same. The amount of ultrasound energy received by the transducer can be increased by using a transducer with a larger area or adjusting the transducer position and angle so that maximum echo amplitude is measured. Experimental results also confirm that only one echo occurs when the sinus is filled in air in the cases of both shear mode and longitudinal mode propagation.

Our comparison results reveal that ultrasound transmission through the skull bone with shear mode conversion for sinus fluid detection is more efficient than the longitudinal mode in which no detectable back wall echo was observed. Although the attenuation coefficient of a shear wave is higher than that of a longitudinal wave [19], [20], from the CT scan, the sinus bone is very thin ($\sim$1 mm); so the reflection loss in this application is more significant than the loss due to attenuation. Using the shear mode technique, the back wall echo waveform clearly shows the back wall echo time, and thus the approximate distance between the transducer and the back wall and that between the front and back sinus walls are 30 mm and 16.5 mm, respectively, assuming the speed of sound in water and shear wave speed in bone are 1500 ms^{-1}. These results are consistent with the measurements from the CT images and were expected because the shear wave encounters reduced refraction and temporal distortion due to the similarity between the speed of shear wave in bone and the speed of sound in water.

VI. CONCLUSION

A computer-controlled ultrasound pulser-receiver system incorporating a shear mode technique was proposed and successfully demonstrated for transskull fluid detection. The presence of fluid in sinuses of an *ex vivo* human was clearly distinguished using shear wave propagation in skull bone, but the longitudinal method failed to detect with the same pulser parameters.

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REFERENCES

[1] M. Desrosiers, J. M. Klossek, and M. Benninger, "Management of acute bacterial rhinosinusitis: Current issues and future perspectives," *Int. J. Clin. Pract.*, vol. 60, pp. 190–200, Feb. 2006.

[2] R. Gonzales, J. G. Bartlett, R. E. Besser, R. J. Cooper, J. M. Hickner, J. R. Hoffman, and M. A. Sande, "Principles of appropriate antibiotic use for treatment of acute respiratory tract infections in adults: Background, specific aims, and methods," *Ann. Intern. Med.*, vol. 134, pp. 479–486, Mar. 2001.

[3] J. B. Anon, M. R. Jacobs, M. D. Poole, P. G. Ambrose, M. S. Benninger, J. A. Hadley, W. A. Craig, and Sinus and Allergy Health Partnership, "Antimicrobial treatment guidelines for acute rhino sinusitis," *Otolaryngol. Head Neck Surg.*, vol. 130, (suppl. 1), pp. 1–45, June 2004.

[4] W. Winstead, "Rhinosinusitis," *Primary Care; Clinics in Office Practice*, vol. 30, pp. 137–154, 2003.

[5] J. Garau and R. Dagan, "Accurate diagnosis and appropriate treatment of acute bacterial rhinosinusitis: Minimizing bacterial resistance," *Clin. Therapeut.*, vol. 25, pp. 1936–1951, July 2003.

[6] Sinus and Allergy Health Partnership, "Antimicrobial treatment guidelines for acute rhinosinusitis," *Otolaryngol. Head Neck Surg.*, vol. 123, pp. 1–4, July 2000.

[7] R. D. Herr and S. M. Joyce, "Upper respiratory tract infections," in *Infectious Disease in Emergency Medicine*. 2nd ed. J. C. Brillman and R. W. Quenzer, Eds. Philadelphia, PA: Lippincott-Raven, 1997.

[8] F. R. Melio, "Upper respiratory tract infections: Sinusitis," in *Rosen's Emergency Medicine Concepts and Clinical Practice*. 5th ed. vol. 2, J. A. Marx, Ed. St. Louis, MO: Mosby, 2002, ch. 70, pp. 981–985.

[9] D. E. Low, M. Desrosiers, J. McSherry, G. Garber, J. W. Williams, Jr., H. Remy, R. S. Fenton, V. Forte, M. Balter, C. Rotstein, C. Craft, J. Dubois, G. Harding, M. Schloss, M. Miller, R. A. McIvor, and R. J. Davidson, "A practical guide for the diagnosis and treatment of acute sinusitis," *Can. Med. Assoc. J.*, vol. 156, (suppl. 6), pp. 1–14, 1997.

[10] W. Mann, C. Beck, and T. Apostolidis, "Liability of ultrasound in maxillary sinus disease," *Eur. Arch. Oto-Rhino-Laryngol.*, vol. 215, pp. 67–74, Mar. 1977.

[11] M. Jannert, L. Adréasson, and N. Holmer, "Diagnostic ultrasonography of paranasal sinuses," in *Proc. IEEE Ultrason. Symp.*, 1982, pp. 727–728.

[12] H. Varonen, M. Mäkelä, S. Savolainen, E. Läärä, and J. Hilden, "Comparison of ultrasound, radiography, and clinical examination in the diagnosis of acute maxillary sinusitis: A systematic review," *J. Clin. Epidemiol.*, vol. 53, pp. 940–948, 2000.

[13] T. Puhakka, T. Heikkinen, M. J. Mäkelä, A. Alanen, T. Kallio, L. Korsoff, J. Suonpää, and O. Ruuskanen, "Validity of ultrasonography in diagnosis of acute maxillary sinusitis," *Arch. Otolaryngol. Head Neck Surg.*, vol. 126, pp. 1482–1486, Dec. 2000.

[14] M. Lindbæk and P. Hjortdahl, "The clinical diagnosis of acute purulent sinusitis in general practice—A review," *Br. J. Gen. Pract.*, vol. 52, pp. 491–495, June 2002.

[15] T. Jansson, H. W. Persson, N. Holmer, P. Sahlstrand-Johnson, and M. Jannert, "Ultrasound Doppler for improved diagnosis of disease in the paranasal sinuses," in *Proc. IEEE Ultrason. Symp.*, 2005, pp. 839–841.

[16] F. Lucchin, N. Minicuci, M. A. Ravasi, L. Cordella, M. Palu, M. Cetoli, and P. Borin, "Comparison of A-mode ultrasound and computed tomography: Detection of secretion in maxillary and frontal sinuses in ventilated patients," *Intens. Care Med.*, vol. 22, pp. 1265–1268, Nov. 1996.

[17] M. Revonta and J. Suonpää, "Diagnosis and follow-up of ultrasonographical sinus changes in children," *Int. J. Pediatr. Otorhinolaryngol.*, vol. 4, pp. 301–308, Oct. 1982.

[18] M. Luukkala, P. Mattila, and M. Revonta, "Sinuscan, a hand held ultrasonic unit to detect maxillary sinusitis," in *Proc. IEEE Ultrason. Symp.*, 1982, pp. 724–726.

[19] G. T. Clement, P. J. White, and K. Hynynen, "Enhanced ultrasound transmission through the human skull using shear mode conversion," *J. Acoust. Soc. Amer.*, vol. 115, pp. 1356–1364, Mar. 2004.

[20] P. J. White, G. T. Clement, and K. Hynynen, "Longitudinal and shear mode ultrasound propagation in human skull bone," *Ultrasound Med. Biol.*, vol. 32, pp. 1085–1096, July 2006.

[21] C. H. J. Hauman, N. P. Chandler, and D. C. Tong, "Endodontic implications of the maxillary sinus: A review," *Int. Endodont. J.*, vol. 35, pp. 127–141, 2002.

[22] LM3478 High Efficiency Low-Side N-Channel Controller for Switching Regulator, National Semiconductor Corporation, Santa Clara, CA, product folder, 2003, http://cache.national.com/ds/LM/LM3478.pdf.

[23] P. Wood, Transformer-isolated gate driver provides very large duty cycle ratios, International Rectifier, El Segundo, CA, Application Note AN-950B http://www.irf.com/technical-info/appnotes/an-950.pdf.

[24] 10-Bit, 65/80/105 MSPS, 3 V A/D Converter: AD9215, Analog Devices, Inc., Data Sheet, 2004, http://www.analog.com/UploadedFiles/Data_Sheets/AD9215.pdf.

[25] P. J. White, S. Palchaudhuri, K. Hynynen, and G. T. Clement, "The effects of desiccation on skull bone sound speed," *IEEE Trans. Ultrason., Ferroelect., Freq. Contr.*, vol. 54, pp. 1708–1710, Aug. 2007, to be published.

[26] F. J. Fry and J. E. Barger, "Acoustical properties of the human skull," *J. Acoust. Soc. Amer.*, vol. 63, pp. 1576–1590, May 1978.

Sai Chun Tang (S'97–M'01) was born in Hong Kong in 1972. He received the B.Eng. degree (with first class honours) and the Ph.D. degree in electronic engineering at City University of Hong Kong in 1997 and 2000, respectively. After he graduated, he worked as a research fellow at the same university. He joined the National University of Ireland, Galway, Ireland, as a visiting academic in 2001, and then the Laboratory for Electromagnetic and Electronic Systems at Massachusetts Institute of Technology (MIT), Cambridge, MA, as a postdoc in 2002. Since 2004, he has been working at the Focused Ultrasound Laboratory at Brigham and Women's Hospital, Harvard Medical School, Boston, MA, responsible for the developments of ultrasound diagnosis devices and non-invasive treatment systems using an intensive-focused ultrasound beam. His research interests involve high-frequency electromagnetism, low-profile power converter design, and analog electronics.

Dr. Tang is a member of Sigma Xi. He received the Best Paper Award (for posters) at The 16th European Conference on Solid-State Transducers (Eurosensors XVI) in 2002. He won the championship of the Institution of Electrical Engineers (IEE) Hong Kong Younger Member Section Paper Contest 2000, and received the first prize of IEEE HK Section Student Paper Contest'97. He is the inventor/co-inventor of two U.S. patents.

Kullervo Hynynen received his Ph.D. from the University of Aberdeen, United Kingdom, in 1982. After completing his postdoctoral training in biomedical ultrasound, also at the University of Aberdeen, he accepted a faculty position at the University of Arizona in 1984, where he developed several ultrasound systems for induction of moderate temperature elevations in tumors to sensitize the cells to radiation therapy and investigated ultrasound interactions with tissue. He joined the faculty at the Harvard Medical School and Brigham and Women's Hospital in Boston, MA, in 1993. There he founded and directed the Focused Ultrasound Laboratory until 2006 when he moved to University of Toronto. He is currently the Director of Imaging Research at the Sunnybrook Health Sciences Centre and a Professor in the Department of Medical Biophysics at University of Toronto, Toronto, Ontario, Canada. His research has focused on the investigation of ultrasound propagation through living tissue and its biological effects. He is currently investigating the use of ultrasound phased arrays for therapy (noninvasive surgery, vascular surgery, targeted drug delivery, and genetherapy) and diagnosis. After demonstrating that high power ultrasound sources can be made MRI compatible and that the ultrasound treatments can be done under MR image guidance, Dr. Hynynen has concentrated on moving MRI guided focused ultrasound surgery into clinical practice. His research involves considerable multi-disciplinary collaboration across institutions and industry.