Program Digest, 2019 IEEE International Ultrasonics Symposium (IUS)
Glasgow, Scotland, October 6-9, 2019

Attenuation coefficients of human skull cadavers measured by shockwave from a CNT composite transducer and simulated by Sim4Life software

Jooho Lee
Department of Ocean System Engineering
Jeju National University
Jeju, South Korea
seraph035@naver.com

Dong-Guk Paeng
Department of Ocean System Engineering
Jeju National University
Jeju, South Korea
Department of Radiation Oncology
University of Virginia
Charlottesville, VA, USA
paeng@jejunu.ac.kr

Kanglyeol Ha
Department of Physics
Pukyung National University
Busan, South Korea
hakl@pknu.ac.kr

Abstract— **Carbon Nanotube (CNT) composite transducers generate shock waves with wide frequency band and high sound pressure. The attenuation coefficients of 3 human skull cadavers by the shockwave from a CNT composite transducer were measured and compared with the simulation results. The average densities and sound speeds of 3 skulls near the bregma were computed from computed tomography (CT) images to 2.004 ± 0.022, 1.995 ± 0.032, and 2.085 ± 0.035 g/cm^3 and 2977 ± 33, 2964 ± 48, 3096 ± 52 m/s, respectively. In the experiment, the average attenuation coefficients near the bregma of 3 skulls were measured to 3.66, 5.00, and 1.1 np/cm/MHz. The attenuation coefficients simulated by Sim4life were 3.11, 4.66, and 3.21 np/cm/MHz. The first two coefficients were similar but the other was much different, requiring further research.**

Keywords—Carbon Nanotube (CNT) composite transducer, Attenuation coefficient, Shock wave, Human skull

I. Introduction

An acoustic wave generated by a focused ultrasound transducer is distorted at the focus by transmission through the human skull [1]. Attenuation by the human skull is an important factor for transcranial ultrasound, and various studies have been conducted to measure attenuation by the human skull and brain tissue.[1],[2] Measuring attenuation is dependent on the main frequency band of the transducer. However, there is a limitation in increasing the bandwidth of the piezoelectric transducer. In order to measure attenuation with wide frequency bands, several transducers of narrow band frequency are necessary. This has the drawbacks of accuracy as well as equipment complexity and high cost. However, the shockwave generated from a focused Carbon Nanotube (CNT) composite transducer has a wide frequency band, up to several MHz, in a single pulse.[3] Therefore, the attenuation coefficient from the broadband frequency signals can be measured with a single transducer. The objective of this study is to measure the attenuation of human skull cadaver using the broadband frequency of the shockwave generated by the CNT composite transducer and compare it with the simulated results of a commercial software, Sim4life [4].

.

II. Method

A. Computation of the human skull parameters

Computed tomography (CT) images were used to obtain density, sound velocity, and thickness. The density and sound velocity of the skull were calculated from the value of Hounsfield units (HU), a unit representing the radiation density of CT. HU value of the measurement location was extracted and the same location was extracted 10 times and averaged. The average HU value of the five regions measured by the transducer was extracted. The density of the skull was calculated by substitution of the extracted HU value into Equation (1). HU_{max} and HU_{min} values are 2400 and −1024, respectively [4].

$$\rho = \rho_{min} + (\rho_{max} - \rho_{min})\frac{HU-HU_{min}}{HU_{max}-HU_{min}} \quad (1)$$

Sound velocity of the skull was calculated as a linear function of density by substituting the density into Equation (2).

$$C = C_{min} + (C_{max} - C_{min})\frac{\rho-\rho_{min}}{\rho_{max}-\rho_{min}} \quad (2)$$

C_{min} is assumed to be 1500 m/s and the C_{max} is assumed to be 4000 m/s. The density and sound velocity of the skull near the bregma, calculated from the HU values, are shown in Table

1.

Table 1 Parameters of the human skulls near the bregma extracted from CT data

	Density [g/cm^3]	Sound speed [m/s]	Thickness [mm]
Skull 1	2.004 ± 0.022	2977 ± 33	7.5 ± 0.4
Skull 2	1.995 ± 0.032	2964 ± 48	6.7 ± 0.3
Skull 3	2.085 ± 0.035	3096 ± 52	5.4 ± 0.2

B. Experimental set up

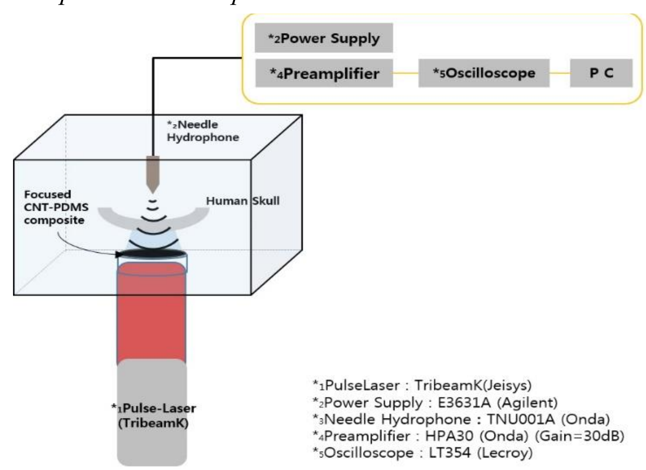

Fig. 1 A laser-generated focused CNT/PDMS transducer and hydrophone measurement system

As shown in Figure 1, when the laser is applied to the focused CNT composite photoacoustic transducer (F# = 1, Focal length = 5cm) immersed in the water, the CNT composite transducer generates shock pulses. A pulsed laser system (Tribeam, Jeisys, Medical Inc, Seoul, Korea) with a wavelength of 532 nm and energy of 175mJ/pulse was used to generate the shock pulse with pulse repetition frequency of 2 Hz. A needle hydrophone (TNU001A, Onda, Sunnyvale, CA, USA) was used to measure the shock pulse transmitted through the skull. The hydrophone was used with a 30 dB preamplifier (HPA30, Onda, Sunnyvale, CA, USA) powered by to a 15V power supply (E3631A, Agilent, Santa Clara, CA, USA). The signal was monitored with an oscilloscope (LT354, Lecroy, New York, USA).

C. Simulation set up

The diameter and focal length of the transducer were 80 and 64mm. The simulation setup of transducer position was the same as that of the experimental measurement. We simulated with a narrow band from 200 kHz to 1000 kHz at intervals of 100 kHz using Sim4life software in order to avoid heavy and unstable computation of broad band simulation

Ⅲ. Results and discussion

A. Transcranial sound pressures and frequencies

Sound pressure and frequency band before and after the shock wave penetrates Skull 1 are shown in Figure 2. The maximum sound pressure before transmission was 392 kPa, the center frequency and the band width were 1.25 MHz and 3 MHz, respectively (Figure 2(a)). After penetrating the skull, the maximum sound pressure was 22 kPa, the center frequency and the band width were 248 kHz and 0.8 MHz, respectively (Figure 2(b)). In the same way, the measurement results of Skull 1, 2, and 3 were normalized by dividing the measured values recorded prior to penetrating the skull (Table 2).

The shockwave generated by a CNT composite transducer was measured after transmission through three human cadaver skulls. Each human skull varied in thickness, sound speed, and attenuation. The third cadaver skull transmitted the sound energy most efficiently. This would be attributed to the geometrical differences and skull density ratio. Further investigation is required into the higher pressure at the frequency band transmitted through this skull.

Sound pressure of the shockwave measured in this study was lower than that of another research [3], but it is enough to transmit to measure the attenuation coefficients of the human skull. However, to be applied to brain applications, higher sound pressure and precise targeting must be gauranteed. Therefore, a transducer with improved performance over the existing transducer will be manufactured and tested.

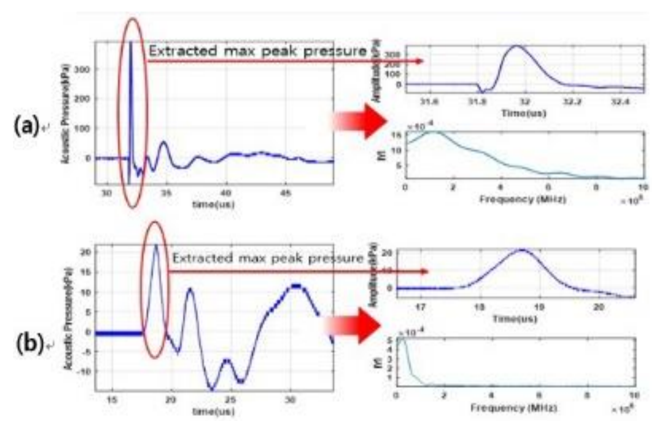

Fig. 2 Waveforms and sound pressure and frequency bands of shock waves before and after transmission of skull 1

Table 2 Normalized sound pressure and center frequency at the measurement position of skull 1, 2, and 3

	Normalized pressure	Normalized center frequency
Skull 1	0.053	0.20
Skull 2	0.05	0.08
Skull 3	0.38	0.47

B. Broad band attenuation coefficients

The attenuation coefficient was calculated using the sound pressure before and after skull penetration by the shockwave. The measured attenuation coefficients were compared with the simulation results. Figure 3 shows attenuation coefficients from 200 to 1000 Hz near the bregma of three skulls from the simulation and experimental results. The attenuation coefficients from the experiments and simulations in Skull 1 were 3.66 and 3.11 np/cm/MHz, and r^2 is 0.91 and 0.73, respectively. The attenuation coefficients in Skull 2 were 5.00 and 4.67 np/cm/MHz, and r^2 is 0.93 and 0.87, respectively. The ones in Skull 3 were 1.1 and 3.21 np/cm/MHz, and r^2 is 0.83 and 0.8, respectively.

Table 3 Fitted linear slope (Attenuation coefficient) near the bregma of each skull in experiment and simulation.

			Bregma
Skull 1	**Simulation results**	**Slope [np/cm/MHz]**	2.91
		R2	**0.**68
	Experimental results	**Slope [np/cm/MHz]**	3.66
		Rr	**0.**91
Skull 2	**Simulation results**	**Slope [np/cm/MHz]**	4.67
		R2	**0.**91
	Experimental results	**Slope [np/cm/MHz]**	5.00
		R2	**0.**93
Skull 3	**Simulation results**	**Slope [np/cm/MHz]**	2.96
		R2	**0.**83
	Experimental results	**Slope [np/cm/MHz]**	1.1
		R2	**0.**83

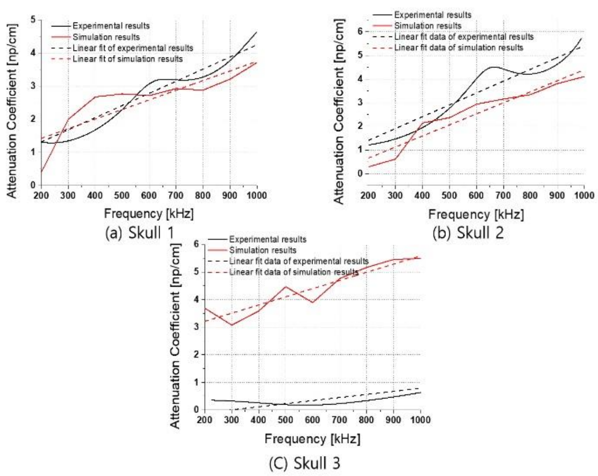

Fig. 3 Attenuation coefficients by linear fitting of the broad band measurement by a CNT composite transducer and simulated by Sim4life with continuous wave from 200 to 1000 kHz at the central site

Skull 3 was different from the simulation, which may be caused of the other factors than the shape, sound velocity, and density of the skull. It is necessary to investigate the cause of the difference in the attenuation coefficients.

The estimated attenuation coefficients were measured to 0.338(±0.76), 2.31(±0.15), and 3.34(±0.42) np/cm for the frequencies of 270, 836, and 1402 kHz, respectively, by Hynynen group [1], and measured to 2.00 and 3.80 np/cm for frequencies of 836 and 1402 kHz, respectively by Fry & Barger [2]. The attenuation coefficients measured in this study are similar to, or larger than, that measured by the others. The reasons are probably that the attenuation coefficients were measured using shockwaves with broadband frequencies and measured attenuation coefficients, including reflection and refraction, as well as scattering and absorption [1], [2].

Ⅳ. Conclusion

In this study, experiments were performed to investigate the acoustic characteristics of the shockwave generated by the laser-generated CNT composite transducer traveling through the human skull cadavers. Shockwaves with a broadband frequency were used to measure the attenuation coefficients and compared with the simulation results. The thickness of the skull was determined to be an important factor for attenuation coefficients. In the experiments, the average attenuation coefficients of the three skulls were similar to the simulation results, except for Skull 3. The skull penetration mechanisms of shockwaves generated in laser-pulsed CNT composite transducers were measured and documented. They could provide important data for future applications of laser-generated shockwaves in brain applications.

Acknowledgment *(Heading 5)*

This research was supported by the Focused Ultrasound Foundation. This work was also partially supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIP-Ministry of Science, ICT and Future Planning) (No. 2018R1A2B2007997).

References

[1] S Pichardo, V W Sin, K Hynynen, ″Multi-frequency characterization of the speed of sound and attenuation coefficient for longitudinal transmission of freshly excised human skulls.″, Phys Med Biol. 2011 January 7; 56(1): 219-250.

[2] Fry F and Barger J, "Acoustical properties of the human skull", J. Acoust. Soc. Am., 1978, 63 1576

[3] H. W. Baac, J. G. Ok, A. Maxwell, K.-T. Lee, Y.-C. Chen, A. J. Hart, Z. Xu, E. Yoon, and L. J. Guo, ″Carbon-nanotube optoacoustic lens for focused ultrasound generation and high-precision targeted therapy.,″ Sci. Rep., vol. 2, no. 989, pp. 1–8, 2012.

[4] L Marsac, D. Chauvet, R. La Greca, A.-L Boch, K. Chaumoitre, M. Tanter and J.-F. Aubry, ″Ex vivo optimisation of a heterogeneous speed of sound model of the human skull for non-invasive transcranial focused ultrasound at 1 MHz″, International Journal of Hyperthermia, 2017, Vol. 33, No. 6, 635-645.