Acoustic Detection of Blunt-Induced Cavitation in the Head

Christopher P. Eckersley, Joost Op 't Eynde, Mitchell Z. Abrams, Allen W. Yu, Mucong Li, Junjie Yao, Cameron R. Bass

Abstract The occurrence of cavitation in the brain from blunt impact is difficult to investigate and remains controversial. The objective of this study was to investigate cavitation formation from blunt impact, without compromising the cranial cavity, using novel acoustic biomarkers. These biomarkers were developed using a laser-induced cavitation study, acrylic surrogate impact tests, and fresh non-frozen pig cadaver impact tests. Laser-induced cavitation displayed a ~125 and 250 kHz response on high frequency sensors, and a ~13–20 kHz, ~50–70 kHz and ~100–140 kHz frequency response on hydrophones. For surrogate tests, a harmonic response (~50–70, 100–140 and 250 kHz) was recorded 0–5 ms following confirmed cavitation impacts. In cadaver tests, largest impacts elicited a coupled low frequency (~50–70 kHz) and high frequency (~100–140 kHz) acoustic response 0–5 ms following impact. Negative control pig cadaver head tests provided low frequency response but were not associated with high frequency content for any impact. Using a series of validation tests and negative controls, this study developed an acoustic biomarker, a low frequency response coupled with a high frequency harmonic, which is sensitive and specific to CSF cavitation without compromising the cranial cavity. This provided evidence of cavitation within a fresh pig cadaver skull upon blunt impact.

Keywords Injury Biomechanics, Acoustic Emissions, Blunt Trauma, Cavitation, Traumatic Brain Injury.

I. INTRODUCTION

Blunt impacts to the head were the cause of approximately 1.7 million traumatic brain injuries (TBI) requiring a hospital visit in 2014 [1]. These injuries range from mild concussion to severe, life-threatening bleeds within the brain. They are prevalent both in the civilian population, from car accidents, falls and sports injuries, and in the military population. Literature has proposed numerous mechanisms of blunt TBI, with the current prevailing theory being the strain of brain tissue as shear waves propagate through the skull [2-4]. However, multiple plausible theories have garnered less TBI research attention due to either a lack of observation technology or interest. One of these theories, first introduced in the 1950s, is cavitation within the cerebrospinal fluid (CSF) [5].

Violent bubble collapse following cavitation in water has long been identified as the culprit of pitting damage on the propellers and hulls of ships [5]. Given its propensity for damage in metals, researchers began to investigate the damage cavitation can present to soft tissue [6-9]. The field of shock wave lithotripsy in particular has noted that the focusing of acoustic shockwaves within the kidney results in cavitation that both breaks up kidney stones and damages surrounding tissue [6,7,10-13]. Furthermore, researchers have begun to investigate the amount of damage cavitation can inflict on the brain if it occurs in the skull [8,14-16]. While investigators have found cavitation can be associated with injury, cavitation formation within the skull, particularly following blunt impact, is an unsettled phenomenon within the biomechanics community [17-19].

Primary experimental probes into blunt impact CSF cavitation were two test series, one conducted by Lubock and Goldsmith [20] and another by Nusholtz [17,21-23]. Lubock and Goldsmith utilise two different head surrogates, a simple acrylic shell and a back-filled human calvarium, both filled with various CSF simulants [20]. While they did observe cavitation during peak tensile stresses of approximately -1330 kPa, it is unclear how CSF permutations affected this threshold as cavitation was reported to occur in every acrylic cylinder model without further discussion. Additionally, the acrylic skull was thinner with a larger radius than the human skull, which may limit the biofidelity of its impact dynamics. Nusholtz *et al.* performed impact studies using repressurised human cadaver heads and live rhesus monkeys, and found areas of negative pressures coupled with large pressure spikes. However, there was no direct mention of the presence of cavitation; they simply reported measured negative

C. P. Eckersley (e-mail: cpe4@duke.edu; tel: 919-660-8272), J. Op't Eynde, M. Z. Abrams and M. Li are candidates in Biomedical Engineering. A. W. Yu is a PhD graduate of Biomedical Engineering. J. Yao is an Assistant Professor of Biomedical Engineering. C. R. Bass is an Associate Research Professor of Biomedical Engineering. All authors are affiliated with Duke University in Durham, NC, USA.

pressures [21]. It is unclear whether the introduction of the instrumentation caused local nucleation sites or bubbles that compromised the experiment. Follow-up studies used an aluminium cylinder as a surrogate head coupled with a numerical analysis [17,22,23]. These detected cavitation at impact levels ranging from 150 g to 200 g and found pressure drops within the cylinder reached only one atmosphere because of fluid cavitation on the wall boundary.

Blunt impacts have not been the sole focus of cavitation-induced neurotrauma. Due to the increased prevalence of blast neurotrauma in military and civilian arenas, a number of studies examined the role cavitation might play in this mode of injury [24-27]. These studies contain both experimental and modelling components but, much like blunt impact cavitation studies, they do not arrive at a consistent observation. This is the result of a number of factors, including experimental and modelling design, but is primarily due to a variety of assumptions in the pressure threshold for cavitation formation [24-27], a value that has not been experimentally agreed upon [18,19,25,28].

The skull has long served as a barrier for observing phenomena within the head, particularly in-vivo. Bone prevents any light penetration for optical analysis in the visible spectrum, and most alternative methods (ultrasound, MRI, or X-Ray) lack the proper combination of penetration depth and temporal resolution [29-32]. However, cavitation bubbles have been shown to generate point source acoustic emissions upon their collapse [33]. These cavitation acoustic emissions have been shown to be audible and highly specific, indicating cavitation formation can be identified from its acoustic output [34]. These acoustic emissions have been used to detect cavitation in soft tissue, though this often involves detection in the 1–3 MHz range [10,13,35,36]. Due to the acoustic impedance mismatch and the viscoelastic properties of the tissue, waves at these frequencies can be attenuated 10–30 dB by the skull, making higher frequencies difficult to differentiate from noise [37]. Lower frequencies of cavitation collapse, while able to pass through the skull with less damping, can also be muddied by other events surrounding the impact. Because of this, the signal needs to be decomposed appropriately in both time and frequency.

One technique for analysing data so that both time evolution and frequency response can be assessed is the wavelet transform. To determine frequency information, a mother wavelet with a particular frequency content is compressed and dilated at a particular location in the signal. These transformations are then translated through the signal to generate time information.

There were two key objectives of this study. The first was to develop an acoustic biomarker that was both a selective and a sensitive indicator of cavitation formation. The second was to use this acoustic biomarker for investigating cavitation formation under blunt impact in a fresh whole pig cadaver without compromising the skull cavity. These objectives were achieved through a series of three experiments. First, a controlled experiment where a laser-induced cavitation within a clear water-filled tank. Acoustic sensors on both the interior and exterior of the vessel were coupled with high-speed footage to determine the unhindered acoustic signature of cavitation formation and collapse. Next, a clear acrylic head surrogate was subjected to blunt impacts from a pneumatic ram. High-speed video was collected in concert with acoustic sensors mounted to the exterior of the surrogate. This allowed testing of both the sensitivity and the selectivity of the acoustic biomarker in a blunt impact scenario. The last series impacted a set of fresh pig cadavers using a pneumatic impactor to investigate cavitation formation within an uncompromised, biofidelic head model.

The hypothesis for the study was that upon collapse, cavitation bubbles will emit a harmonic acoustic biomarker with frequency content between 30 kHz and 100 kHz. Unlike the 1-3 MHz signatures seen in soft tissue cavitation, the frequency of this biomarker is low enough to pass through the skull and associated brain tissues. However, it is still higher than any other expected frequency during a blunt impact. Therefore, the biomarker can be observed through fresh cadaveric pig tissue while still being specific to cavitation events during a blunt impact.

II. METHODS

The methodology of this study can be divided into three separate test series: a highly controlled laser-induced cavitation study in a water tank; a clear acrylic head surrogate impact test; and a series of fresh, non-frozen, fullbody pig cadaver tests. Acoustic data for each test were collected using a PicoScope 5444B (Pico Technologies, UK) and analysed in Matlab R2017A (MathWorks, US). Wavelet transforms were conducted using a Morlet wavelet, pictured in Fig. 1, for two reasons: its similarity to an acoustic emission trace and its consistent resolution in the time and frequency space. All tests utilizing acoustic analysis underwent a similar process outlined in Torrence 1998 [38]. In order to prevent lower frequency information from dominating the wavelet plot[38] each frequency band is normalized by its maximum value so that the peak signal in all wavelet plots is 1. The noise in the acoustic signal prior to impact is characterized as a normal distribution by a mean and standard deviation, true signal is considered to be three standard deviations above the noise mean and is outlined by red contours.



Fig. 1. Depiction of the real portion of the Morlet Wavelet in time space.

Laser-induced Cavitation

A series of highly controlled laser-induced cavitation bubble tests was conducted to determine the acoustic signature of bubble collapse without the confounding noise of a blunt impact. This technique eliminates the influence of remnant wall nucleation sites in containers on cavitation. An open-air glass tank was filled with deionised water. Water was used instead of a more complex surrogate because the dynamics and acoustic response of cavitation is dominated by the bulk modulus of the medium containing the cavitation bubble. Laser pulses (532 nm up to 20 mJ of power) were focused to a consistent location in the glass tank at levels known to generate cavitation bubbles [10]. The power of the laser was modulated to vary bubble size between 1.5 mm and 2.8 mm, selected as realistic sizes for meningeal bubble formation. Acoustic data were captured using two types of sensor. High-frequency information (100–500 kHz bandpass filter) was collected at 18 MHz using three Physical acoustic (NJ, USA) S9225 sensors (300-1800 kHz flat frequency response) mounted to the exterior of the tank using cyanoacrylate glue. Low frequency information (1–100 kHz bandpass filter) was collected at 18 MHz using a Reson TC 4013 (Slangerup, Denmark) hydrophone (1–180 kHz flat frequency response) submerged in the water within the tank (Fig. 2). High-speed video was collected at 150,000 frames per second (Phantom v711, Vision Research, NJ, USA). To determine cavitation bubble diameter, a needle of known width was positioned in the high-speed frame. Based on trigger timing, the high-speed video of bubble formation and collapse was matched in time with acoustic traces and wavelet transforms of the signal.





Pneumatic Blunt Impactor

A pneumatic impactor was constructed to produce repeatable blunt impacts for testing both the acrylic surrogate and the pig cadavers. This consisted of three components, as shown in Fig. 3. The first was the impactor, a 5 kg aluminium mass selected to resemble the mass of an impacting head in a head-to-head collision. It was fixed to a linear track that enabled a single degree of motion (Fig. 3). The mass was attached to the track bearings using hose clamps and could be easily removed to change the overall mass of the impactor. Connected to the mass was a removable impacting puck: a rubber disk that could be exchanged to alter the impact stiffness. For these tests, the impact was controlled by a 70A Shore, 2.5 cm thick, neoprene rubber. The second component was a pneumatic piston with an 11.5 cm bore diameter and 45.75 cm stroke length. The piston was modified by drilling holes in the rod exit endcap to reduce the exiting air-flow restriction during the piston stroke and ensure maximum velocity. The linear track was longer than the piston stroke length, allowing the piston and impactor to decouple prior to the impact zone. This ensured that the impact was dominated by the momentum interaction and not the driving piston. Last was a 113.5-litre, 200 psi rated charging tank that was regulated and large enough to provide a consistent pressure to the air piston. The tank was connected to the piston by a 2 in NPT pipe through a manual ball valve that enabled a rapid transfer of air from the charging tank to the piston. The impactor system was capable of driving the impactor mass at speeds up to 12 m/s, high enough to recreate severe blunt impacts.



Fig. 3. (A) Illustration of overall blunt impactor. (B) Picture of impactor used for blunt tests.

Clear Acrylic Head Surrogate

Positive and negative controls for the acoustic emission of cavitation formation were provided using a clear acrylic head form. This consisted of an acrylic cylinder 14.6 cm in diameter, 14.6 cm tall, with a 0.63 cm wall thickness to resemble the approximate dimensions, thickness and volume of the human head (Fig. 4) [39,40]. Acrylic was used because it closely resembles the stiffness of cortical bone, has a comparable compressive and shear speed of sound, and can be imaged through using a high-speed camera to capture cavitation formation (Table I).

TABLE I			
MATERIAL PROPERTIES OF ACRYLIC AND SKULL			
Material	Modulus of Elasticity	Compressive Speed of	Shear Speed of Sound
		Sound	
Acrylic	2.76–3.30 [41]	2746 [42]	1392 [42]
Bone	~5 [43]	1500 ± 140 [44]	2820 ± 40 [44]

Distilled water was used to fill the surrogate. It was degassed to remove bubbles, then allowed to equilibrate to CSF gas partial pressures [45]. The acrylic cylinder was instrumented with two Physical Acoustics (NJ, USA) S9220 acoustic sensors (flat frequency response of 100–900 kHz) on the contra-coup using cyanoacrylate glue. Acoustic data was sampled at 41 MHz and bandpass filtered between 15 kHz and 500 kHz. One Endevco (NC, USA) 7264 linear accelerometer was rigidly secured to the lid of the surrogate, sampled at 2 MHz, and low pass filtered at 1650 Hz [46] to determine the impact acceleration of the surrogate (Fig. 4). High-speed video (Phantom v711, Vision Research, NJ, USA) was collected at two focal lengths, a wide angle at 14,000 fps to image the overall

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impact event, and a macro angle of the contra-coup wall at 22,000 fps to image the formation of cavitation bubbles. The surrogate was struck at varying velocities (2.3–3.7 m/s), determined using high-speed video, by the pneumatic blunt impactor. Positive control was considered a test where cavitation was confirmed using high-speed footage. Negative control was considered a lower magnitude test where cavitation was not present in the high-speed footage. The high-speed video, linear acceleration, and acoustic data were aligned to the trigger signal to determine the positive and negative control cavitation acoustic signature during a surrogate blunt impact.



(A)



(B)

Fig. 4. (A) Image of coup side of the surrogate, with accelerometer mounted on the front of the lid. (B) Image of the contra-coup side of the surrogate with the acoustic sensors mounted to the cylindrical surface of the surrogate.

Fresh, Non-Frozen, Full-body Pig Cadaver

Fresh, non-frozen, full-body pig cadavers were tested 3–5 hours post mortem to investigate cavitation formation without compromising the cranial cavity. The pig was instrumented with two Physical Acoustic S9220 acoustic sensors (flat frequency response of 100–900 kHz) and a six degree-of-freedom (6DOF) kinematics package (three Endevco 7264 linear accelerometer, three DTS angular rate sensors). Skin on each side of the head was cut using a cautery tool to expose both the left and right temporal fossa of the pig. One acoustic sensor was then fixed to each of the temporal fossa using cyanoacrylate glue (Fig. 5). The cautery tool was also used to expose a square window on the nasal bone of the pig where the 6DOF kinematics package was rigidly fixed with bone screws (Fig. 5). This sensor setup left the frontal bone unobstructed, providing the optimal collision site for the impactor. Prior to each test, the impact site of the frontal bone was lined up with the indentor, and high speed footage confirmed uniform impact sites for each tests (Fig. 5). Like the acrylic surrogate, the cadaveric pig head was exposed to impacts of increasing severity from the linear impactor. Following the full-body cadaveric pig tests, the head was removed for a series of negative control tests. The brain and all cranial contents were removed through the foramen magnum, leaving only air in the cranial cavity thus making CSF cavitation impossible and leaving only structural response.



Fig. 5. (A) Illustration of surgical cut sites on the cadaveric pig head. (B) Location of sensor mounting points. (C) Impact location of pig studies.

In order to determine the variation in acoustic damping between the skull and acrylic surrogate, a transmission test at 40 kHz was conducted using the same sensors as the impact tests. Similar to the control tests, a fresh cadaveric pig head was removed from the body and the cranial contents were removed from the foramen magnum. Acoustic sensors were positioned at the same locations on the head as the impact studies and the skull was back filled with water. A 40 kHz speaker was then placed inside the skull at full power and the acoustic signal was recorded on the outside of the skull. The same test was then done for the clear acrylic surrogate skull, it was filled with water and the speaker was placed inside while acoustic information was recorded from sensors glued to the outside of the skull. In each test careful consideration was taken to ensure similar locations of the speaker relative to the sensor. A wavelet transform visualized the frequency information for the acoustic signals, ensuring a majority of the power was around 40 kHz. The signals received a band pass filter from 30 - 50 kHz. The values from each sensor were then averaged and the averages between the cadaver and surrogate were compared to determine the damping difference in dB between the cadaver and the surrogate

III. RESULTS

Figure 6 depicts the beginning, middle and end video frames of a laser-induced cavitation event. The data show, at both formation and collapse, that the cavitation bubble emits a harmonic response of ~125 kHz and 250 kHz measured by the high frequency acoustic sensor and frequency content bands of ~13–20 kHz, ~40–60 kHz, and ~90–125 kHz measured by the low frequency hydrophone. Bubble size varied from 1.5 mm to 2.8 mm in diameter. The small variation in bubble diameter achieved by altering the power influenced the strength of the acoustic signal but did not appear to substantially alter the frequency bands. Figure 7 shows the negative control of the laser firing but no cavitation formation. The wavelet transforms indicate little evidence of acoustic response beyond noise at any frequency.



Fig. 6. (A) Cavitation formation (magenta line in wavelet), (B) peak bubble size, 2.81 mm (white line in wavelet), (C) Cavitation collapse (red line in wavelet). Red arrows indicate key frequency content bands ~125 kHz and 250 kHz from high frequency sensor and ~13–20 kHz, ~40–60 kHz, and ~90–125 kHz from hydrophone.





Fig. 7. Negative control of laser-induced cavitation test. Laser is fired (bright spot on calibration needle), but no bubble is formed and no acoustic signature is present at any frequency.

There were three key results from the blunt impact tests on the surrogate: a large cavitation bubble formation (~17 mm); a medium cavitation bubble formation (~4 mm); and no cavitation formation. The bubbles and their relative size can be seen in Fig. 8. Figure 9 displays the wavelet transforms for each of the three cases, respectively. The peak linear accelerations for each test are 273 g, 185 g and 160 g for the large bubble, medium bubble and no bubble tests, respectively. From high-speed footage review, collapse of the large bubble occurred at -0.176 ms with respect to the trigger, with a second collapse occurring at 0.232 ms. Collapse of the medium bubble occurred at 2.15 ms with respect to trigger, with a second collapse at 2.35 ms. The large bubble collapse occurred approximately 3 ms following impact, while the medium bubble collapse occurred approximately 2.25 ms following impact. Red arrows on Figure 9 A and B indicate for both the large and medium bubbles the strong acoustic content is seen at the same 50 – 70, and 100 – 140 kHz bands as the laser induced cavitation tests. For the negative control test, low strength acoustic information is present at the time of impact but the circle on the plot indicates the lack of signal in the 50 - 70, and 100 - 140 kHz bands 2 - 3 ms following impact. Low strength frequency information is also present prior to impact in the negative control test. The difference in signal power between the large and small bubble was 23.4 dB. As with the laser-induced cavitation test, the bubble diameter only influenced the relative strength of the wavelet transform peaks and not the general character of the frequency bands of the cavitation response.











Fig. 9. (A) Large cavitation bubble (~17 mm) wavelet transform, peak acceleration 273 g with bubble collapse at 3 ms post impact. (B) Medium cavitation bubble (~4 mm) wavelet transform, peak acceleration 185 g with bubble collapse at 2.25 ms post impact. (C) No cavitation bubble formed, peak acceleration 160 g, low strength acoustic information seen at the point of impact. Red arrows point to frequency content in 50 - 70 kHz and 100 - 140 kHz range in positive tests that is absent in negative control. Red lines on time axis indicate impact moment while green lines indicate bubble initiation. Red contour outlines indicate areas that are above three standard deviations of the noise distribution.

In the full-body pig cadaver tests, the wavelet transforms of the two highest-level impacts are seen in Fig. 10(A) and (B), with peak resultant linear accelerations of 333 g and 327 g, respectively. Using interspecies scaling [47], these acceleration values correlate to approximately 167 g and 164 g in a human head. This is assuming equal modulus of elasticity of the pig and human heads and the characteristic length of the human head being twice that of the pig head. Highlighted by red arrows, these impacts display frequency bands at approximately 50 – 70 kHz and 100 - 140 kHz 1.5 ms following impact on both acoustic sensors. Both tests also display frequency information 1.5 ms prior to impact on the sensor closest to the table (left side). The negative control test (Fig. 10(C)) had a peak resultant acceleration of 268 g (scaled to 134 g) and displayed the most frequency content of the eight control tests. Impact occurred approximately -1 ms with respect to the trigger, with non-time synched acoustic information occurring in the frequency band of ~20–50 kHz for 1 ms following impact. The results of the 40 kHz transmission test showed 18.4 dB of damping by the cadaver head compared to the clear acrylic surrogate. Both positive cavitation results saw similar signal powers of .00051 and .00078 respectively indicating similar bubble sizes. These values were 27 dB lower than the acoustic power of smaller bubble collapse in the surrogate tests.







(B)

IV. DISCUSSION

The goal of this study was to first develop an acoustic biomarker that was both selective and sensitive to the presence of cavitation bubbles and, secondly, to use this acoustic biomarker for investigating cavitation formation under blunt impact in a fresh whole pig cadaver without compromising the skull cavity. While current literature has proposed that cavitation bubbles have the potential to damage soft tissue throughout the body, including the brain, this phenomenon has not been shown in a biofidelic closed head model. It was hypothesised that upon collapse, cavitation bubbles emit a harmonic acoustic biomarker between 30 kHz and 100 kHz. This was shown to be true in the laser-induced cavitation tests and the acrylic surrogate impact tests. Furthermore, the acoustic biomarker seen during these tests was prominent frequency information in the bands of 50–70 kHz, 100–140 kHz, and 250 kHz. Controls showed lower frequency information (50–70 kHz) was not enough to indicate cavitation formation but needed to be associated with a higher frequency band (100–140 kHz). As hypothesised, these frequencies were low enough to pass through a fresh, non-frozen cadaveric pig skull and associated brain tissues, and control test showed these frequencies were higher than those expected during a blunt impact without cavitation. These tests provided strong evidence that the biomarker can be observed through fresh cadaveric pig tissue while still being specific to cavitation events during a blunt impact.

In the cadaver tests, numerous potential confounding events could be sources of the high frequency emissions observed. The first is noise in the acoustic sensor or a detachment from the skull. This is not the source of the emissions because in these tests, to be an indication of cavitation formation, the acoustic biomarker needed to be present in both sensors at identical time points. If the emissions were a result of a sensor complication, the signal would be present on only one sensor and not the other. The second potential complication could be high frequency content from skull fracture or other bony fracture. However, cortical bone fracture has been shown to give acoustic emissions of much higher frequency (200–400 kHz) [48] than what are seen in the acoustic emissions from these tests, indicating that this is not the source of these emissions. The emissions could also be from the lower jaw of the pig colliding with the upper jaw upon impact. This was prevented as a confounding variable by clinching the mouth shut with foam between the jaws. The final source could be from some flexure mode of the skull causing vibrations that are picked up by the acoustic sensor. This was eliminated as a confounding source through the negative control test, which did not show the acoustic emissions related to cavitation formation.

Laser-induced cavitation tests and the surrogate impact tests provided information on the role of bubble size in the acoustic signature. These tests provided frequency information for bubbles ranging from 1.5 mm to 14 mm in diameter. For these tests, while the bubble size did not strongly influence frequency content in the range tested, it played a large role in the strength of the signal. In the surrogate tests, reducing bubble size by nearly an order of magnitude resulted in a decrease in the acoustic signal strength by nearly an order of magnitude.

The acoustic emissions in the full body pig cadaver tests are 27 dB lower than the small bubble from the acrylic surrogate test. This can be attributed to four causes, viscoelastic damping during transmission across the dura, acoustic impedance across the skull damping the signal, acoustic attenuation in both the dura and the skull, and the smaller size of the bubbles in the cadaveric tests relative to those in the acrylic surrogate. The skull has been shown to attenuate acoustic signals in the range of frequencies relevant to this study [43,44], and our transmission test showed that for 40 kHz, the skull attenuated 18.4 dB of the signal content compared to the surrogate. While this accounts for a third of the signal damping seen in the biomarker between the pig cadaver and the surrogate, it is likely the rest can be attributed to a smaller bubble size in the cadaver. The duration between impact and collapse in the cadaveric pig was at most 1.5 ms while for the 4 mm surrogate bubble the time from impact to collapse was approximately 2 ms. In the surrogate tests, shorter collapse times are associated with smaller bubble radii which correspond to lower signal magnitudes. In the cadaveric pig testing, bubbles formed in a few millimeter thick CSF layer making it unlikely bubbles as large as those seen in the acrylic surrogate tests form.

Since it is difficult to observe high rate phenomenon such as cavitation through the skull, finite element (FE) models and numerical analysis are valuable tools for cavitation analysis. These are ineffective, however, without an accurate value for the CSF cavitation threshold pressure. Numerous studies have aimed to tackle this problem through various experimental methods, determining answers from -100 kPa to -20 MPa [18,19,25,28]. This variation is primarily due to the effect of nucleation sites, both in the amount of dissolved gasses in the fluid and imperfections on the surface of the containment vessel. It is difficult to control and ensure the biofidelity of these variables. This study used a novel method of cavitation detection, which did not rely on controlling these

variables, and ensured the cranial cavity was not compromised prior to testing.

A number of limitations are present within this study. First, the blunt impacts were not controlled to mimic a particular blunt impact event. The goal of this study was to develop an acoustic biomarker and to show the plausibility of cavitation formation during a blunt impact event, but not in any event in particular. Secondly, while the impact tests were conducted using a fresh cadaver (~3–5 hr post-mortem), the brain tissue may have begun to deteriorate and the CSF layer may have been altered compared to a live animal. Next, while these tests indicate the plausibility of cavitation formation, they do not provide any evidence for the actual location of cavitation in the model or its implication in the role of TBI or potential for injury. Finally, the acoustic signal from cavitation collapse across the skull, while detectable, is still very small, making it difficult to provide rigorous statistical analysis and an injury criterion within this limited study.

Future work will be conducted to address these limitations. A study looking at the acoustic damping across both the acrylic surrogate and cadaveric pig skull of a wider range of frequencies of interest (30–100 kHz) will be conducted to provide evidence for the expected signal strength of the cadaveric bubble collapses compared to those in the surrogate. Furthermore, impact tests will be conducted in live pigs to ensure the biofidelity of the cranial cavity and provide a more realistic model to in-vivo humans. Following impacts, the brains will be removed and fixed for histology to provide evidence for injuries associated with cavitation in TBI.

V. CONCLUSIONS

This study developed a specific and selective acoustic biomarker for the collapse of a cavitation bubble; frequency information in the bands of 50–70 kHz and 100–140 kHz synchronised in time less than 5 ms following a blunt impact. This biomarker is supported by a number of positive and negative control tests. Furthermore, this biomarker was shown to be present following impacts to a fresh, non-frozen cadaveric pig, indicating that it is plausible cavitation occurs within the cranial cavity from blunt impacts. This showed as well that the acoustic biomarker consists of frequencies low enough to be detected through the skull and a negative control test indicated these frequencies are unique to cavitation collapse and are not associated with the impact resonances in the head.

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