Experimental Study of Cerebrospinal Fluid (CSF) Cavitation in Blast- and Impact-Induced Traumatic Brain Injury

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I. INTRODUCTION

The injury mechanism of Blast-induced Traumatic Brain Injury (BTBI) is still not well understood. Recent neuropathological analyses of brain tissue from post-mortem cases of BTBI have shown that the brain tissue close to the cerebrospinal fluid (CSF) sustains damage [1]. However, this type of injury has not been observed in Impact-induced Traumatic Brain Injury (ITBI) cases. CSF cavitation is a potential injury mechanism for this type of injury. The micro-jets generated from the collapse of cavitation bubbles may penetrate the nearby tissue and cause damage. In this study, we built a one-dimensional human head surrogate model and tested the model under both typical blast and impact loadings. We tested whether fluid cavitation can occur in the CSF during a typical blast exposure, but not in typical impact loading. We also investigated the distinct differences between these loading conditions, with particular attention to the acceleration and relative fluid/skull velocity.

II. METHODS

One-dimensional surrogate model for human head

We simplified the human head into a one-dimensional model (Fig. 1A), consisting of skull, CSF, brain tissue and ventricle. The skull was modelled with acrylic material. The CSF/ventricle was modelled with distilled water. A previous study [2] analyzed MRI of human head to estimate the dissolved oxygen in healthy human CSF. The results showed that the oxygen partial pressure in the CSF close to the skull can exceed 200 mmHg, which contains 8.06 ppm dissolved oxygen. We degassed the water and kept the dissolved oxygen to be 8.06 ± 0.05 ppm. This ensured the CSF surrogate has similar cavitation threshold to real human CSF. The brain tissue was modelled with agar gel with 0.65% concentration, as suggested in previous studies [3-4].

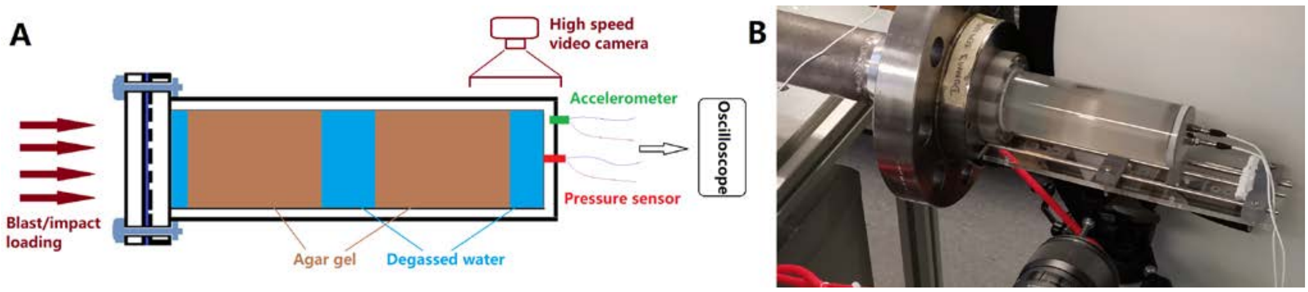

Fig. 1. A: the one-dimensional surrogate model. B: the setup for blast loading test.

An accelerometer (PCB 353B14) and a pressure sensor (Dytran 2300v3) were used to measure the acceleration and pressure history data (Fig. 1A). The accelerometer was mounted on the back cap to measure its acceleration history. The pressure sensor was also mounted on the back cap, contacting the water to measure the local pressure in the contre-coup CSF, where initial cavitation was expected. For the pressure sensor, the acceleration sensitivity in axial direction is 0.0069 kPa/g. In this study, the maximum acceleration in blast test is 930g, resulting in a negligible 6.42 kPa error in pressure. Both sensors were connected to an oscilloscope with a sampling frequency of 50M/s. To capture the bubble formation and collapse in the fluid, a high-speed video camera (Phantom V2511) was used. The resolution was chosen to be 128*360 pixels, which provided 79,000 frame per second recordings. The contre-coup CSF area was captured in the videos.

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Blast loading tests

The blast exposure tests were conducted on the 60mm-diameter shock tube (Fig. 1B) at Centre for Blast Injury Studies, Imperial College London. It was designed to generate a wide range of blast waves. In real world, the overpressure produced by improvised explosive devices (IEDs) ranges from 50 kPa to 1000 kPa [5]. In this study, we selected two typical blast loadings, listed in Table I.

Table I Blast and impact test conditions

Blast tests	**Incident overpressure**	**Positive duration**
Blast 1	1.5 bar	0.714 ms
Blast 2	2.4 bar	1.275 ms
Impact tests	**Impact speed**	**Thickness of EPS foams**
Impact 1	5.21 m/s	40 mm EPS50
Impact 2	4.64 m/s	30 mm EPS70

Impact loading tests

We used a pendulum impact hammer (3 kg) to create impact loadings on the surrogate model. We attached EPS 50/70 foams with different thicknesses onto the front cap of the surrogate model, which created a typical impact loading acceleration history curve comparable to road traffic and sports collisions. Different release angles resulted in different impact speeds. Two impact velocities were used in this study (Table I).

III. INITIAL FINDINGS

The acceleration histories of the back cap are reported in Fig. 2A. As shown, the peak accelerations of blast loading tests are much higher than impact tests. The peak accelerations of Impact 1 and Impact 2 tests are 160 g and 100 g, respectively, and they are reached roughly at the middle of the total hammer/surrogate model interaction time (9.2 ms and 14.2 ms, respectively). However, the peak accelerations of Blast 1 and Blast 2 tests are 650 g and 930 g, respectively. In contrast, these peak accelerations are reached around 0.25 ms, while the entire blast wave/surrogate model interaction time is around 4 ms.

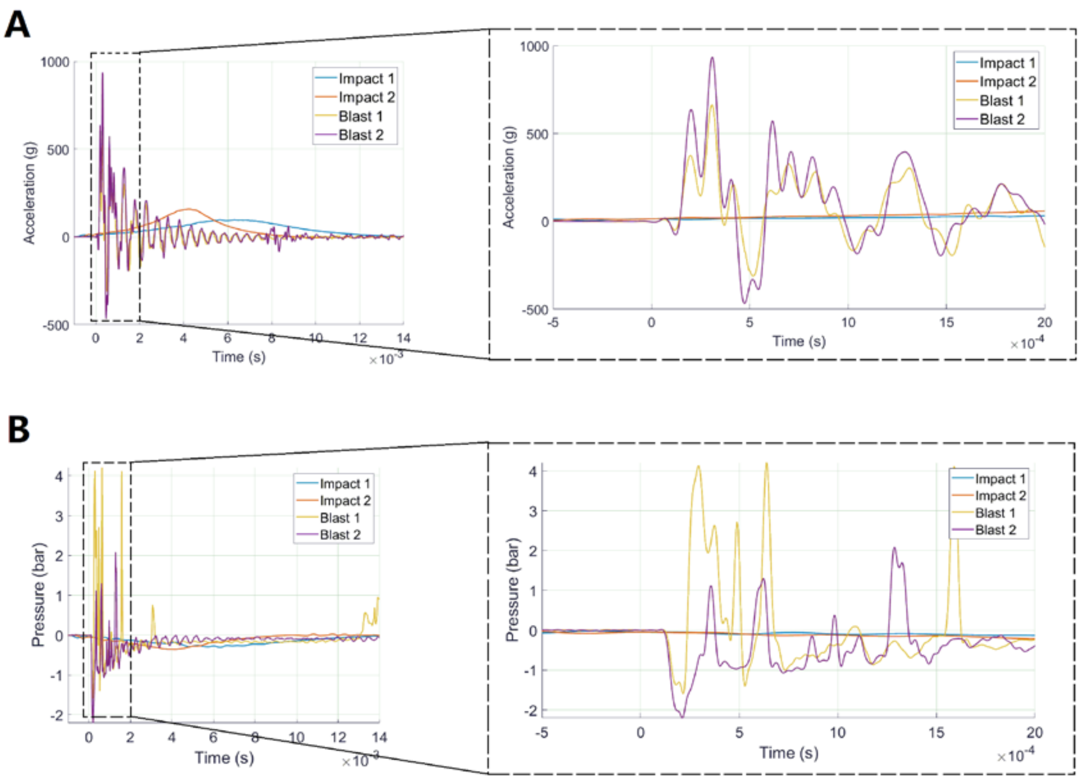

Fig. 2. A: the acceleration histories of the back cap. B: the pressure histories at the contre-coup CSF.

Fig. 2B shows the pressure histories at the contre-coup CSF. The minimum pressure during the four tests are -0.31 bar (Impact 1), -0.35 bar (Impact 2), -1.59 bar (Blast 1) and -2.17 bar (Blast2). The time of reaching minimum pressure in impact tests is around the middle of total hammer/surrogate model interaction time, similar to acceleration histories. For blast tests, this time is much earlier, around 0.21 ms.

From the high-speed video footage, we observed fluid cavitation phenomenon only in the two blast tests. No cavitation was observed in the impact tests. This correlates with the pressure histories that in the blast tests, pressures drop lower than suggested cavitation threshold (-1 bar) [6], while in impact tests, minimum pressures are far from the cavitation threshold. Figure 3 shows the generation and collapse of cavitation bubbles in Blast 2 test.

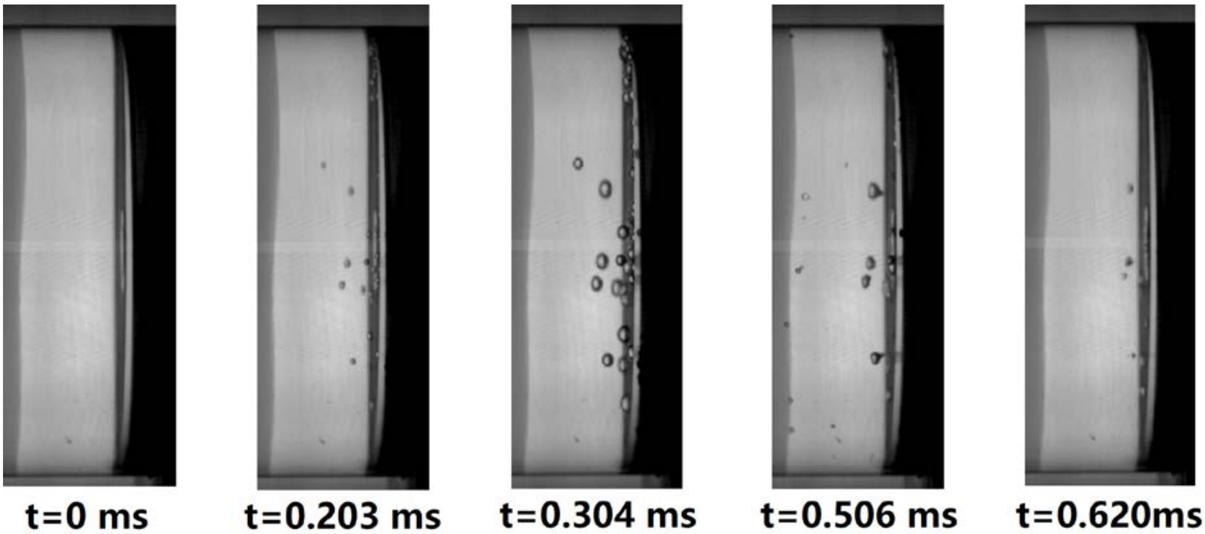

Fig. 3. The generation and collapse of cavitation bubbles in Blast 2.

IV. DISCUSSION

In this study, we applied typical blast and impact loadings to a one-dimensional human head surrogate model. We showed that fluid cavitation can occur under blast loading but not under impact loading typical in helmeted head and sporting collisions. This is confirmed by both pressure data and high-speed videos.

A key difference between impact and blast loading is the loading/head interaction duration. A typical blast loading acts on the head for 3–5 ms, while impact loading interacts with the head for 8–20 ms. This results in the different shapes of acceleration history. The acceleration history curves from impact loading have a bell-shape with a slow rise and fall. However, blast loadings generate much higher peak accelerations in a very short time, resulting in a rapid acceleration rise. This rapid high acceleration creates large relative velocity between the back cap and the contre-coup CSF. The relative velocity is likely to initiate a rarefaction wave into the CSF, which reduces the local pressure. The generated rarefaction wave may drop the local fluid pressure close to cavitation pressure. This study therefore suggests that mitigating rapid head acceleration during blast exposure should be considered in the design of combat helmets.

One limitation of this study is using a simplified model. Human head has a 3D shape and the dynamics of the skull at the contre-coup region can be influenced by its curvature. Nonetheless, this study provides initial evidence for the mechanism of cavitation generation under blast loading. This can be extended in future by using 3D skull models to better understand the effects of rapid head accelerations on generation of cavitation in CSF and to test protective equipment for its ability to mitigate the effects of this injury mechanism.

V. ACKNOWLEDGEMENT

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VI. REFERENCES

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