Blast-induced cerebrospinal fluid cavitation: a potential mechanism for blast-induced traumatic brain injury

***Xiancheng Yu*[1,2], *Mazdak Ghajari*[1,2]**

[1] *Centre for Blast Injury Studies, Imperial College London, London, United Kingdom*
[2] *Dyson School of Design Engineering, Imperial College London, London, United Kingdom*

Introduction

Blast injury has been a prevalent injury in various conflict scenarios in recent years. Although blast waves differ from traditional shock waves used in medical treatment, they share fundamental characteristics and offer valuable insights into the dynamics of wave propagation and tissue interactions. Understanding the mechanisms underlying blast-induced injuries, particularly injuries to the brain, can contribute to advancements in the field of shock wave treatment in medicine.

Recent neuropathological analyses of brain tissue from post-mortem cases of blast injuries have shown that the brain tissue close to the cerebrospinal fluid (CSF) sustains damage. 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. This study presents both experimental and computational investigations to study the occurrence and mechanism of blast-induced CSF cavitation, providing insights that can potentially inform and enhance shock wave treatment strategies within the medical domain.

Material & Method

We developed a one-dimensional head (1D) surrogate to model blast wave propagation across different tissues in the human head (Figure 1A). The geometry of the model allowed us to focus on nearly one-dimensional wave propagation across the tissues. The skull, brain and CSF were modelled with acrylic material, distilled water (with designated air saturation) and agar gel, respectively. The head surrogate was exposed to nonlethal blast waves generated by a shock tube (Figure 1B). To capture the dynamics of CSF cavitation, high-speed videography and pressure sensors were utilized to observe and record the formation and collapse of cavitation bubbles in the CSF simulant.

Next, we simulated the blast experiments using an anatomically detailed three-dimensional (3D) finite element (FE) model of the human head to understand the experimental observations and explore the mechanism of blast-induced CSF cavitation.

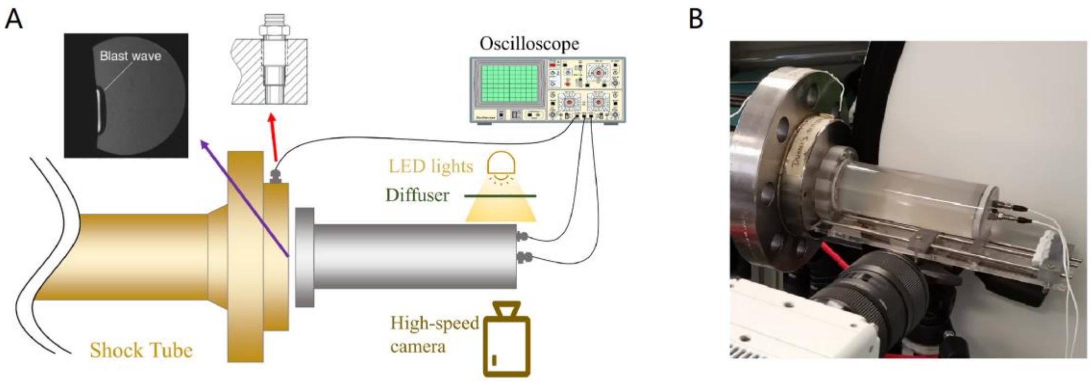

Figure 1 The setup of the blast wave test.

Results

We observed fluid cavitation phenomenon in the CSF simulant at the contrecoup region from the high-speed video footage (Figure 2A). Moreover, we observed micro-jets formation from the asymmetric collapse of bubbles in the tests. The sequential video footage (zoom-in region, Figure 2A) shows the process of a micro-jet formation following the asymmetric collapse of a bubble. The bubble was compressed by the pressure wave approaching it from the left side, which led to its collapse and generation of micro-jets in the travelling direction of the pressure wave.

The FE modelling shows that the blast wave initiates two pressure waves in the human head model: the outer wave propagating in the skull and the inner wave propagating across the brain and CSF (Figure 2B). Due to the higher acoustic impedance of the skull, the outer wave travels faster than the inner wave. At 0.23 ms, the outer wave reaches the contrecoup skull and accelerates it, which creates a relative velocity at the contrecoup skull and CSF interface. This decreases the CSF pressure creating a negative pressure zone at the contrecoup area, which induces cavitation bubbles observed in the tests. In the meantime, the inner wave continues its propagation and finally cancels the negative pressure in this region. As the inner wave compresses the cavitation bubbles from one side, this will cause them to collapse asymmetrically and produce micro-jets in the direction of the inner wave propagation, which explained the observation from the high speed video footage.

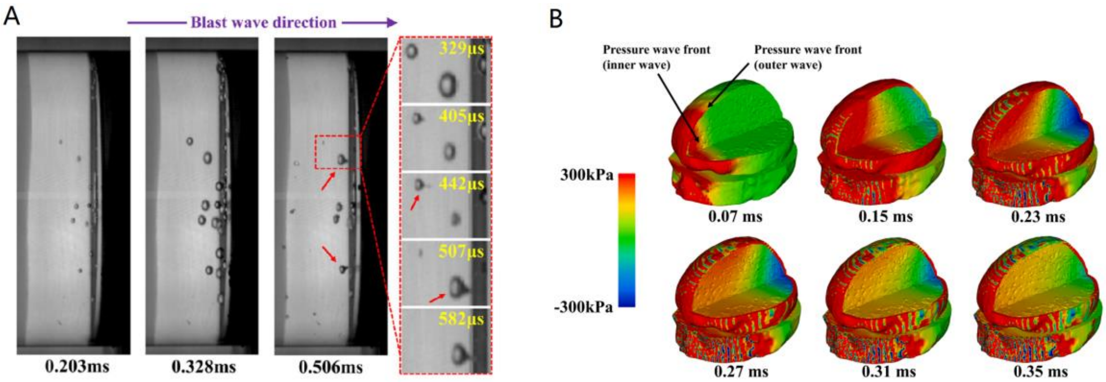

Figure 2 The generation and collapse of cavitation bubbles in the CSF simulant.

Discussion

In this study, we showed that exposure to blast waves can induce CSF cavitation and micro-jets, which was allowed by using a new physical surrogate for the human head. The human head FE model allowed us to explain this phenomenon by proposing the outer and inner wave mechanism. These findings can improve our understanding of the blast wave effect on brain injury and may have implications on the protection strategy and measures in shock wave medical treatment.

One limitation of this study is the utilization of the simplified 1D head surrogate. Given that the human head possesses a 3D shape, the pressure response of the head may be influenced by its curvature. To further investigate the effects of blast waves on CSF cavitation and explore the potential induction of CSF cavitation by shockwaves used in medical treatment, future research could incorporate three-dimensional skull models.

COI: No conflict of interestsss