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Invited review

Shock tubes and blast injury modeling

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ABSTRACT

Explosive blast injury has become the most prevalent injury in recent military conflicts and terrorist attacks. The magnitude of this kind of polytrauma is complex due to the basic physics of blast and the surrounding environments. Therefore, development of stable, reproducible and controllable animal model using an ideal blast simulation device is the key of blast injury research. The present review addresses the modeling of blast injury and applications of shock tubes.

With the use of improvised explosive devices (IEDs) as tactical weapons in recent military conflicts and terrorist attacks, blast injury has become the most prevalent military injury.[1,2] There are also a large number of civilian blast injuries and casualties suffering from explosion in mine, oil and gas field and other industrial accidents. Therefore the blast injuries are an increasing problem in both military and civilian practice. The blast injury is a kind of polytrauma resulting from direct or indirect exposure to an explosion. Explosions are physical, chemical or nuclear reactions that involve the rapid release of considerable amounts of energy. An explosion generates an instantaneous increase in pressure and temperature in the immediate vicinity of the explosion which travels outwards from the source of the explosion promptly through the surrounding medium (i.e. air, water, soil, stone, and steel). The high pressure usually lasts a few milliseconds and is followed by a fall in pressure (negative pressure) or suction of the blast wave. This is the formation of a shock wave.[3,4] There are four patterns of blast injury. Primary injuries, also called pure blast injuries, are caused by blast waves such as overpressure waves or negative pressure waves directly, primarily affecting air-containing organs and cavities such as the lung, ear and abdomen. Secondary, quaternary and tertiary injuries are indirect ones caused by the fragments of debris propelled by the explosion, by the acceleration of the body or part of the body by the blast wind, and by miscellaneous factors including dust, flash burns, hot gases and fires, respectively. The basic physics including peak overpressure and negative pressure, the overpressure duration time, spreading speed and the number of pulse depend on the type and the equivalent of the explosion, the medium in which it explodes, and the degree of focusing due to a confined area or walls. This makes the magnitude of the damage hypervariable.[3,5] Thus development of stable, reproducible and controllable animal model is the key of blast injury research. And the key of a successful model is an ideal blast-driven device that simulates shock waves with realistic pressure–time profiles and relevant durations. The present review addresses the modeling of blast injury and applications of shock tubes.

1. Blast injury models

Blast injuries to experimental animals were first studied systematically in 1914.[6] Blast research has attracted much attention during World War II. Since then, blast injury research has been driven by the increasing mortality of conventional weapons and the tremendous blast effects caused by nuclear detonations. The most remarkable work has been done in the United States and Sweden, especially by White and Richmind in Lovelace Biomedical and Environmental Research Institute, Albuquerque, New Mexico and by Clemedson and Jonsson in Swedish Defense Research Agency. Blast injury research in China has been on since the 1950s and been conducted uninterruptedly

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since China's the first atomic explosion in 1964. Wang investigated to determine the blast levels required for threshold injuries, severe injuries and mortality from nuclear and high-explosive blast, as well as repeated low-level blasts, and published the world's first monograph on blast injury.[7]

Various species of animals, from large animals such as dogs, sheep, goats, swine, and monkeys to small animals such as rabbits, rats, mice and guinea pigs, as well as insects such as drosophila were subjected to blast injury research. Besides those living animals, *in vitro* organs, tissues and cells were also used in blast injury modeling.

The charge explosion was the main way to inflict injury in the early studies of blast injury. The biological effects of the blast wave depend on the peak overpressure and the positive phase duration. The simplest form of a blast wave is described as the Friedlander waveform (Fig. 1) when detonation occurs in a free field. At the arrival of the shock-front, the pressure increases effectively instantaneously to a maximum (peak overpressure), from which it falls exponentially to sub-atmospheric levels and returns to the ambient pressure (Fig. 2A). This model has been performed using various types and equivalents of explosive sources and large sets of animals of different species and sizes.

However, in practice, a large proportion of explosion occurred in confined spaces such as buildings, vehicles and cabins. Unlike the free-field waveform, waveform in confined spaces does not represent an ideal Friedlander wave, but complex ones because of reflection, diffraction, focus, or interaction with the initial shock wave (Fig. 2B). The blast peak pressure is up to 8 times higher and positive duration time is longer in free field compared with the same charge in a confined space. So explosion in confined space is associated with greater morbidity and mortality.[8] Many reports have demonstrated the blast injury modeling performed in those conditions. Animals were lying, standing or hanging up in the structures. The charge was placed in or out of the structure. The biophysics, damage effects and mechanisms were investigated in those researches.[9]

Underwater explosions generate a huge volume of energetic underwater gaseous bubble and a shockwave which is propagated towards the surrounding water. This is reflected as a negative pressure wave on the water surface, which is disrupted, forming a dome of spall. The initial compression pulse from the explosion transmits through the water. Upon reaching the surface, given the change in mechanical impedance at this interface, it is reflected as a release wave. Given the broadly triangular shape of the pressure history from an explosive, the combination of this release with the later parts of the explosive pulse, can result in a region of tensile stress in the water, opening a region of low pressure, where cavitation may be seen in the water. The overall effect is that high positive pressures are only seen fleetingly at the surface, away from the surface and the duration of the pressure pulse will be longer, therefore floating on the surface will result in lower injury compared to in vertical treading water. The reflected tension wave interacts with the compressive shock wave and accelerates its decay (Fig. 2C). Therefore underwater blast wave was characterized by high propagation speed, high peak overpressure value, great impulse, however, short duration. Under the same explosion condition, the propagation speed of underwater blast wave is about 4 times higher than that of air blast wave, the peak overpressure value may reach about 200 times higher, and the impulse is 8.48–11.80 times greater than that of air blast wave.[10] Animal treading water will therefore experience the integral of pressure over time lower portion of the body. Regions of the body which are deeper in the water are more severely affected by the blast wave. Individuals at risk of immersion blast are therefore safer floating on the surface of the water rather than treading water in an upright position.[3]

The above experiments have determined thresholds for mortality and injuries, provided fundamental data for effects of blast with waveforms (Friedlander waveform) and dose response curves (the Bowen curves).[12–15] These experiments also allowed for realistic models with large animals that are more similar in size to humans. Although these models are closely similar to a real accident from an explosion, it is very difficult to collect accurate experimental parameters and to perform on animals early functional examination on the test field. Outdoor conditions in combination with a mass of animals in a single experiment also leads to decreased controllability, less stability, poorer reproducibility and higher cost and hazard. To overcome the above shortcomings, a device that can stimulate real explosive blast waveforms in a controlled laboratory environment is demanded. The bio-shock tube is the one best developed and most widely used.

2. Blast injury modeling using shock tubes

2.1. Bio-shock tubes

Shock tubes have been proven to be a most versatile and resilient tool for the investigation of shock-wave-related problems under a laboratory condition covering a wide variety of fields both in fundamental science and in applied technology. They have been used to study high speed aerodynamics, shock wave characteristics

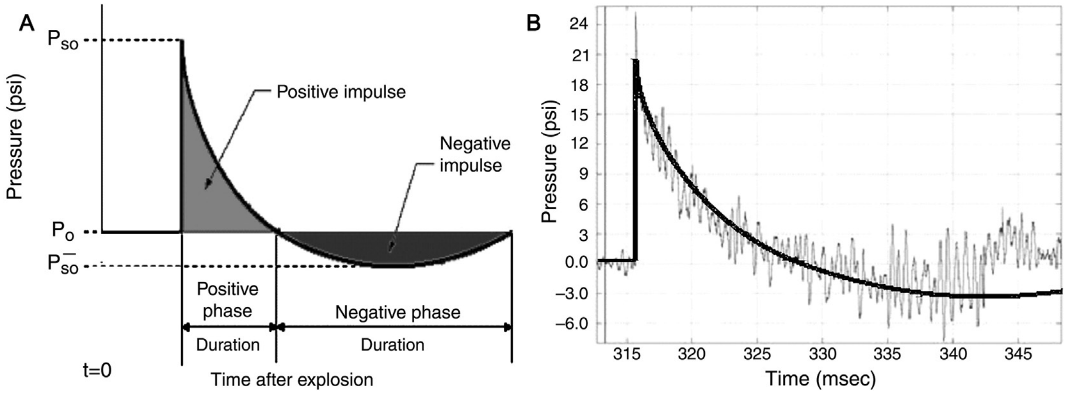

Fig. 1. (A) A drawing of an ideal Friedlander wave showing the peak pressure, the positive impulse and phase duration, and the negative impulse and phase duration. (B) An actual pressure–time history for an explosive blast in the tube. The up-and-down oscillations are caused by the vibration of the needle gauge. The overlaid smooth curve is a replot of the ideal Friedlander waveform shown in (A).[9]