Controlling blast wave generation in a shock tube for biological applications

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Abstract. The shock tube is a versatile apparatus used in a wide range of scientific research fields. In this case, we are developing a system to use with biological specimens. The process of diaphragm rupture is closely linked to the shock wave generated. Experiments were performed on an air-driven shock tube with Mylar® and aluminium diaphragms of various thicknesses, to control the output. The evolution of shock pressure was measured and the diaphragm rupture process investigated. Single-diaphragm and double-diaphragm configurations were employed, as were open or closed tube configurations. The arrangement was designed to enable high-speed photography and pressure measurements. Overall, results are highly reproducible, and show that the double-diaphragm system enables a more controllable diaphragm burst pressure. The diaphragm burst pressure was linearly related to its thickness within the range studied. The observed relationship between the diaphragm burst pressure and the generated shock pressure presents a noticeable difference compared to the theoretical ideal gas description. Furthermore, the duration of the primary shock decreased proportionally with the length of the high-pressure charging volume. Computational modelling of the diaphragm breakage process was carried out using the ANSYS software package.

1. Introduction
The shock tube is able to generate well-defined pressure pulses of various intensities and durations. Since its invention in 1899, it has found application in fields such as aeronautics, chemical kinematics and plasma physics [1]. The sudden rupture of the diaphragm brings the high-pressure driver gas into contact with the driven gas of low pressure. Simultaneously, a rarefaction wave and a compression wave are formed in the driver and driven section respectively. As the expansion wave spreads out with time, the compression wave forms a shock front that travels along the tube [2].

A well-defined theory for shock waves in a shock tube is the ideal gas description, which assumes ideal gases in both the driver and driven sections, no friction or heat transfer and instantaneous diaphragm bursting. In practice, gases are not ideal and the specific heat ratio is dependent on temperature. Together with a finite diaphragm opening time and the boundary-layer effect, this leads to many cases of departures from the ideal gas description [2].

A blast wave lasts for a very short time, but can cause severe damage to surrounding objects and structures through drastic changes in pressure, flying debris and strong propulsions following the incident shock front. Exposure to shock waves causes unique pathologies to develop within the body. For example, heterotopic ossification, blast lung, and nerve damage within...
the brain (mild traumatic brain injury) may develop long after exposure to the blast event. The ability to re-create blast effects in the laboratory environment is essential in order to study blast injuries, which is the aim of our studies using the shock tube. The shock tube allows various cellular suspensions (e.g. osteoblast and Schwann cell cultures) to be exposed to shock waves of predefined intensity and duration. By mounting these suspensions in a sterile, sealed environment at the end of the shock tube, the dynamic pressures evolved within the fluid may be measured using piezoelectric pressure sensors. Post-shock investigations on these biological samples will allow the effects of differing shock profiles on cell function to be more fully understood. Ultimately, it is hoped that the cells exposed to shock compression may offer the potential for clinical treatments that prohibit the development of these unique pathologies to be established. Bo et al. [3] reported the use of this shock tube as one of their platforms in studying the properties of biological samples (cells, tissues and organs) under extreme conditions and the effects of blast wave such as post-traumatic physiological and biochemical changes at the cellular level.

2. System Overview

The stainless steel shock tube (figure 1), 3.8 m long with 59 mm in internal diameter, uses compressed air in the high-pressure driver section and atmospheric pressure in the low-pressure driven section. Dynamic pressure gauges orientated laterally (sensors 1) and head-on (sensor 2) to the shock wave were installed at the middle and end of the driven section. The end of tube was either sealed off (closed tube) or unsealed (open tube). In the open configuration, the head-on sensor 2 was installed on a bull-nose of 2 cm in diameter to measure pressure pulses exiting the shock tube.

In figure 2, the pressure traces between the open and closed tube configurations with 50 \( \mu m \) Mylar\textregistered diaphragms are compared. While the open set-up is more relevant for a sample subjected to real shock waves (e.g. an air blast); the closed set-up, with reflected shocks from the outlet flange, can give more information about shock magnitude and speed as well as the interference between the initial shock wave and rarefaction wave. The detail of the initial rises (figure 2) of four traces, from the two configurations, shows that the shock waves are highly reproducible. Thus what is learnt from the closed tube can be applied to the open tube. In addition, the oscillation observed here suggests a systematic feature likely caused by the vibration of the system. This will be studied and reported in future publications.

Figure 1. Full shock tube schematic.
3. Diaphragm Rupture and Burst Pressure

Mylar® and aluminium diaphragms of different thicknesses were used in either the single-diaphragm or the double-diaphragm configuration (figure 1). The diaphragm at A was made to either fracture under built-up pressure in the single-diaphragm arrangement (no diaphragm at B) or under the blast wave produced from the rupture of diaphragm B in the double-diaphragm system. A Phantom v7.3 high-speed camera along with 1000 W static lighting was used to record the process of diaphragm rupture in both diaphragm configurations.

Linear relationships between the average diaphragm burst pressure and the diaphragm thickness for Mylar® film and annealed aluminium foil are shown in figure 3. The diaphragm thickness is the most important parameter deciding the burst pressure. Using multiple layers to produce the required thickness does not affect this behaviour.

Mylar® diaphragms give higher burst pressure than aluminium diaphragms of the same thickness. This is because Mylar® is more ductile than aluminium, hence it can bulge more and a higher pressure can build up before rupture. However, cracks propagate much faster in Mylar®: 252 µs to reach the diaphragm circumference compared to 549 µs for 40 µm and 558 µs for 100 µm aluminium foil (figure 4 and figure 5). The difference in the fracture toughness of the two materials (24 MPa m$^{1/2}$ and $\sim$ 1 MPa m$^{1/2}$ for aluminium alloy and polyester respectively) shows that aluminium foils are more resistant to crack propagation, and thus have a longer crack propagation time or diaphragm opening time. Greater levels of thinning result from the bulging seen in Mylar® may also be another reason for the faster crack propagation.

The double-diaphragm set-up is more dynamic, giving higher burst pressure and a more controllable way of producing shock waves (figure 5). In the single bursting, a crack appears
at the centre of the diaphragm then propagates outward in a symmetrical fashion. The double bursting shows multiple cracks appearing simultaneously and propagating in an irregular way.

The firing pressure in the single-diaphragm set-up is controlled by the diaphragm material and thickness, varying by 1 bar depending on the charging rate. In the double-diaphragm set-up, it is the venting of the space between the diaphragms that causes the rear diaphragm to burst and the rapid pressurisation on the second diaphragm causes it to burst almost immediately. Both the timing and the burst pressure can be controlled to a greater degree in the double-diaphragm configuration. Traces recorded by sensor 1 for 40 µm aluminium diaphragms in the double-diaphragm system and 23 µm Mylar® diaphragms in the single-diaphragm system are compared in figure 5. Here, aluminium diaphragms (∼ 1.52 bar burst pressure) were made to burst around the burst pressure of Mylar® diaphragms (∼ 2.15 bar). The dip at the tail of the double-diaphragm trace is a results of the volume between the diaphragms. In this case, the breaking of the rear diaphragm sends a wave back into the main driving volume before the front diaphragm breaks. This small wave is seen at the end of the main pulse.

![Figure 5](image)

Figure 5. Left: the rupture of 40 µm aluminium in single (top) and double (bottom) arrangements. Right: double- (blue) and single- (red) diaphragm systems, both at ∼2.15 bar burst pressure.

4. Output Pressure Pulse

The magnitude of the output shock wave can be controlled by adjusting the diaphragm burst pressure, i.e. choosing the right diaphragm type and thickness. Figure 6 shows the relationships between the burst pressure and the measured pressure at the end of the shock tube for both closed and open systems. As the bull-nose has a diameter three times smaller than the internal diameter of the shock tube, it is more relevant to small samples (e.g. small tissue such as mouse lung and tendons) whereas the profile from the closed configuration is more relevant to large samples. Comparing to the theoretical predictions by the ideal gas description [2], experiments give a lower output for the same burst pressure. This is because the heat capacity and adiabatic coefficient of real gas is not constant and there is always heat exchange as well as friction in the gas flow inside the tube. The actual pressure that samples experience is also influenced by the impedance of the sample.

![Figure 6](image)

Figure 6. Driving pressure against output shock pressure for large sample (solid line, triangle) and small sample (solid line, square) in comparison with theoretical predictions (dashed line).

The duration of the shock can be manipulated by changing the volume of high-pressure gas in the driver tube using polyethylene inserts. The magnitude stays approximately the same while the shock duration increases linearly with the driving volume (figure 7). Furthermore, for 10%
volume, a clear exponential decay can be seen in the shock magnitude as it travels back and forth inside the shock tube.

![Graph A: Duration vs Driving Volume](image)

![Graph B: Pressure vs Time](image)

**Figure 7.** Different high-pressure volumes: shock duration is linearly proportional to driving volume (A) and 10% volume shows exponential decay of shock wave (B).

5. **Finite Element Simulation**

Explicit dynamics with principle stress failure was chosen in our simulations of diaphragm rupture (figure 8). Aluminium diaphragms of 500 ${\mu}m$ were modelled in this paper. The minimum element size of 1 mm was used as a compromise with the run time of the simulation. This resulted in an energy uncertainty of less than 10%, despite a coarse mesh for the diaphragm which is treated as a thin surface. A 0.5 ms sinusoidally increasing pressure load was applied to one side of the diaphragm to simulate the effect of pressurised gas. A gas fluid was not used since it would significantly increase the computational time and complexity of the simulation. A minimum peak pressure of 13 bar was required to burst the diaphragm, which is of similar magnitude to the extrapolated value of 18 bar from experimental results shown in figure 3.

![Finite Element Model and Pressure Loading History](image)

**Figure 8.** Left: The cut-away section finite element model and the pressure loading history. The frictionless contact surfaces between the holder and the diaphragm were designed to immitate an o-ring in order to reduce sharp edge effects. The diaphragm was made to be thicker at the circumference to avoid slipping. Right: result highlights 14 bar and 50 bar bursting.

Highlights of the modelling results are displayed in figure 8: bursting at 14 bar and 50 bar peak pressures. Bulging occurs in both scenarios, but for a very short period as applied pressures were increased in only 0.5 ms. Due to the simple model of the holder without o-rings, stress is more concentrated at the edge of the diaphragm. The simulated behaviours are very similar to observations made using a high-speed camera. As the pressurising time is fixed (0.5 ms), the higher the peak pressure, the faster the rate of pressurisation. Hence, the 14 bar case resembles the single-diaphragm bursting and the 50 bar case resembles the double-diaphragm scenario. The diaphragm rupture in the simulations are approximately three times quicker compared to those from experiments. This difference is likely due to the imposed 500 ${\mu}s$ run-time of the simulations, the differences between simulated and experimental diaphragm thickness, and non-ideal material properties. Future simulations introducing air into the system and following the formation and evolution of the shock along the tube will be conducted, and they will be more closely based on the exact experimental arrangements.
6. Summary
The shock tube can be used to study blast effects on biological samples representing injuries in open space as well as inside vehicles. The high reproducibility of experiments allows the information obtained from the closed set-up to be applied on the open tube case. The double-diaphragm system enables the diaphragm to be burst at a specific chosen pressure and time, i.e. giving more control over the output shock wave.

The magnitude of the shock can be manipulated with the diaphragm burst pressure which is linearly proportional to the diaphragm thickness. For the same thickness, the more ductile the diaphragm, the higher burst pressure and hence, output pressure that can be achieved. On the other hand, in both closed and open configuration, to the first degree, the duration of the shock pulse can be tailored, without significantly affecting its magnitude, by adjusting the length of the high-pressure driver volume.

High-speed photography and finite element modelling can also be used to deepen understanding of the diaphragm rupture process. However, the high-speed 3D digital image correlation technique and a better simulation model using gaseous bodies should be employed in the future.

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