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Methodologies and gauges for intracranial pressure measurements

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Abstract. The present work describes the development of methodologies to reliably make in-situ pressure measurements inside biological tissue, with a particular focus on intracranial pressure (ICP) in blast environments. Shock propagation in tissue presents some unique pressure measurement challenges due to the heterogeneous and primarily liquid environment. The relative incompressibility of water as compared to air leads to microsecond-scale blast waves and unique phenomena such as cavitation which must be considered when designing a measurement approach. In the present work, we examine the behaviour of a number of different pressure gauge types, e.g. piezo-electric, piezo-resistive, optical / interferometric, under different blast conditions. An apparatus consisting of a fluid-filled, thin-shelled sphere mounted inside a blast wave simulator was used to replicate some of the shock interactions in blast – ICP situations. The results of this work outline specific limitations of different gauges such as bandwidth, orientation dependence, and the generation of signal artefacts. In addition, we will discuss the necessary signal conditioning and recording characteristics, and overall approaches to accurately reproduce pressure histories of shock and blast interactions in biological tissue.

1. INTRODUCTION

The present work examines methodologies for measuring intracranial pressure (ICP) from an underwater blast measurement perspective. ICP measurements typically involves delicate in-vivo gauge insertion inside the skull of a subject, and recent interest in Traumatic Brain Injury (TBI), has spurred the need for making these measurements in harsh blast environments. Blast environments typically involve very large and rapid pressure fluctuations due to shock interactions, and present new challenges to ICP measurements which are normally done at low pressures, under relatively quiescent conditions. Moreover, the fluid-like properties of the brain and other biological tissue lead to shock properties that differ from those in air, causing additional diagnostic measurement challenges. This study draws on techniques and approaches developed for underwater explosion research and applies them to ICP measurements for TBI research.

The instruments used for TBI research must be small and non-intrusive to minimize the disturbance to the test subject, rugged enough to survive the blast environment, and be responsive enough to perform accurate and reliable measurements of blast properties. The advent of new sub-miniature gauge technologies has led to pressure gauges down to less than a millimetre in size. These gauges have made ICP measurements more practical and accurate, however their applicability to blast measurements has not been fully assessed. Nevertheless, the need to understand primary blast injury mechanisms has spurred efforts to accurately determine the in-situ pressure insult to the brain tissue, and ICP measurements in blast conditions have been performed using two main types of gauge: optical interferometric gauges [1-4] and piezo-resistive gauges [5,6].

Methodologies for the measurement of underwater blast waves have been developed since the 1940s [7] to the extent that the majority of underwater blast pressure measurements are now performed in a free-field configuration (with the entire gauge suspended in the fluid rather than mounted on a rigid supporting structure), using piezo-electric tourmaline gauges due to their proven reliability and accuracy. These gauges, along with the associated signal conditioning and data acquisition instrumentation have been designed for the particular characteristics of underwater blast, such as very high pressures, very short durations, and cavitation. The analogy between underwater blast scenarios and TBI scenarios presents the opportunity to apply some of these techniques to ICP measurements.

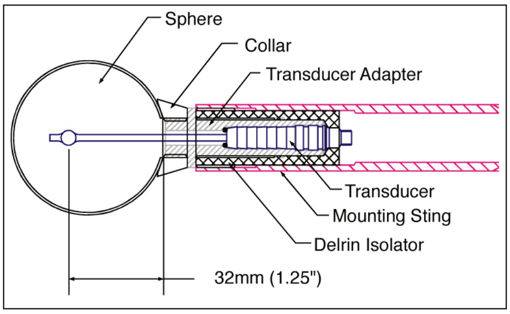
In the present work, we investigate the application of underwater blast measurement techniques to a simulated ICP apparatus consisting of a water-filled plastic sphere. Pressure gauges commonly used for ICP measurements are compared to underwater blast gauges, and the accuracy and fidelity of the ICP gauges will be discussed. Three types of gauge were chosen to represent the ICP gauges most commonly found in the literature: an optical interferometric catheter gauge, a miniature piezo-resistive catheter gauge, and a miniature piezo-resistive air blast gauge. This evaluation is part of a larger more extensive study on ICP gauges detailed in [8].

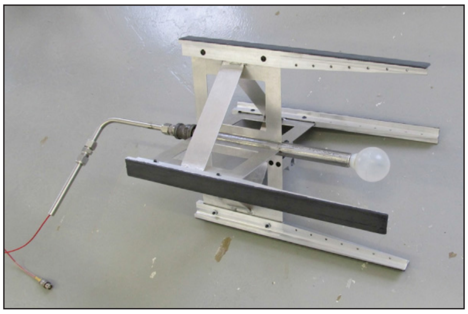
2. METHODS

2.1 ICP Apparatus

The test blast waves were generated in a compressed-gas-driven shock tube. The shock tube consisted of diverging driver and expansion sections to produce a spherically-expanding shock, a cylindrical test section 30 cm in diameter, and finally an end wave eliminator to mitigate the open-end reflections and tailor the waveform shape. This arrangement reproduced the main features of real spherical blast waves from high explosive charges. Details of the shock tube have been presented elsewhere [11].

A water-filled plastic sphere was used to reproduce blast conditions similar to those in an actual ICP blast experiment. Although the apparatus has the approximate dimensions of a 1/11th-scale human head, it was only meant to qualitatively recreate key blast features from an actual blast interaction with a head, such as shock propagation through the sphere, internal reflections, and compression and expansion of the head. The sphere was a 50-mm diameter polyethylene ball with a non-uniform wall thickness from 0.5 mm up to 1 mm. A hole with a threaded collar was installed on the sphere to allow it to be filled with water and for insertion of a candidate pressure transducer (Fig. 1a). Once the arrangement was ready for testing, it was mounted in the shock tube using a light aluminium structure to secure it in position along the central axis of the tube (Fig. 1b).





(a) **(b)**

Figure 1. Water-filled sphere used to reproduce ICP shock interactions with a) the gauge mounting arrangement, and b) the structure for mounting inside the shock tube.

2.2 Underwater blast methodologies

The underwater blast produced by a submerged explosive charge typically has very high pressures in the megapascal range and durations down to a few microseconds for small charges at close range. Unlike air blast, there is only a minimal negative pressure phase, because water only sustains minimal tension before it undergoes cavitation. In the case of transmission of air blast into a fluid medium, pressures are lower as they are dictated by the reflection conditions at the air / fluid boundary. The durations of the wave can still be in the microsecond range because the relative incompressibility of water causes rapid spherical expansion waves when reflecting off non-planar boundaries, such as a curved head.

To establish a reference pressure trace showing the variations inside the sphere following blast impact, a common underwater explosion gauge was used. The gauge selected was a Commercial Off-The-Shelf (COTS) PCB® 138A01 from PCB Piezotronics [9]. This gauge is used extensively for underwater explosion research, and consists of a tourmaline piezo-electric crystal coupled to an integrated charge amplifier. The unique crystalline structure of tourmaline allows it to exhibit a non-directional piezo-electric response [10], making ideal for free-field measurements, i.e. completely immersed in a fluid. The particular gauge model was chosen for its high sensitivity and ability to resolve the relatively low pressures relevant to TBI shock and blast environments. Both the gauge and its associated signal conditioning respond at a maximum bandwidth of 1 MHz, and combined with a data recording system of over 5 Megasamples/second, provide the necessary bandwidth to resolve the high frequency components of a water-borne shockwave.

The 138A01 tourmaline gauge is too large to be used for ICP applications. Though the exact size of the crystal itself is unknown, it is encased in a metallic braid to shield it from electromagnetic noise, and the overall size of the sensing head is approximately 5 mm in diameter (Fig. 2). Its purpose in this study is to provide a pressure history from an established underwater blast gauge to compare with various candidate ICP gauges.

Figure 2. Sensing tourmaline crystal in a PCB 138A01 underwater piezo-electric blast gauge.

The pressure measured inside the water-filled sphere is shown in Figure 3. For comparison, the incident shock pressure measured at the same axial location, along the tube wall is also shown. The two traces are quite different, highlighting the very different shock interactions between an ICP measurement and the outside incident pressure. The speed of sound in water is 1450 m/s, as opposed to 340 m/s in air, which causes a series of very rapid back-and-forth shock reflections inside the sphere before the air shock has finished passing over the sphere. Some notable features include a pressure spike higher than the incident air pressure due to a converging reflected shock, high-frequency pressure variations, and a lower average pressure from 0-4 ms. These general features have been reproduced in several numerical simulations of shocks impinging on water-filled shells [12]. An undesirable high-frequency noise appeared in the signal due to vibration of the gauge connector, however the first 0-3 ms of the pressure history inside the sphere following shock impact was clean and repeatable (Fig. 4). Cavitation, which appears as a sharp cut-off of the blast pressure, was not observed at this particular gauge location.

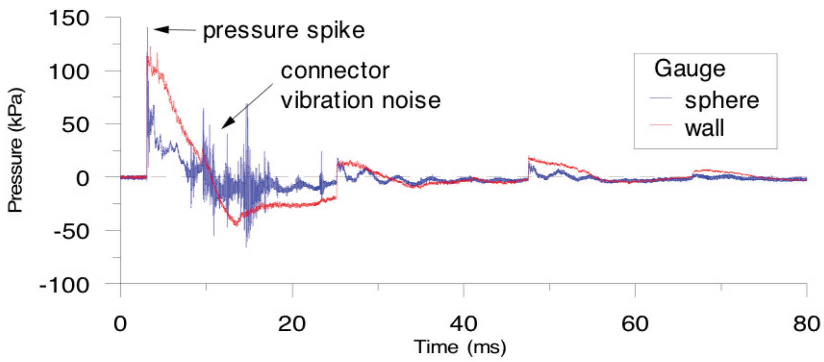


Figure 3. Pressure histories for gauges located inside the sphere, and on the shock tube wall outside the sphere.

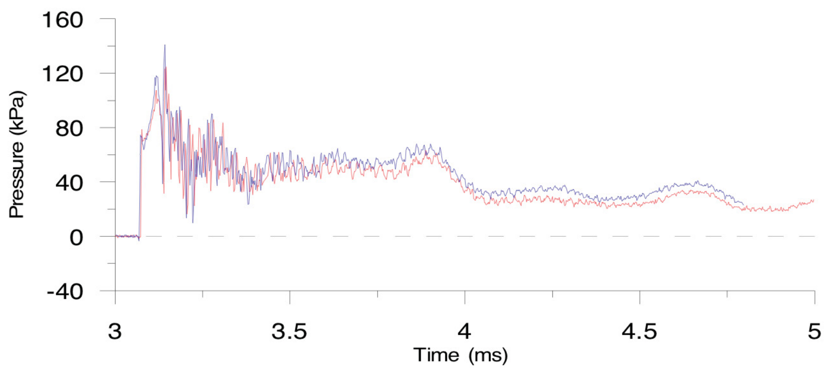


Figure 4. Pressure histories for gauges located inside the sphere for separate tests at the same conditions.

A closer examination of the pressure in the sphere reveals complex shock interactions within the sphere boundaries (Fig. 5). After the air blast impacts the front of the sphere, a spherically-diverging shock propagates ahead of the air shock due to the high sound speed, and decreases the pressure to about 75% of the peak air blast pressure after it has propagated 18 mm into the sphere to reach the immersed gauge (A). As the air blast starts to engulf the sphere, the pressure rises as it equilibrates to the surrounding pressure behind the air shock (B). The water shock reaches the back half of the sphere and a rarefaction wave reflects back in the opposite direction, reaching the gauge and causing a sharp pressure drop at approximately 40 μs (C). The initial water shock also reflects from the hard metal stem at the furthest point at the back of the sphere and reflects back, reaching the gauge almost immediately after the rarefaction wave (D). Reflection of the air blast from the sphere and its mounting assembly causes back and forth reflections between the assembly and the side wall, which can be seen as small peaks in the side wall gauge (E and G). A recompression (F) occurs at approximately 3.8 ms, which corresponds roughly to the period of the natural resonance frequency of the sphere (~1 kHz).

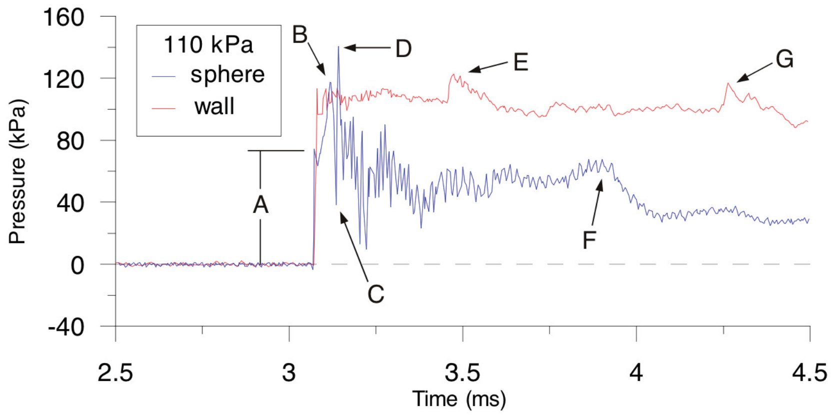


Figure 5. Expanded view of pressure histories for gauges located inside the sphere and on the shock tube wall.

3. RESULTS AND DISCUSSION

3.1 Optical gauges

The optical gauge evaluated was a Fiso® FOP-MIV-PK-C1-F1-M2-R3-ST. This gauge is a miniature pressure transducer consisting of a 500-micron diameter glass cavity at the end of a 50-micron diameter glass fiber-optic cable. The cavity is closed by a diaphragm that deflects with pressure, and the entire fiber and gauge are protected by a 1-mm diameter plastic (PTFE) sheath. Changes in the cavity length are measured through Fabry-Pérot interferometry, and the fringe shifts in an interference pattern are converted into deflection distances, which are then converted to pressure. The particular model tested had a specified pressure range of -40 to 1 MPa. This transducer is primarily used in medical research, where it is integrated into instrumented catheters to provide time-resolved in-situ blood pressure measurements.

The signal conditioner used was a two-channel Veloce 50 model supplied by Fiso®. This signal conditioner performed real-time signal processing to convert the interference signal into a voltage linearly-calibrated to pressure. The unit provides the light source and detector for the measurement and operates at a maximum rate of 200 kS/s. Every 5 μs, the position of the diaphragm is calculated by fringe counting, and a corresponding output voltage is generated. The discrete output voltage levels are filtered to provide a continuous analogue output signal. If the fringe count is lost, the diaphragm position is recalculated through a cross-correlation with the absolute position.

The Fiso® gauge was tested at peak incident air blast pressures of 22, 50, 62, 85, and 110 kPa inside the water-filled sphere. The resulting pressure histories up to 85 kPa are shown together with a tourmaline (138A01) pressure history for comparison in Figure 6. The Fiso gauge was found to lack the high-frequency response to follow the abrupt pressure rise of the shock, as initial rise time was longer than that of the tourmaline gauge. An overshoot of up to 50% was also observed at the initial rise, and an ensuing resonant frequency of approximately 30 kHz unrelated to the pressure variations persisted for the first 150 μs. This resonance appeared to increase with increasing pressure. Finally, the Fiso pressures deviated significantly from the tourmaline pressures at later times beyond ~600 μs. Interestingly, the agreement between the Fiso and tourmaline gauges was much closer at a higher peak incident pressure of 110 kPa up to ~1.1 ms (Fig. 7a), however, the Fiso appeared to completely lose its tracking ability beyond 4 ms (Fig. 7b).

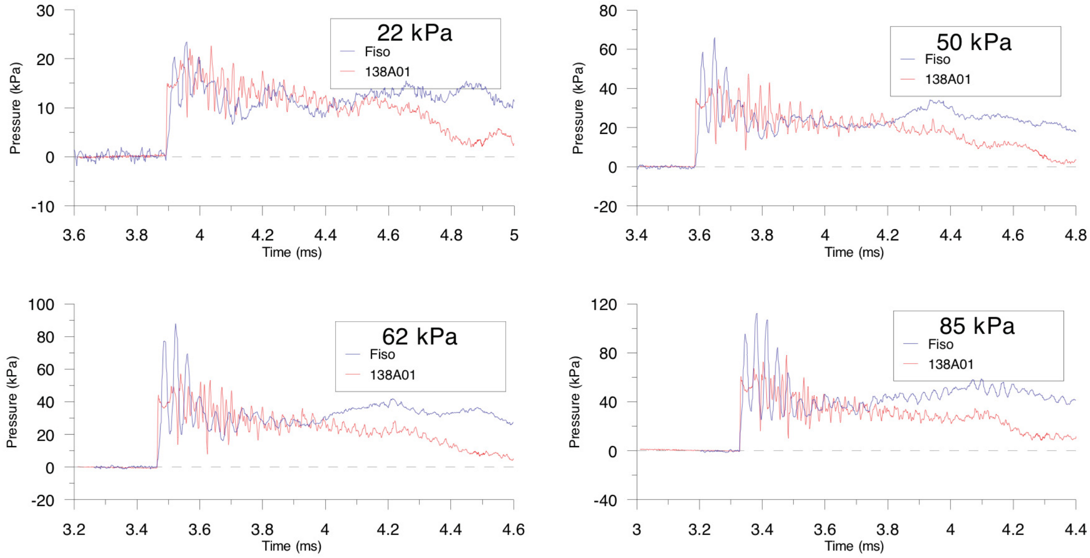
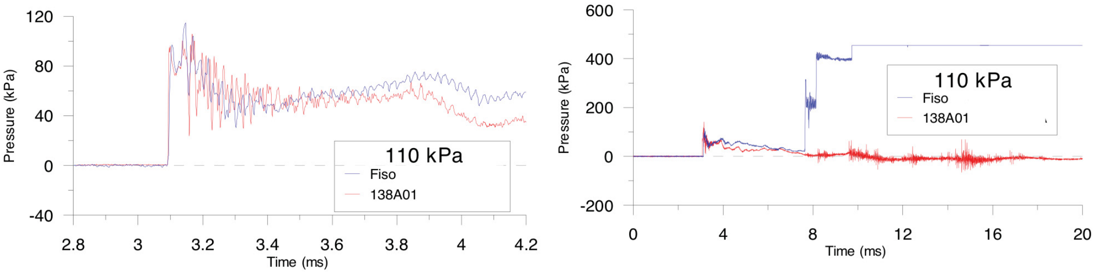


Figure 6. Pressure histories for Fiso® gauges located inside the sphere at peak incident pressures of 22-85 kPa.

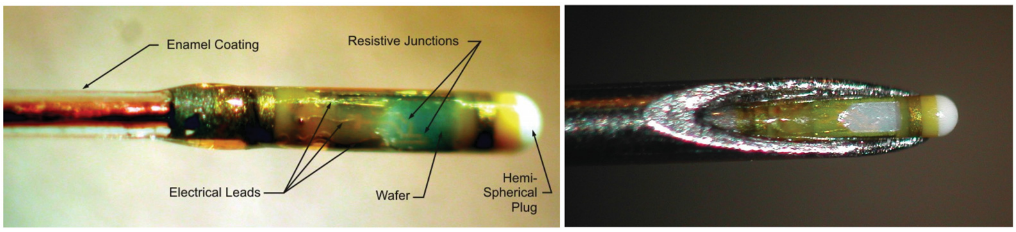


(a) (b)

Figure 7. Pressure histories for Fiso® gauges located inside the sphere at peak incident pressures of 110 kPa compared with the tourmaline gauge (138A01) at a) early time up to ~1.1 ms, and b) later times.

3.2 Piezo-resistive catheter gauge

The piezo-resistive catheter gauge evaluated was a Millar® Mikro-Tip Catheter model Number SPR-671. The 0.45-mm diameter sensor head was connected to a fine, 3-conductor cable approximately 0.35 mm in diameter with an enamel-like coating (Fig. 8a). Very little information was found on the design and construction details of the sensor, although it appears to contain two piezo-resistive arms of a Wheatstone bridge. The manufacturer has indicated that the sensing element consists of a titanium diaphragm with piezo-resistive strain gauges integrated onto the edge using Micro-Electro-Mechanical Systems (MEMS) technology [13]. These components could not be identified upon examination of the sensor head (Fig. 8a), however it appeared to consist of a sensing wafer with circuit board connections immersed a type of gelled silicon, encased in a cylindrical capsule. Because of the fragility of the sensor, it was decided to mount it inside a 20-gauge hypodermic needle using Mbond200® adhesive (Fig. 8b). This arrangement was intended to provide a rigid support to minimize strain on the sensor head and associated connections.



(a) **(b)**

Figure 8. Millar® Mikro-Tip Catheter with a) sensor head details, and b) mounted inside a 20-gauge hypodermic needle.

The nominal sensitivity specifications supplied for the gauge were: 37.6 uV/V/kPa (0.259 mV/V/psi) with a rated excitation of between 2.5 - 7.5 VDC [14]. A somewhat unusual design feature was that the cable plug for the gauge contains circuitry to calibrate all models of this type to the same sensitivity. The working range was -6.7 kPa to 40 kPa (5.8 psi) with an over-pressure range from a complete vacuum to 530 kPa (76 psi). The nominal input and output impedance were both 1000 ohms. The natural resonant frequency for the gauge was specified as greater than 10 kHz, suggesting that the upper bandwidth limit is below this value.

The gauge was supplied with a Low Voltage Control Unit, model number SD-974, that provided the excitation voltage and signal conditioning for the transducer. This unit supplied an excitation of 3.3 VDC resulting in a gain of 42.4, and an output of 700 mV/1000mmHg (36.2 mV/psi) [15]. The controller gain is fixed with no ability to adjust it.

The Millar gauge was tested at peak incident air blast pressures of 22, 50, 62, 85, and 110 kPa inside the water-filled sphere. The results initially showed that the limited high-frequency bandwidth of the gauge was inadequate to resolve the shock interactions in the fluid (Fig. 9). However, it was decided to replace the Millar signal conditioner with one commonly used for blast applications with a higher bandwidth. The bridge-type signal conditioner used was a Vishay® 2310B [16], which was configured to provide a 5 VDC excitation voltage with an output gain of approximately 40X. This provided an output sensitivity of 7.25 mV/kPa (50 mV/psi) with a high-frequency bandwidth limit of 250 kHz (-3 dB) for the gain selected. With the Vishay 2310B signal conditioner, the rapid shock interactions were resolved with a much higher degree of accuracy than with the Millar SD-974 (Fig. 9). The microsecond pressure jump of the shock arrival was captured, as opposed to the slow rise with the Millar signal conditioner, and many of the ensuing multiple shock reflections within the sphere were also reproduced. Comparison with the tourmaline pressure gauge (138A01) also showed a very good agreement (Fig. 10), with all the main shocks captured, although the higher amplitude of the oscillations in Millar gauge trace suggests a moderate amount of overshoot.

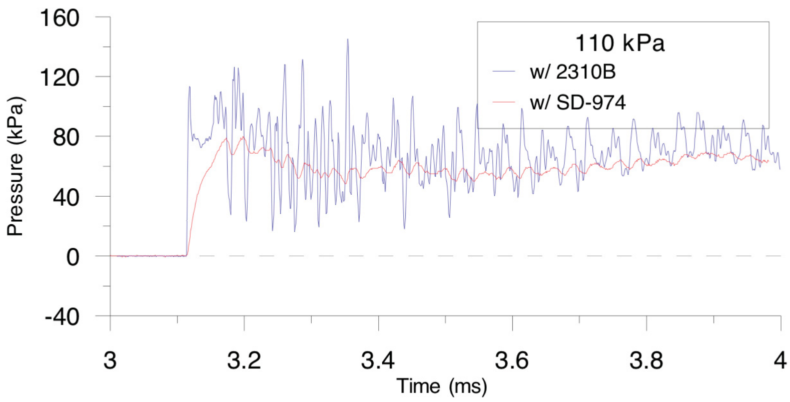


Figure 9. Pressure history for the Millar gauge tested with a peak air blast pressure of 110 kPa in the sphere using two types of signal conditioners: the Vishay 2310B, and the Millar SD-974.

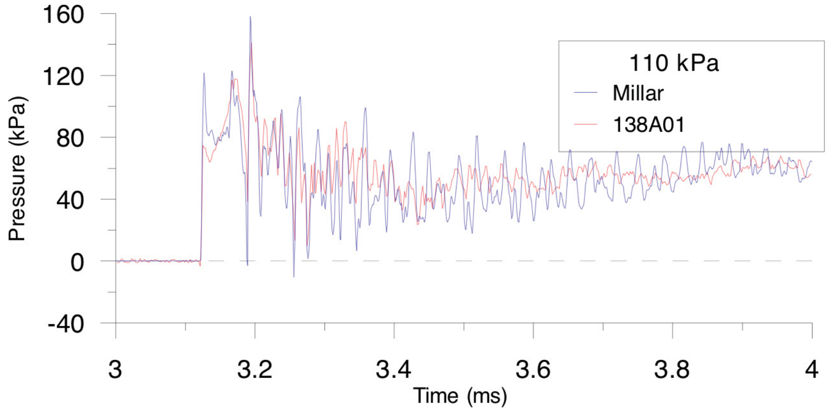


Figure 10. Pressure history for the Millar gauge tested with a peak air blast pressure of 110 kPa compared with the tourmaline gauge (138A01).

3.3 Piezo-resistive air blast gauge

The piezo-resistive air blast gauge evaluated was an EPIH-343-100P transducer manufactured by Measurement Specialties. The EPIH-343-100P is a small cylindrical 1.8 mm in diameter and just under 10 mm long. The transducer is a standard full bridge piezo-electric device. Four MEMS strain gauges are located at the high strain edges of a responding a diaphragm. The pressure is monitored by measuring the change of resistance of the strain gauges as the diaphragm deflects with pressure. Five delicate individual leads extended approximately 44 cm back to a small in-line compensation module. The four standard leads for piezo-resistive transducers, two for excitation, two for signal, extended from the other end of the module. To protect the lead wires and to provide some physical support for positioning the transducer within the sphere, the leads and most of the transducer cylinder were encased in heat-shrink tubing (Fig. 11). The pressure-sensing components of the gauge were shielded behind a protective screen behind small holes in the front face of the casing. Although the manufacturer indicates that the gauge is "suitable for dry gas and some fluids with Parylene or RTV protection" [17], consultation with the manufacturer revealed that only the active face of the transducer, and not the body, is intended to be exposed to the sensing fluid, making it unsuitable for immersion in fluid without additional protective measures.

Figure 11. EPIH-343-100P pressure transducer in protective heat-shrink tubing.

This particular model was an absolute pressure transducer without a reference pressure port tube, and had a working range of 689.6 kPa (100 psi). The sensitivity of the transducer was 0.02222 mV/kPa/V (0.15326 mV/psi/V), based the specified full-scale output of 76.63 mV and an excitation voltage of 5.0 VDC. As with the Millar gauge, a Vishay 2310B signal conditioner was used.

As for the other gauges, the EPIH gauge was tested at peak incident air blast pressures of 22, 50, 62, 85, and 110 kPa inside the water-filled sphere. Because it is an air blast gauge intended only for exposure to pressures on its front face and not full immersion, the directional sensitivity of the gauge was tested using two different sphere orientations: the standard reflected orientation with the blast impacting the top of the sphere, and a side-on orientation with the blast impacting the side of the sphere. The results of the tests showed a clear lack of high-frequency bandwidth, as the slow response of the gauge failed to capture the sharp rise of the shock pressure as well as most of the subsequent shock interactions in the water (Fig. 12). There was also some directional sensitivity as the peak side-on pressure was slightly lower than the peak reflected pressure. This result was somewhat surprising since the gauge is designed for shock measurements, however it is speculated that the protective screen integrated in gauge may be trapping air in front of the sensing elements, creating a cushion of gas between the fluid outside the gauge and the sensor. This cushion could cause a damping effect which reduces the response of the gauge, making it unsuitable for measurements of underwater shocks.

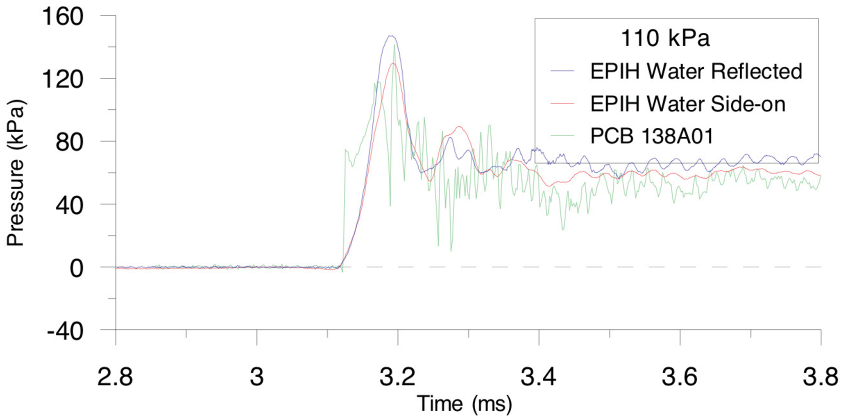


Figure 12. Pressure history for the EPIH gauge compared to the tourmaline gauge (138A01).

4. CONCLUSIONS

Using an underwater blast gauge with a signal conditioner and data acquisition system having a high-frequency bandwidth limit of 1 MHz, rapid back and forth, non-planar shock wave interactions were observed inside a water-filled plastic sphere subjected to air blast. This experimental arrangement was used to identify several drawbacks and features for three types of ICP gauge: an optical gauge, a piezo-resistive catheter gauge, and a small piezo-resistive air blast gauge.

The main drawback of the three types of gauge tested was the lack of high-frequency bandwidth, as none initially proved responsive enough to resolve the shock interactions inside the water-filled sphere. The Fiso also showed some signal artefacts such as a resonant oscillation of approximately 30 kHz and loss of pressure tracking at later times. The Millar gauge however, proved capable of resolving most of the rapid pressure fluctuations in the sphere, but only after replacing its signal conditioner with a blast-type signal conditioner, although some overshoot was observed. The EPIH gauge lacked the high-frequency bandwidth in spite of using a blast-type signal conditioner.

The complexity of the shock interactions inside the relatively simplified version of a head used in this study suggests that ICP pressure inside a live subject may exhibit an even richer spectrum of shock phenomena inside the head. It is clear that these types of measurement are extremely challenging, and to fully elucidate the blast insult at all locations in the head requires a careful choice of the gauge and instrumentation. Underwater blast methodologies provide approaches that address some of these challenges, and future work may further exploit these methodologies to provide a more complete map of the pressure histories throughout an entire head model.

Acknowledgments

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References

[1] Chavko, M., Koller, W.A., Pruzaczyk, W.K., and McCarron, R.M., Measurement of blast wave by a miniature fiber optic pressure transducer in the rat brain, J. Neuroscience Methods 159, (2007), pp. 277–281.

[2] Bolander, R., Mathie, B., Bir, C., Ritzel, D., and VandeVord, P., Skull Flexure as a Contributing Factor in the Mechanism of Injury in the Rat when Exposed to a Shock Wave, Annals of Biomedical Engineering, Vol. 39, No. 10, (2011), pp. 2550–2559.

[3] Säljö, A., Mayorga, M., Bolouri, H., Svensson, B., Hamberger, A., Mechanisms and pathophysiology of the low-level blast brain injury in animal models, NeuroImage 54, (2011), pp. 83–88.

[4] Leonardi, A.D.C., Bir, C.A., Ritzel, D.V., VanderVord, P.J., Intracranial Pressure Increases during Exposure to a Shock Wave, Journal of Neurotrauma 28, (2011), pp. 85–94.
[5] Shridharani, J.K., Wood, G.H., Panzer, M.B., Capehart, B.P., Nyein, M.K., Radovitzky, R.A., Bass, C.R., Porcine Head Response to Blast, Frontiers in Neurology 3, (2012).
[6] Sundaramurthy, A., Alai, A., Ganpule, S., Holmberg, A., Plougonven, E., Chandra, N., Blast-Induced Biomechanical Loading of the Rat: An Experimental and Anatomically Accurate Computational Blast Injury Model, Journal of Neurotrauma 29, (2012), pp. 2352–2364.
[7] Cole, R.H., Underwater explosions. Dover Publications Inc, New York, (1965).
[8] Rude, G., Lee, J., Evaluation of Pressure Transducers for the Measurement of Transmitted Shockwave Profiles in Biological Tissues, Defence R&D Canada Technical Memorandum TM-2013-056, Suffield, Canada, (2013).
[9] PCB Piezotronics Inc., Model 138A01 ICP® Pressure Sensor Installation and Operating Manual, PCB Piezotronics Inc., Depew, New York, USA, (2008).
[10] Walter, P.L., Measuring Underwater Explosions: Transducers and Their Application, Technical Note TN-28, PCB Piezotronics, Depew, NY, USA, (2011).
[11] Ritzel, DV et al., "Experimental Blast Simulation for Injury Studies", presented at the HUMAN FACTORS & MEDICINE PANEL HFM-207 Symposium, Halifax, Nova Scotia, 3-5 October 2011, NATO, (2011).
[12] Donahue, L. & McLennan, S. Computational Modelling in Support of Blast TBI Research – Part 2, Lloyd's Register Technical Report # TR-13-19, Martec Limited / Lloyd's Register, Halifax, Nova Scotia, Canada, (2013).
[13] Fleck, B. Personal communication, Millar Inc. (2012).
[14] Millar Instruments Inc., Mikro-Tip Catheter Pressure Transducer, Instructions for Use, User manual, Millar Instruments Inc., Houston, Texas, USA, (2004).
[15] Millar Instruments Inc., Model SD-974 Control Unit, Instructions for Use, User manual, Millar Instruments Inc., Houston, Texas, USA, (2009).
[16] Vishay Micro-Measurements, Signal Conditioning Amplifier 2310 Instruction Manual, Vishay Micro-Measurements, Raleigh, North Carolina, USA(2011).
[17] Measurement Specialties, EPIH datasheet, downloaded at http://www.meas-spec.com/product/pressure-sensors/epih.aspx, Measurement Specialties, Fremont, California, USA, (2011).

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