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Direct comparison of the primary blast response of a physical head model with post-mortem human subjects

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ABSTRACT

As the gathering of information on the prevalence of blast-induced traumatic brain injuries (bTBI) continues, there is a need for the development and validation of a physical model (headform) reproducing the mechanical response of the human head to the direct loading from a blast wave. The chain of events leading to an injuries following direct exposure to a blast wave is very complex and its full determination is still the topic of several research efforts. The first step in the injury cascade is necessarily the mechanical insult of the blast wave to the human head. With a combination of representative anatomical features, adequate material selection and careful instrumentation, a validated physical model could measure real external pressure field history and predict resulting intra-cranial pressures (ICP) for any blast loading scenario. In addition, a physical model has the unique ability to measure quantitatively the effect of protective headwear. The following article discusses the validation of the BI^{2}PED (Blast-Induced Brain Injury Protection Evaluation Device) response against post-mortem human subjects (PMHS). Previously reported PMHS blast wave generator tests were methodically replicated in the same facility using the BI^{2}PED. Loading conditions, instrumentation type and position as well as the head mounting technique were reproduced to ensure that the only difference between the two series of experiments was the model itself. A direct comparison of measured ICP histories is presented for two loading orientations and three loading magnitudes. It is demonstrated that the physical model response is in good agreement with that of the PMHS response. From signal analysis, additional evidences supporting skull deformation as the main contributor to ICP variations are discussed. Finally, external pressure fields from the blast wave generator experiments are compared to full scale free-field tests.

1. INTRODUCTION

There is a preponderance of clinical and experimental evidences that suggest that traumatic brain injury (TBI) can occur as a result of a direct exposure to blast wave [1]. The chain of events leading to such injuries is likely very complex and its full determination is still the topic of several multi-disciplinary research efforts [1]. Highly controlled laboratory experiments on post-mortem human subject as well as the development of physical and numerical head models can certainly provide useful information on the first step in the cascade of events leading to injury, which is considered to be the mechanical insult of the blast wave to the human head. As a thorough understanding of the injury mechanism is developed, the need for physical models capable of reproducing the mechanical response of the human head under blast loading increases. A validated physical model combining representative anatomical features, adequate material selection and careful instrumentation provides three clear benefits. First, it can help to characterize the head external pressure field history (i.e. the loading) for any blast scenario. Operational blast scenarios are infinite and it is only by characterizing the real mechanical input to the head that it will be possible to distinguish between them. Second, a physical model can help estimate the magnitude of the stresses developed in the brain. This is essential to provide a link between external mechanical insult and the potential for injury. Finally, it can help evaluating the performance of protective headwear systems.

The direct exposure of the head to a blast wave creates a very short duration high amplitude loading that is very different in nature from loadings resulting from impacts seen in automotive or sport accidents. Willinger *et al*. [2,3] have comprehensively discussed how the duration of a loading on the head can determine the nature of the strain and stress fields in the brain. They distinguished between three lesion mechanisms, each of which is particular to a range of loading duration. For long

duration loading above 10-12 ms, distributed lesions throughout the brain are attributed to the generation of intra-cranial stresses from inertial forces. In such regime, the whole head is subjected to the same translational and rotational acceleration field. For duration between 4-10 ms, the skull motion and brain motion are decoupled. This regime has been the subject of numerous studies since the development of the rapid skull motion theory by Viano *et al*. [4]. Willinger stated that for such loading durations, the first resonance frequency of the head, which he cites as being between 100-150 Hz, may be excited. Skull to brain relative translational and rotational motion can cause bridge vein shearing and contusion if direct contact occurs. Finally, for impact duration below 4 ms, the loading can excite a second resonant frequency observed between 700-800 Hz [3-6]. This is a wave-dominated regime where local skull deformation occurs. In the context of blast TBI research, such mechanism has also been referred to as "skull flexure" or simply "direct stress transmission" [7-10]. Flexure happens when the loading energy is delivered rapidly enough so that the skull does not have time to reach force equilibrium throughout its structure. The skull doesn't move as a rigid body but rather sustain local deformation, which then propagates in the structure as waves. Local deformations in the skull may generate compressive and tensile intra-cranial stresses and lesions in nearby brain regions.

Operational blast waves may excite the head structure through more than one frequency band and potentially create lesions from a combination of the aforementioned mechanisms. For example, skull deformation may occur along with relative brain-skull motion, at different times but still within a single event. An important question to answer is which of these mechanisms dominates in the generation of brain stresses following blast exposure. Clearly, simple physical models, such as automotive test devices (ATD), which only records head global accelerations, cannot provide the answer to such question. Even though they can be representative of certain shock severity level and therefore certain risk of cerebral lesions, they cannot distinguish between lesion mechanisms [3]. The study of the effect of blast on the brain requires a more direct measurement.

When a high-pressure blast wave travels across a body (head), it reflects off and diffracts around to form a transient pressure field that is unique to each individual blast scenario. This pressure field is influenced by the blast propagation direction, magnitude and duration at the location of interaction, but also by surrounding reflecting surfaces, including the ground. The stresses generated within the brain following blast exposure therefore also depend on all of these characteristics.

The BI^{2}PED headform shown in Figure 1 has been developed by Defence Research and Development Canada (DRDC) Valcartier research center to characterize head external pressure field history following any given blast exposure, to predict resulting global head acceleration and brain intra-cranial pressure (ICP) variations. It is understood that biological material failure in a real scenario may also occur under shear loads, but it is assumed that ICP is representative of the magnitude of injurious stresses generated within the brain. Shear stresses or strain within brain or brain-like materials would be very difficult to measure experimentally. It has been shown that the BI^{2}PED presents the necessary physiological feature and representative selection of material to estimate head response to blast [11]. Nevertheless, a critical aspect of this physical model to fully meet its purpose is the validation of its response against real human head response (post-mortem). Until this is achieved, there is no guarantee the evolution of ICP follows that from a human head.

Bir *et al.* [10] has recently reported blast wave generator tests where instrumented post-mortem human subjects (PMHS) heads were subjected to blast waves of 3 different intensities and in 4 different orientations. Fluctuation in intra-cranial pressures was monitored at 4 locations within the brain and skull strains were measured at 5 locations. This parametric approach rendered a dataset that is well fitted to begin the validation process of the BI^{2}PED. It is understood that the full injury cascade cannot be assessed using PMHS, but the BI^{2}PED model focuses on reproducing the mechanical response of the head and the stress transmission mechanism, not the injury itself. Through a collaboration agreement, DRDC Valcartier Research Center and Wayne State University (WSU) Biomedical Engineering Department teamed up to replicate the reported PMHS tests using the BI^{2}PED headform. Loading conditions, instrumentation type and position as well as head mounting technique were reproduced to ensure that the only difference between the two series of experiments was the use of BI^{2}PED or PMHS. Direct comparison of measured ICP histories was therefore possible.

Figure 1: *The Blast-Induced Brain Injury Protection Evaluation Device (BI²PED).*

2. EXPERIMENTAL METHOD

The BI²PED construction, materials and instrumentation are detailed in Ouellet *et al.* [11] and are only summarized here for the purpose of this article. The current version of the headform replicates the skin, skull, cerebrospinal fluid (CSF), membranes and brain structures. The skin, skull, flax and tentorium membranes are of uniform thickness and are made from different polymers selected to match elastic material properties of their biological counterpart. The brain is made of a silicone gel. It rests on the bottom of the cranial cavity and is held in place by the membrane structures. It is slightly suspended in water, which acts as the CSF. The headform is instrumented with five flat pressure transducers which are flush mounted with the skin in a custom design sleeve. They are positioned on the forehead, right side, left side, back and top of the head. Pressure transducers are also casted within the brain surrogate at varying locations depending on the purpose of the trial. These transducers are carefully positioned using very thin wires which are pulled out of the gel during curing. These intracranial transducers are modified to ensure that the sensing diaphragm is in intimate contact with the gel as it cures. When used in full scale blast testing, the headform is typically mounted on a Hybrid III neck. It is then equipped with 6 accelerometers at the base of the neck which allows for the calculation of resultant translational and rotational accelerations. To replicate the original PMHS study from WSU and allow for a direct comparison of intra-cranial pressures, three sets of parameters needed to be replicated as precisely as possible; The nature, orientation and position of the instrumentation, the loading conditions and finally the head orientation and mounting technique.

2.1 Instrumentation

For the internal instrumentation, focus was put on replicating three of the ICP measurement from the original PMHS study, namely the frontal lobe, parietal lobe and occipital lobe ICPs. The current version of the BI²PED uses modified Kulite piezo-resistive XCL-072 pressure sensors (Figure 2a) for monitoring ICP. They are 1.9 mm in diameter and uni-directionnal. They proved to be very reliable when adequately casted in the brain surrogate. The transducers have a sufficient bandwidth (> 25 kHz) to resolve rise time on the order of ten microseconds. They are sufficiently acceleration insensitive (0.0001% of full-scale output per g) to be adequate for the headform operational range. They have a linear output for pressures up to 14 bars and a resonant frequency over 550 kHz.

The original WSU study used FISO fiber-optic pressure sensor to monitor ICP. The FISO FOP-MIV (Figure 2) sensor is 550 microns in diameter. It has the advantage of being extremely small. However, it was also found to be very fragile. For that reason, FISO does not recommend bending the fiber-optic wire above a 30-40 mm radius. The manufacturer does not provide detailed technical information about the transducer aside

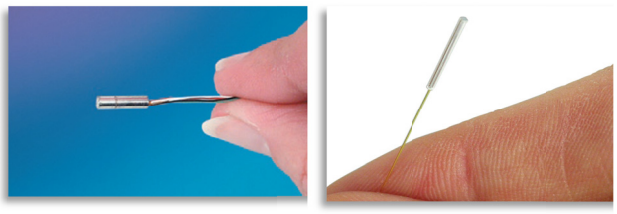

Figure 2: *Relative size of pressure sensors a. Kulite piezo-resistive XCL-072 sensors and b. FISO FOP sensor.*

from its operating range. Internal DRDC calibration showed a linear output for pressures up to 1500 kPa. The sensor needs to be used in conjunction with FISO data acquisition system (Veloce 50) which has a maximum sampling rate of 250 kHz. Given the lack of technical information on the capacity of the FISO sensors to monitor the ICP variations adequately (e.g. bandwidth, acceleration effects) and that fragility of the sensors had been a problem in the original study, it was decided to use both the piezo-electric and fiber optic sensors side by side in the BI^{2}PED headform. This method would provide validation of past and current FISO sensor measurements and provide back-up readings if a sensor was to break during the test series. Great care was taken to ensure that sensing elements were aligned and both sensors were attached to each other at the base. Following the test series, raw and processed signals from both sensors were compared.

Replicating the original orientation of the sensors was challenging. The original PHMS study ran the FISO pressure sensors through the skull, perpendicular to the skull surface tangent and toward the center of the head. This was obviously the less intrusive way to position the ICP sensors in a PMHS. The downside to this method is that it exposes the sensor wires significantly, particularly the ones reaching into the frontal lobe. In a physical model, casting the sensors into the surrogate brain allows for the possibility to run the wires together, in the opposite direction from the blast. To ensure that we could perform several repetitions in the test series and to make sure that the bending limit of the fiber optic wires was not exceeded, it was decided to run the wires out together toward the back of the head. Inevitably, the resulting orientation is different than in the original PMHS study. However, the assumption was that the effect of a different orientation may be minimal if a certain range of angles of incidence with regards to the blast direction was maintained. A unidirectional pressure sensor casted in a solid gives a measure of stress in the direction of measurement. It is technically a measure of longitudinal stress. Nevertheless, brain tissues as well as silicone gel have a bulk modulus that is orders of magnitude higher than their shear modulus, with a Poisson's ratio approaching 0.5. The pressure component of stress likely dominates the stress state and the measure from the sensor should be relatively orientation independent. The only effect that could be seen is when the angle of incidence with the stress direction is such that the transducer itself impedes the measurement.

The position of sensors in the original PMHS study was specified in the three axis using distance from the nasion bone towards the back of the head, distance from the head mid-plane and depth from outer skull surface. These distances were kept similar even though the BI^{2}PED length and width did not perfectly match the PHMS head dimensions. Final sensor positions were validated using x-ray imaging. Figure 3 shows the x-ray photograph of the BI^{2}PED. The FISO sensors are invisible to x-ray but follow the same route as the piezo-resistive sensor wires. It can be noticed that minimal bending of the wire was achieved by exiting all wires from the back of the skull. Table 1 lists all sensors intended and final position.

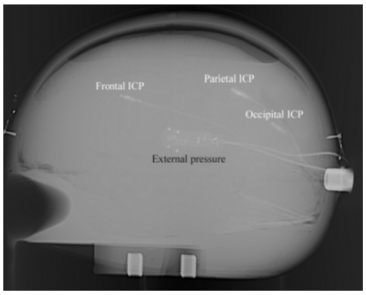

Figure 3: *BI^{2}PED internal pressure transducers positions,*
** Fiber optic sensors are not apparent under x-ray imaging.*

Table 1*, Sensor positions for both PMHS and BI^{2}PED test series.*

	Frontal ICP		Parietal ICP		Occipital ICP	
	PMHS	BIPED	PMHS	BIPED	PMHS	BIPED
Distance from nasion following skull surface (mm)	70	100	190	202	240	242
Distance from mid-plane (mm)	10	12	10	10	10	10
Depth from outer skin surface (mm)	30	42	30	39	30	35

Unfortunately, due to accidental pulling of the wires during pouring of the silicone gel, the frontal sensor was significantly displaced compared to the PHMS. The occipital sensor is the most representative of the PMHS sensor positions and was preferred for the comparative analysis of ICP signals.

Post-processing of the ICP signals was done according to the method used in the original PMHS study. All ICP signals were filtered using an 8-pole low-pass Butterworth filter with a cut-off frequency of 7 kHz. External pressure signals were post-processed following the same method as in previous free-field experiments with the headform [11], which consisted of a filtering using an 8-pole low-pass Butterworth filter with a 10 kHz cut-off frequency.

2.2 Test conditions

The blast wave generator facility of WSU used in the original PMHS study (Figure 4) was used again for the BI^{2}PED validation test series. The shock wave generator is a two part flared tube with a driver section and a driven expansion section separated by a mylar membrane. Compressed helium gas was used to fill the driver section up to a pressure causing the membrane to rupture. Upon rupturing, the gas expands and drives a shock wave down the expansion section. The thickness of the mylar can be increased to increase the rupture pressure and consequently the shock wave pressure. More details about the blast wave generator design can be found in [12].

Figure 4: *Wayne State University shock wave generator.*

Similarly to the original PHMS study, three membrane thicknesses were used to generate shocks with peak incident overpressures of 85, 120 and 140 kPa respectively. Shock duration was on the order of 7.5 to 8.5 ms for the three shock magnitudes. Full incident overpressure histories were measured during calibration shots using a pencil gauge at the target location. Shock generated from classic shock tubes typically have long positive phase duration in the order of tens of milliseconds. With its custom-built expansion section, the current blast wave generator is able to generate shocks below the 10 ms mark. In order to ensure that the generated shocks were representative of an operational blast, a blast profile from free-field tests conducted at DRDC-Valcartier research center was used for comparison. Figure 5 shows pressure histories for the 85 kPa shock from the blast wave generator and for a free-field blast from a 5 kg C4 charge detonated 0.2 m off the ground and at a 5 m distance.

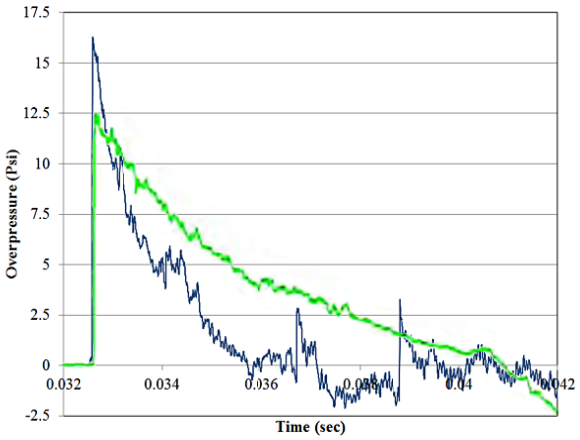

Figure 5: *Comparison of overpressure history generated from shock wave generator and from 5kg C4 charge at 5m (0.2m HOB).*

The BI^{2}PED was evaluated in two orientations; with the head long-axis parallel to the shock propagation direction (i.e. frontal exposure) and with the head long-axis perpendicular to the shock direction (i.e. right side exposure). Three repeats were obtained for each orientation at all three incident pressure levels.

2.3 Head mounting

In the original PMHS study, heads were disarticulated from the torso between the third and fourth vertebrae. They were pressurized and mounted upside-down in a soft net. The net was attached at the top and bottom and stretched tightly by two chains that were fixed to the tube wall. The specimens were centered in the tube as much as possible. The Hybrid III neck was similarily removed from the BI^{2}PED along with the accelerometer bracket. The headform was put upside down in a soft net and mounted in a similar fashion. The net was cut out around the exterior pressure sensors areas. Cabling was protected by bubble wrap and a Kevlar™ sleeve, and taped to the tube wall to avoid slapping of the connectors. Figure 6 shows both models mounted in the shock wave generator.

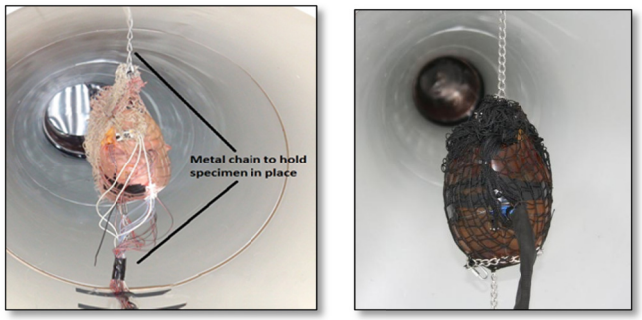

Figure 6: *Reproducing the original PMHS study test conditions with the BI^{2}PED.*

3. RESULTS AND DISCUSSION

3.1 External pressure field

The analysis of the results starts with the analysis of the external transient pressure field surrounding the headform (Figure 7). This analysis is important to confirm a few different aspects from the test, which can influence the intra-cranial pressure variations. First, shock diffraction symmetry is confirmed by looking at the overlapping right and left side pressure signals. Synchronicity between time of arrival of the left and right signals confirms the alignment of the headform with the incoming shock. Given the sampling rate of the acquisition, which was set at 1000 kHz (1 sample every microseconds), even a slight misalignment could be detected from these measurements. Second, the possible influence of tube boundaries was studied. The peak overpressure recorded on the forehead was on average 2.2, 2.4 and 2.6 times the benchmark peak incident overpressure of 85, 120 and 140 kPa respectively. For helium, the theoretical reflected to incident pressure amplification ratio, for this range of peak incident overpressure is expected to be between 2.6 and 3. Naturally, the headform is not perfectly flat on the front surface and clearing effects are expected to make the reflected pressure history deviate away from theory. Previous explosive tests with the headform in free-field conditions generated amplification ratio between 2.6 and 3.2 for a peak incident overpressure around 85 kPa. However, these were obtained in very different ambient condition (dry air at around 5 deg C). In general, the measure peak forehead pressure is in line with what could be expected. The side peak overpressures were on the order of 1.2 to 1.3 times the peak incident overpressure, which is similar to what was observed in free-field. The side pressures are slightly over the incident overpressure because they are not completely parallel to the blast flow direction and the flow is affected by the diffraction from the front portion of the headform. In general, the pressure field is very similar to what would be seen in free-field and therefore, it is concluded that the tube boundaries have limited effect on the loading seen by the headform. Finally, shock speed can be measured from the delay between the forehead signal and the

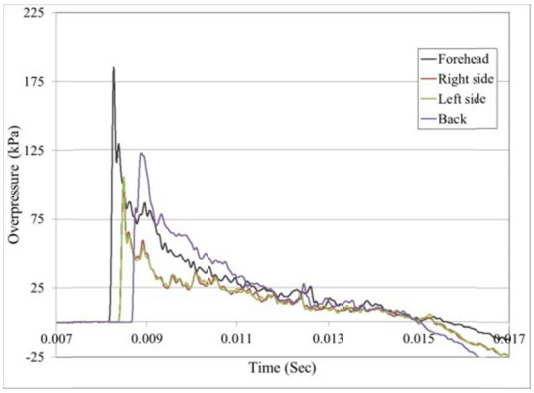

Figure 7: *Pressure field for 85 kPa incident pressure shock (filtered signals).*

right/left pressures, which are measured on the same horizontal plane. The delay for the 85 kPa shock was measured at 0.22 ms, which yields a shock speed of 450 m/s.

3.2 Effect of sensor type and post-processing

The responses of the piezo-resistive and the fiber-optic sensors, which were casted side by side with a spacing of approximately 4 mm, were compared for all tests. Figure 8 shows a representative example of raw occipital ICP measurement from both sensors along with their frequency response and the post-processed signal. The results indicate that the fiber-optic sensor probably had sufficient bandwidth to resolve pressure fluctuations in the brain material. The fiber-optic sensor signals had considerably more high frequency noise, as seen in figure 8a and 8b. Nevertheless, the sensors showed a frequency response that was on par with the validated piezo-resistive sensor. Both FFTs for this test revealed significant content up to approximately 4000 Hz, with an important contribution within the 1000-1200 Hz band, which dominates the early time domain response. The piezo-resistive sensors show minimal content above 4000 Hz compared to the noisier fiber-optic sensors. Once filtered, both responses were very similar, with the exception of an occasional variation on the order of 10% on the first pressure peak. In general, the low-pass filter used in the original PMHS study only removed high frequency noise from the signals.

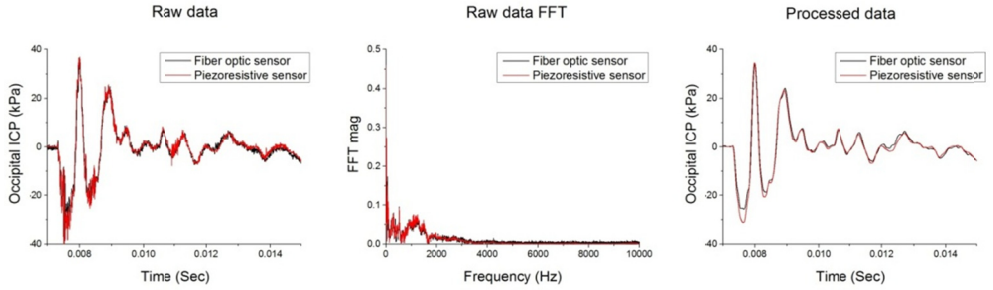

Figure 8: *Example of comparison of intra-cranial pressure measurements obtained from fiber optic sensor and piezo-resistive sensor.*

3.3 Repeatability of ICP measurements

Repeatability of measurements is verified to ensure that the instrumentation is responding correctly throughout the test series and that no internal or external damage to the headform has occurred. This is critical to be able to interpret the results adequately and draw relevant comparison with the original PMHS data. Figure 9 shows a representative example of three shots done at the 85 kPa peak incident pressure level. Great consistency was achieved with the blast wave generator and the headform. Variability on first and second peaks of the ICP signals were generally lower than 5%, part of which can also be attributable to variations in the generated shock wave. Slightly higher variability is observed on the following peaks (up to 10%) and rest of the ICP histories. Overall the repeatability was considered excellent.

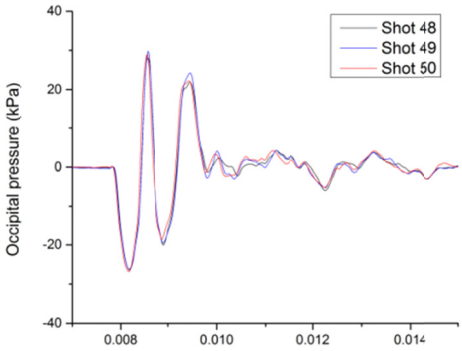

Figure 9*, Example of filtered occipital ICP signals from three different tests using the same loading conditions*

3.4 PMHS-BI^{2}PED ICP comparison

Frontal, parietal and occipital ICP signals were compared with the original PMHS study for both parallel and perpendicular orientation and for all three incident pressure levels. The focus of the analysis in the current article was to put on the occipital since the sensor final position in the BI^{2}PED was the closest to the same sensor location in the PMHS. In general, frontal ICP measurements were similar in shape but significantly lower than in the PMHS. This was expected considering that the

BI^{2}PED frontal sensors were considerably more distant from the skull surface (see Table 2). Parietal ICP showed a level of correlation to the PMHS that was close to that of the occipital ICPs.

3.4.1 Parallel orientation – Occipital region ICP

The direct comparison of occipital ICPs for parallel shocks of 85 kPa, 120 kPa and 140 kPa peak incident overpressure is shown in Figure 10. The ICP histories are plotted over the first 8 ms of signals, which was the timeframe where most of the ICP variations were observed and where the positive and negative peaks were measured.

The signals indicate that the brain material is first loaded in tension and then oscillates between phases of compression and tension at a noticeably specific frequency. The development of tensile stresses in the rear portion of the brain following shock loading of the front surface of the skull (coup-contre-coup injury) has been reported in the literature already [7-9]. This phenomenon has been attributed to the compressive wave initiated at the front of the skull which is reflected off as a tensile wave at the back skull free surface. Because stress waves travel faster in the skull than in the brain, this tensile wave can be transmitted to the back of the brain before the initial compressive wave transmitted from the front reaches the back. Based on skull strain measurements at various locations, the original PMHS study already suggested that there was a direct correlation between skull strain and ICP history in the brain [10]. It is important to understand that stresses in the skull can travel forth and back before the external blast wave even reach the back of the head. The specific frequency of oscillation that is observed is likely linked to a natural frequency of the skull itself. Since these oscillations are not seen in the exterior transient pressure history, they are the result of internal wave activities. The ICP variations due to relative brain-skull motion would occur on a longer time frame since it is a lower frequency phenomenon [2-4]. It is interesting to note that the first compressive phase following the initial tensile phase is of a higher magnitude in every signal. This could be due to the shock in air reaching the back of the head at the same time as the skull back face is unloaded (after approximately 0.4 ms).

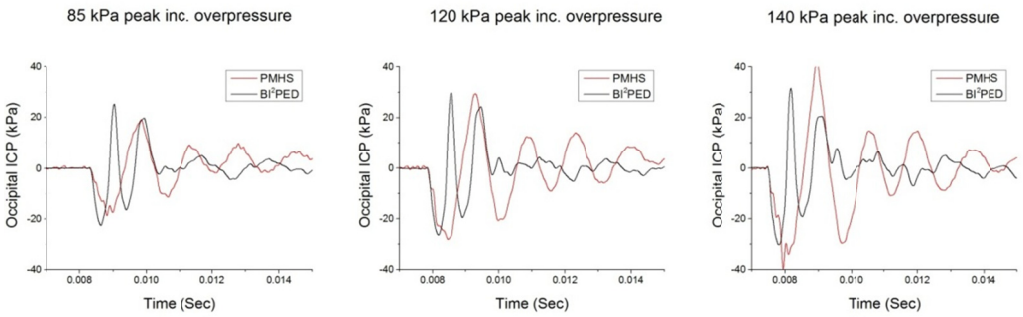

***Figure 10** , Direct comparison of intra-cranial pressure history between PMHS and BI^{2}PED headform for a parallel exposures to different overpressure level.*

In terms of ICP magnitude, the BI^{2}PED response was in very good agreement with the original PMHS results over the three tested blast severities. The increase in blast incident peak overpressure generated an increase in BI^{2}PED ICPs that was very similar to the PMHS. The main discrepancy between the two models was on the main oscillation frequency and on the damping of that oscillation. The BI^{2}PED appears to have a stiffer response than the PMHS, oscillating at a higher frequency and for a shorter period of time. Figure 11 shows the Fast Fourier Transform of the ICP signals for the 85 kPa shock. This plot confirmed the origin of the difference in the response of both models. The PMHS shows a diffuse resonance peak around 700 Hz whereas the BI^{2}PED has a similar diffuse resonance peak around 1100-1200 Hz. Frequency content around between 50-200 Hz, responsible for the ICP fluctuations over longer intervals, also

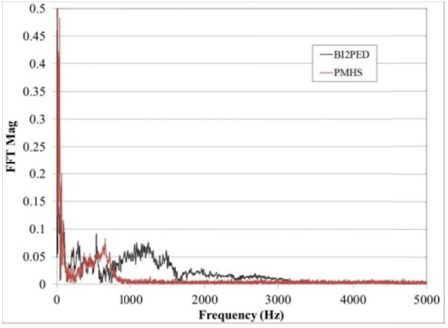

***Figure 11:** Direct comparison of the occipital ICP FFT between PMHS and BI^{2}PED headform for a parallel exposure to a 85 kPa shock.*

showed some discrepancies. In particular, a lower oscillatory fluctuation was observed over a much longer time scale in the time domain in the original PMHS results. This fluctuation occurred at approximately 50 Hz and was not seen with the BI^{2}PED headform. These low frequency fluctuations are likely attributable to a more global motion of the head or to relative brain-skull movement. Therefore, they are inevitably influenced by the head mounting technique and the disarticulation of the PMHS head from the body. These motions are most probably not representative of a realistic response. The fact that this was not observed on the BI^{2}PED could simply indicate that it was more strongly tighten in the net. More so, the BI^{2}PED brain is not expected to move in a biofidelic fashion yet since it is not attached to any spine-like structure in the cranial cavity. Its movement is only limited by the CSF and the flax and tentorium membrane.

The diffuse 700 Hz resonant frequency observed on the PMHS is in accordance with the work of Willinger [2,3] which associated the response of the head to high velocity loading to local skull deformations (i.e skull flexure, direct stress transmission) rather than to relative skull-brain motion or to global head response. The higher resonance frequency in the BI^{2}PED suggests that the skull assembly is slightly too stiff. The magnitude of the ICP being similar, it is likely that the material itself is a good match for skull material. However, the homogeneous geometry of the BI^{2}PED skull also influences its stiffness. Indeed, the human skull is not a homogenous structure. The different bones and sutures surely affect the local and global structural response. Nevertheless, a study on the variability of this second resonance frequency should be considered before trying to match it too precisely with a physical model. The present comparison is based on a very limited amount of PMHS and the BI^{2}PED response may fall within the scatter of a larger population response.

3.4.2 Perpendicular orientation – Occipital region ICP

Occipital ICP comparisons for perpendicular shocks of 85, 120 and 140 kPa peak incident overpressure are shown in Figure 12. The ICP histories were again plotted over 8 ms. Contrarily to the parallel shock, the results show that the right occipital region is now first loaded in compression before oscillating between phases of tension and compression at a specific frequency. The initial compression phase is expected since the right side of the head is exposed first to the shock and the ICP sensors are casted in the right hemisphere. Very rapid compressive loading on one side of the skull generates local deformations which loads the brain region directly underneath in compression. This emphasizes how the brain stress state following exposure to a blast is sensitive to orientation. The ICP increase caused by increasing blast severity is similar to what was seen in the parallel orientation.

A level of correlation between PHMS and BI^{2}PED similar to the parallel shock is observed in the perpendicular orientation. Peak ICPs are very similar for the three blast severities but the frequency at which ICPs fluctuate is again higher in the headform. While the BI^{2}PED ICPs again show a clear resonance around 1100-1200 Hz, the PMHS ICPs oscillation appeared to occur at a slightly lower frequency (500 Hz) than in the parallel orientation (700 Hz). In the original PMHS study, it was observed that damped harmonic oscillations seen in the skull strain signals appeared to be associated with the bone on which the strain gauge was mounted. It was hypothesized that the bones composing the skull may respond quasi-independently of each other and that the localized deformation may drive the stress state in the brain underneath [10]. This would explain the uniform frequency response of the BI^{2}PED, which has a uniform homogenous skull compared to the PHMS.

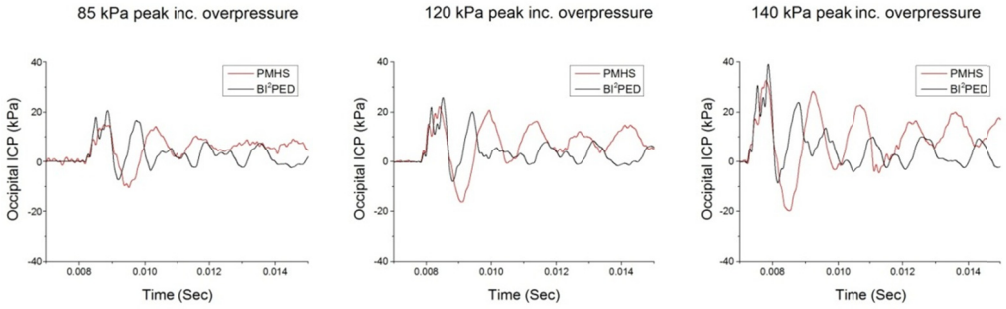

Figure 12*: Direct comparison of intra-cranial pressure history between PMHS and BI^{2}PED headform for perpendicular exposures to different overpressure level.*

4. CONCLUSION

Previously reported PMHS blast tests were methodically replicated using the DRDC Valcartier research center physical head model named BI^{2}PED. The loading conditions, instrumentation type and position as well as head mounting technique were reproduced to ensure that the only difference between the two series of experiments was the use of BI^{2}PED or PMHS. The loading obtained from the blast wave generator was compared to free-field blast loading and it was confirmed that the generator produced relevant loading magnitude and duration for the study of blast-induced TBI. Excellent reproducibility was obtained on the BI^{2}PED intra-cranial pressure measurements. A direct comparison of measured occipital ICP revealed good agreement between the headform and PMHS for three blast intensities (80, 100 and 120 kPa) and two blast orientations (parallel and perpendicular). The ICP magnitudes were particularly close to the PMHS ones, while the frequency of the oscillations was slightly higher in the headform. The BI^{2}PED exhibited specific ICP oscillations around 1000-1200 Hz in both orientations while the PMHS ICP oscillations were respectively around 700 Hz and 500 Hz in the parallel and perpendicular orientations. Based on previous work correlating skull local deformation to early-time ICP variations, these frequencies are linked to the skull natural resonance frequencies. The results suggest that the BI^{2}PED skull assembly may be slightly too stiff compared with the chosen PMHS. The design of the BI^{2}PED skull could be refined but matching its response of a very limited amount of PMHS specimen should be avoided and a survey on the variability of human skull modal response should be done first. There were a few discrepancies on the longer duration ICP variations. However, those variations are not believed to be representative of real human response since the head is no longer attached to the neck and body. The neck provides a compliance that is very different from the soft net in which the heads were mounted for the tests. Lower frequency ICP variations are associated with skull-brain relative motion and head global motion. The BI^{2}PED brain is currently not attached to any spine-like structure in the cranial cavity and its movement is only constrained by the CSF and membranes so it is not currently designed to replicate relative brain-skull relative motion. However, the representative mass and center of gravity of the headform should ensure that a representative global motion can be obtained in an ideal test configuration. Overall, the BI^{2}PED was in very good agreement with the PMHS on the early-time ICP variations, which is where the highest pressure peaks are observed. Assuming that blast-induced TBI may be correlated with these early peaks in ICP, the BI^{2}PED would represent a very useful tool to assess the severity of different blast scenarios and help with the performance evaluation of protective headwear systems.

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