FFI-RAPPORT

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Influence of helmet on blast propagation into the brain

literature survey

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Summary

It has been known for a long time that blast waves can cause brain damage to military personnel. However, only recently questions have been asked about how helmet use can influence the shock wave propagation into the brain. In this report we review the research that has been performed on this topic. This research has mostly been of experimental and numerical character. In any case, the results are very clear. Assuming that the helmet is padded so that shock waves can not freely propagate into the space between skull and helmet, it is beneficial for soldiers to use helmets. This will lead to a reduction of the pressure amplitude inside the brain, as well as having the advantage of also protecting against other threats.

Sammendrag

Det har vært velkjent i lengre tid at sjokkbølger fra eksplosjoner kan forårsake hjerneskade hos militært personell. Imidlertid er det først relativt nylig at det har blitt stilt spørsmål ved om bruk av hjelm kan ha en dempende eller eventuelt forsterkende effekt på trykkforplantningen inn i hjernen. I denne rapporten gjennomgår vi forskningen som er gjort på dette temaet. Denne er forskningen er hovedsakelig av eksperimentell eller numerisk karakter. Konklusjonen er svært entydig. Forutsatt at hjelmen har polstring som hindrer fri bevegelse av sjokkbølger inn i mellomrommet mellom hodeskalle og hjelm, så er det en klar fordel for soldater å benytte hjelm. Det gir en reduksjon av trykknivået inne i hjernen, samtidig som også hjelmen selvsagt beskytter mot andre trusler.

Content

1 Introduction

Blast waves from explosions can cause serious injury to human organs, including the brain. For example, blast was the leading cause of traumatic brain injury (TBI) in military personnel serving in Iraq and Afghanistan. There are even indications that brain injury can occur at relatively small blast pressure levels, for example during peace time training with heavy weapons or explosives [1].

The problem of brain injury from blast waves is very complex and research is ongoing in the scientific community. Previous research at FFI has contributed to the topic by examining both blast wave propagation into the brain [2,3] and the biological impact of blast waves on brain cells [4].

One of many open questions is how the use of a helmet (and other protection equipment) influences the propagation of the shock wave into the brain. Military helmets have traditionally been optimised and tested against ballistic threats and it is only recently that attention has turned to their effect on blast waves. For example, there have been suggestions that helmets could increase the pressure transfer to the brain, due to an “underwash” effect where the shock wave is trapped and amplified between the skull and helmet.

This report presents no original work, but aims to investigate the current status of research on helmets and blast waves through a literature study. Most of the report therefore presents an overview of the scientific findings before finishing with a summary and some conclusions.

2 Literature review

A literature study was performed for articles involving helmets and blast, using both general web searches and searches in databases of scientific literature. In addition, references from the found scientific papers that seemed relevant were also retrieved. Until quite recently, not a huge amount of work had been performed on this topic, and it seems likely that most relevant papers have been found and examined. In many cases the performed work had a larger scope than only examining how helmets influence the blast waves, but here we only present the results that are relevant for this topic.

The scientific work done on this topic generally falls into two categories: Experimental and Numerical. Due to ethical and legal considerations, the experiments are not performed on live humans. Instead a surrogate, either a dummy made in plastic or similar materials (often the industry standard Hybrid III mannequins) or Post Mortem Human Surrogates (PMHS), an euphemism for dead people, are used. In such experiments, typically sensors are placed either inside the “brain”, or on the skull surface, of the dummy/PMHS and detonations are then performed with and without helmet. Figure 2.1 shows a typical Hybrid III mannequin with and without helmet.

Figure 2.1 Hybrid III dummy with and without helmet. (Pictures from [5]).

The blast is usually generated by detonating an appropriate explosive charge, but it is also possible to obtain an equivalent blast wave using a carefully calibrated shock tube. We will see examples of both approaches.

Numerical simulations, provided that they are correct, enable a better understanding of the physics involving the use of helmets. Numerical tools can used to study exactly how the waves propagate through the helmet and into the brain, as well as to perform sensitivity studies to understand which physical parameters are the most relevant. We shall see that a variety of numerical codes have been used, sometimes more than one code for the same problem.

For clarity, in this report we have separated the experimental and numerical work in two different chapters. In cases where both numerical simulations and experiments have been performed, the relevant results have also been put in separate chapters.

3 Helmets

Helmets are worn in a variety of situations and their function is primarily to protect the head from injuries. The helmet design varies according to the most likely threat from a given situation. For example, a bicycle helmet is made to protect against blunt impact from a cycling accident, whereas a military helmet is meant to stop projectiles or fragments from penetrating.

Practical considerations are especially important in helmet design. Ideally, the helmet should be as lightweight as possible while still providing the necessary protection. A helmet weighing several tons will be of little benefit to the user, despite providing excellent ballistic protection. In the middle ages military helmets were made of metal and were heavy, whereas advances in material technology means that today lightweight synthetic materials are typically used instead.

One common helmet is the Personnel Armor System for Ground Troops (PASGT) helmet, which was developed after the Vietnam War in 1975 and replaced the steel M1 helmet in U.S. military service during the 1980s. (Actually PASGT refers to a complete system of helmet and vest). It was first employed by the U.S. military in 1985 and eventually adopted by many other military and law enforcement agencies internationally, sometimes with minor modifications. The shell is made from 19 layers of Kevlar and weighs from 1.41 kg (extra small) to 1.91 kg (extra large).

For the US Marines the PASGT helmet was eventually replaced by the Lightweight Helmet (LWH), which was introduced in 2003, whereas the US Army and several other countries currently use the Advanced Combat Helmet (ACH). An ACH helmet (Figure 3.1) consists of a 7.8 mm-thick outer composite shell based on lower content phenolic resin reinforced with higher-strength Kevlar 129 fibers and a set of discrete foam pads strategically placed on the interior helmet surface. The ACH weighs approximately 1.36 kg (medium size), 1.47 kg (large size) and around 1.63 kg for the extra large version [5]. The ACH, including padding is shown in Figure 3.1.

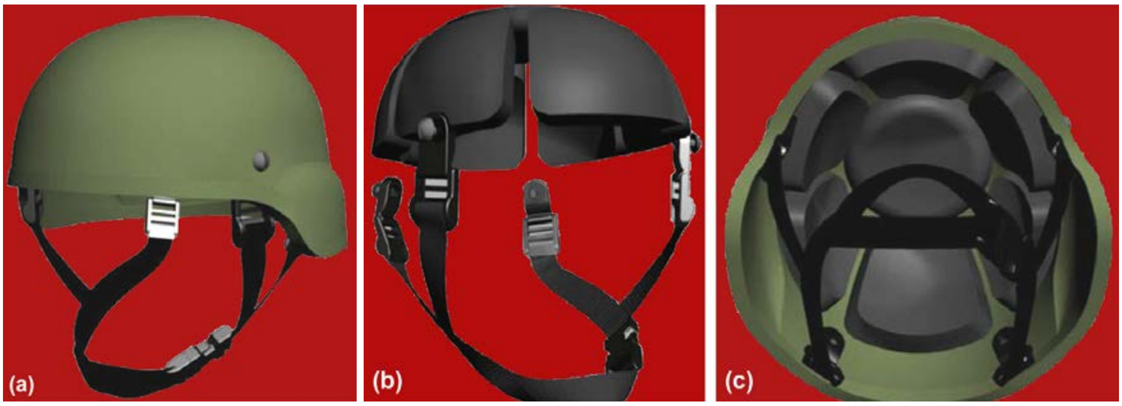

Figure 3.1 Advanced Combat Helmet (ACH) and components (from [6]).

Both the ACH and LWH are planned to be replaced by the Enhanced Combat Helmet (ECH), which is made of an ultra-high-molecular-weight polyethylene material instead of ballistic fibers. The ECH's profile is very similar to the Advanced Combat Helmet but is thicker.

The Norwegian military has traditionally used the Norwegian produced “Cato helmet”, but has recently purchased the FAST HB26 helmets from Ops-Core [7]. The new helmet is made of hybrid composite of Carbon, Uni-directional Polyethylene, and Woven Aramid [8].

4 Experimental studies

In this chapter we will review the available experimental studies on helmets and blast from the scientific literature. This will be followed by relevant numerical studies on the same topic in the next chapter. Since the studies are mostly independent of each other, they will be presented in chronological order.

4.1 Mott et al. (2008)

The first study on helmets and blast (at least which we are aware of) was published by Mott et al. [5] in 2008. While their study was both experimental and numerical, only the experimental part provided relevant results for comparing the effect of blast waves with or without helmet.

In their experiments 0.25 kg C4 charges were detonated at a distance of 1 m from the upper torso and head of the Hybrid III dummy, with and without an LWH (padded). Pressure sensors were mounted at the crown, ear, forehead and rear of the dummy’s head and the mannequin was oriented so that the sensors always faced the charge. The experimental set-up is shown in Figure 4.1.

Figure 4.1 The experimental setup of Mott et al. [5].

Their main results are summarized in Figure 4.2, which shows the measured peak pressure for configurations with and without helmet for the various sensors. It is clearly seen that the peak pressure is lower when the helmet is present, in particular for the sensors at the ear and rear of the head.

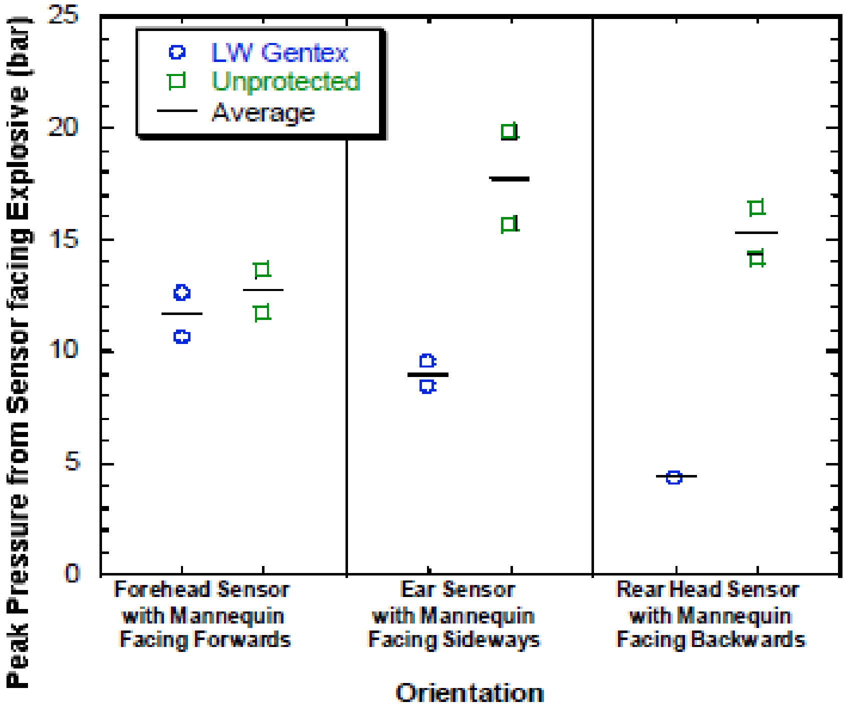

Figure 4.2 Summary of the results of Mott et al. [5]. (Green = Unprotected, Blue = With helmet).

4.2 Rafaels et al. (2010)

Rafaels et al. [9] used both PMHS and a Hybrid III dummy in their study on helmet and blast. Both surrogates were instrumented with pressure transducers and exposed to blast at different orientations, with and without an ACH (padded). In the Hybrid III experiments, pressure gauges were only mounted on the head surface whereas in the PMHS case, sensors were put inside the head at the location of the brain. The blast was generated with a shock tube, using two different pressure conditions: low (p=145 kPa, t=0.66 ms) and moderate (p=228 kPa, t=0.93 ms). The Hybrid III dummy and shock tube is shown in Figure 4.3.

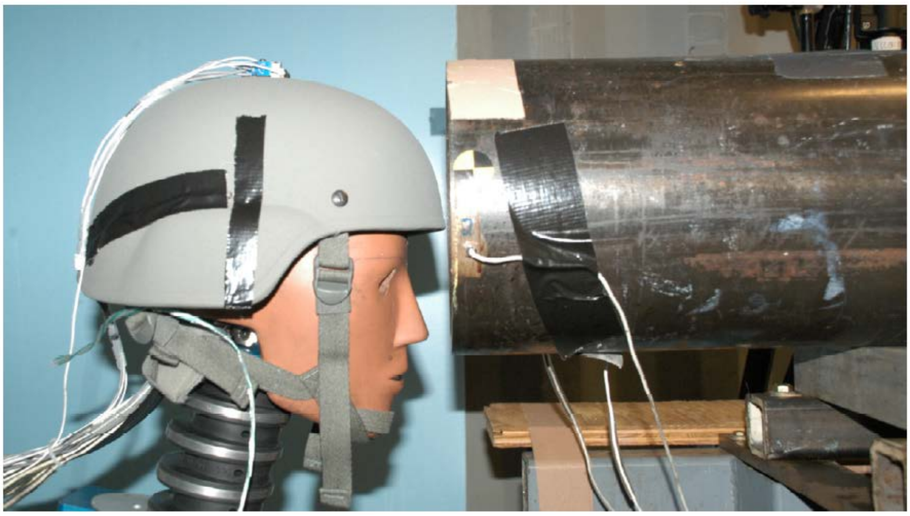

Figure 4.3 Hybrid III mannequin and shock tube in the experiments of Rafaels et al. [9].

For the Hybrid III, pressure amplitudes were seen to be slightly reduced by the helmet. An illustrative example is shown in Figure 4.4, where a sharp and high amplitude peak is transformed into a lower peak but with longer duration.

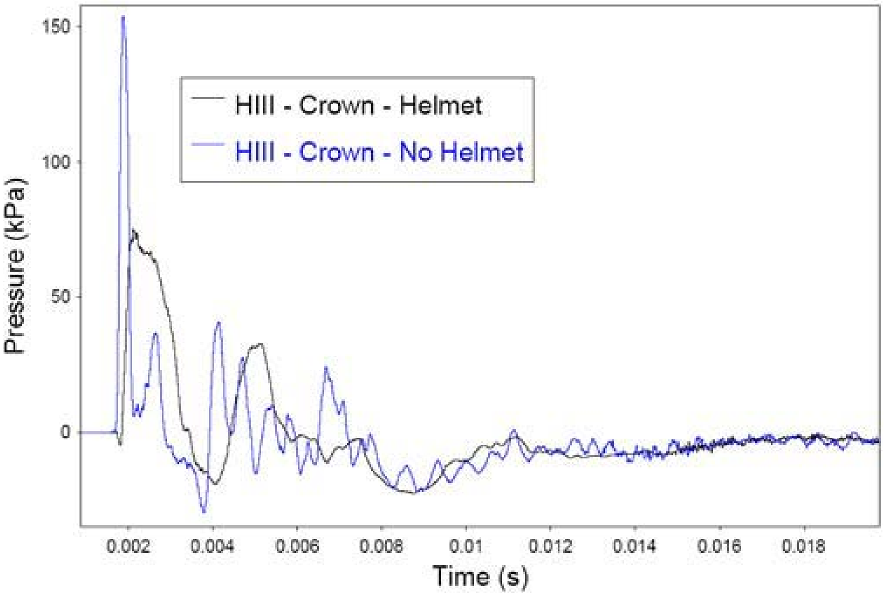

Figure 4.4 Results from [9] for the Hybrid III mannequin.

In the experiments with PMHS, the pressure measurements on the skull surface typically showed little difference for scenarios with and without helmet, although there was some amplitude reduction for the “moderate” shock wave. Measurements inside the brain showed similar behaviour, although there was a small tendency for the helmet to reduce the pressure. This is shown in Figure 4.5.

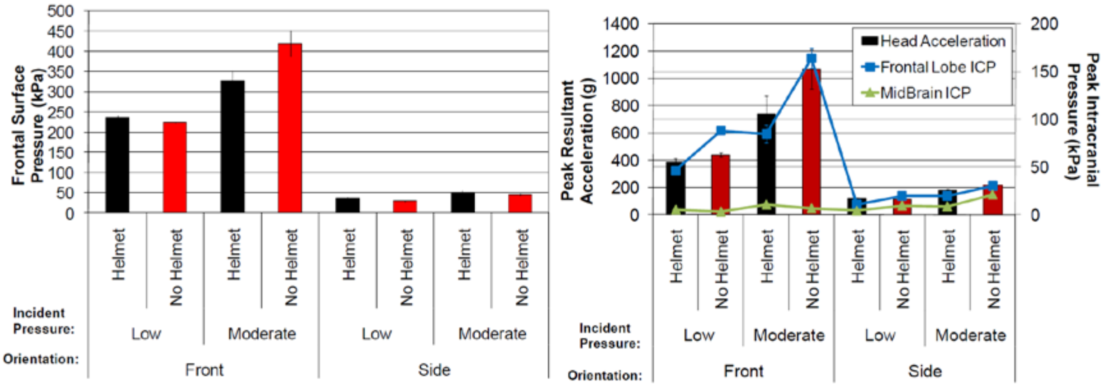

Figure 4.5 Results from Rafaels et al. [9]. Measurements on skull surface (left) and inside the skull (right).

4.3 Merkle et al. (2012)

Merkle et al. [10] used their own Human Surrogate Head Model (HSHM) to investigate the effect of helmet and other protective equipment on shock transmission into the brain. It consisted of a human head (skin, skull, face, brain) and neck, fabricated using biological simulant materials (silicone gel etc). It was exposed to a series of open-field tests with C4 charges of 1.81 kg at 2.3 meters distance. The HSHM and sensor locations are shown in Figure 4.6.

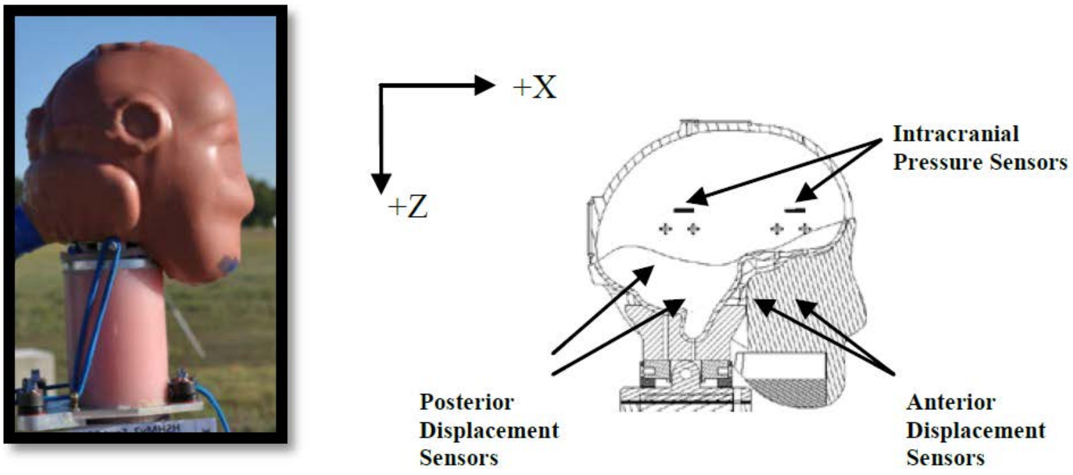

Figure 4.6 Head model of Merkle et al. [10] and sensor locations.

Three different “experimental helmet systems” were tested, all of them with padding included. More precisely, Helmet System A was an experimental multi-component Spectra® shell with foam padding. System B was an experimental system using a single Kevlar shell and foam padding. System C used the helmet from System A with the addition of a pair of double-lens protective goggles.

Some typical results for intracranial pressure measurements as a function of time are shown in Figure 4.7. The results seem to depend on location, but generally for Systems A and B there was little difference compared with an unprotected head. However, System C (including goggles) is clearly seen to decrease the pressure amplitude.

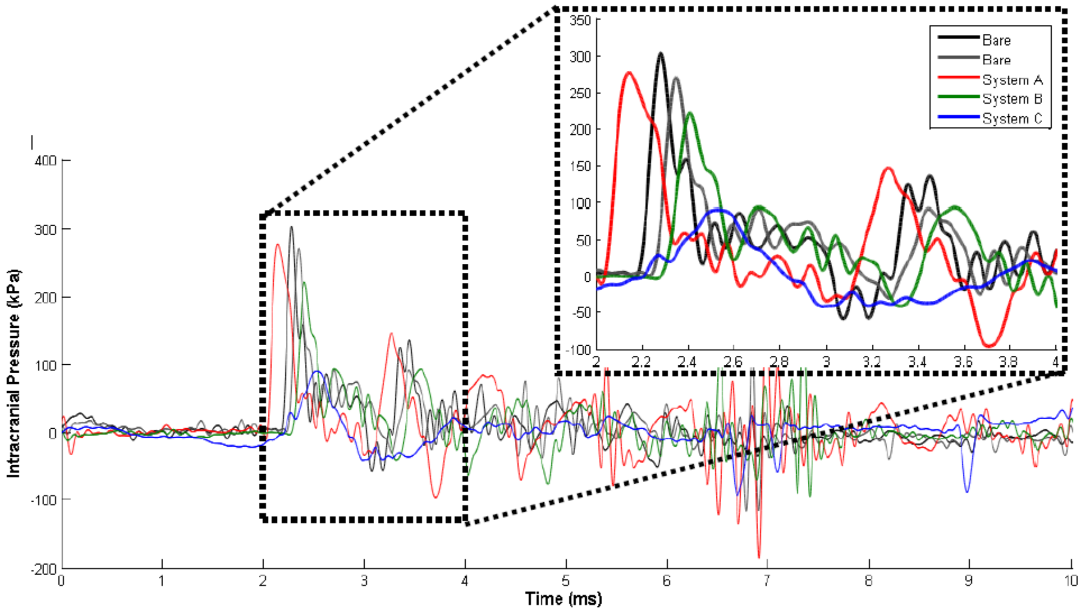

Figure 4.7 Results from Merkle et al. [10].

4.4 Ganpule (2013)

The most comprehensive work on the effect of helmets against blast has been performed by Ganpule [11], including both experiments and numerical simulations. In this chapter we present the experimental results.

Ganpule developed his own dummy, called the Realistic Explosive Dummy (RED) for use in blast experiments with and without helmet. In addition, experiments were performed using a PMHS. Both the PASGT helmet and ACH were studied, but there does not seem to have been any difference in the results between helmets.

A shock tube was used for the experiments. In the RED experiments the incoming amplitude appears to have been 230 kPa. The RED, shock tube and sensor locations are shown in Figure 4.8.

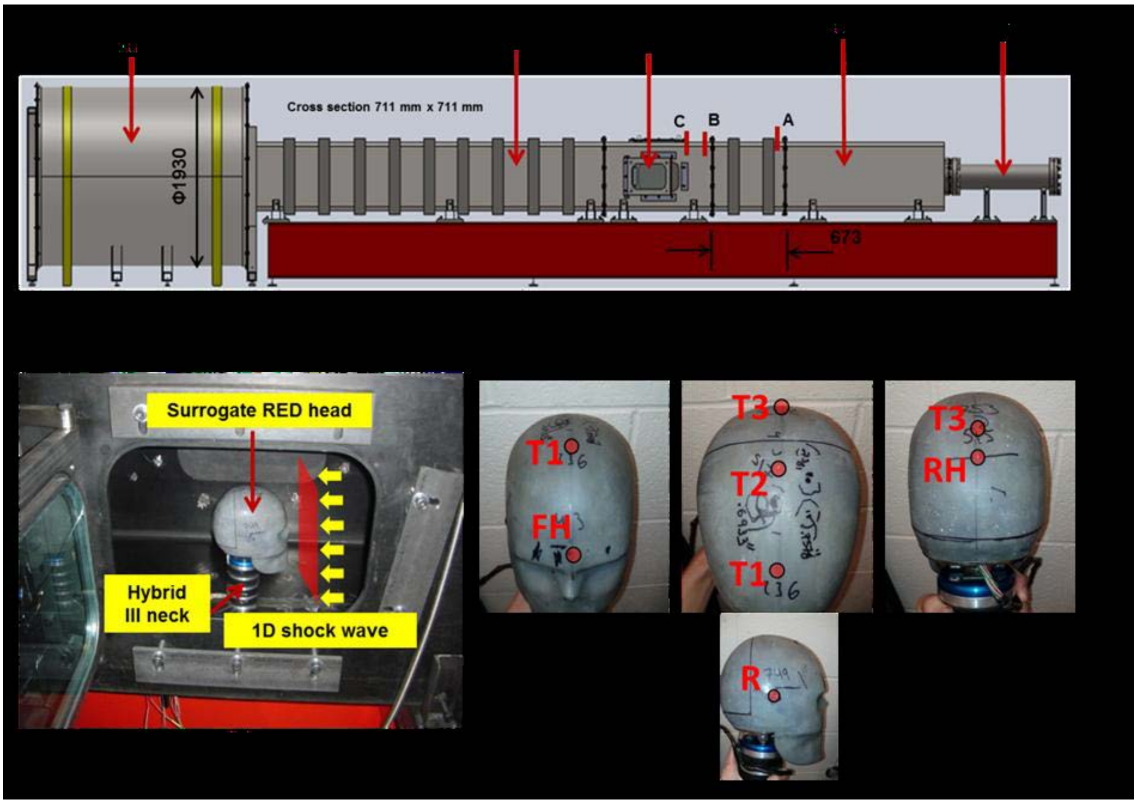

Figure 4.8 Set-up of experiments performed in [11].

Three helmet configurations were considered: no helmet, unpadded (here called “suspension”) helmet and padded helmet. The corresponding pressure measurements are shown in Figure 4.9, from which it is seen quite clearly that the unpadded helmet generally performs the worst. However, the results depend on the location of the sensor and it can not be generally concluded whether an unprotected head or a padded helmet is the best.

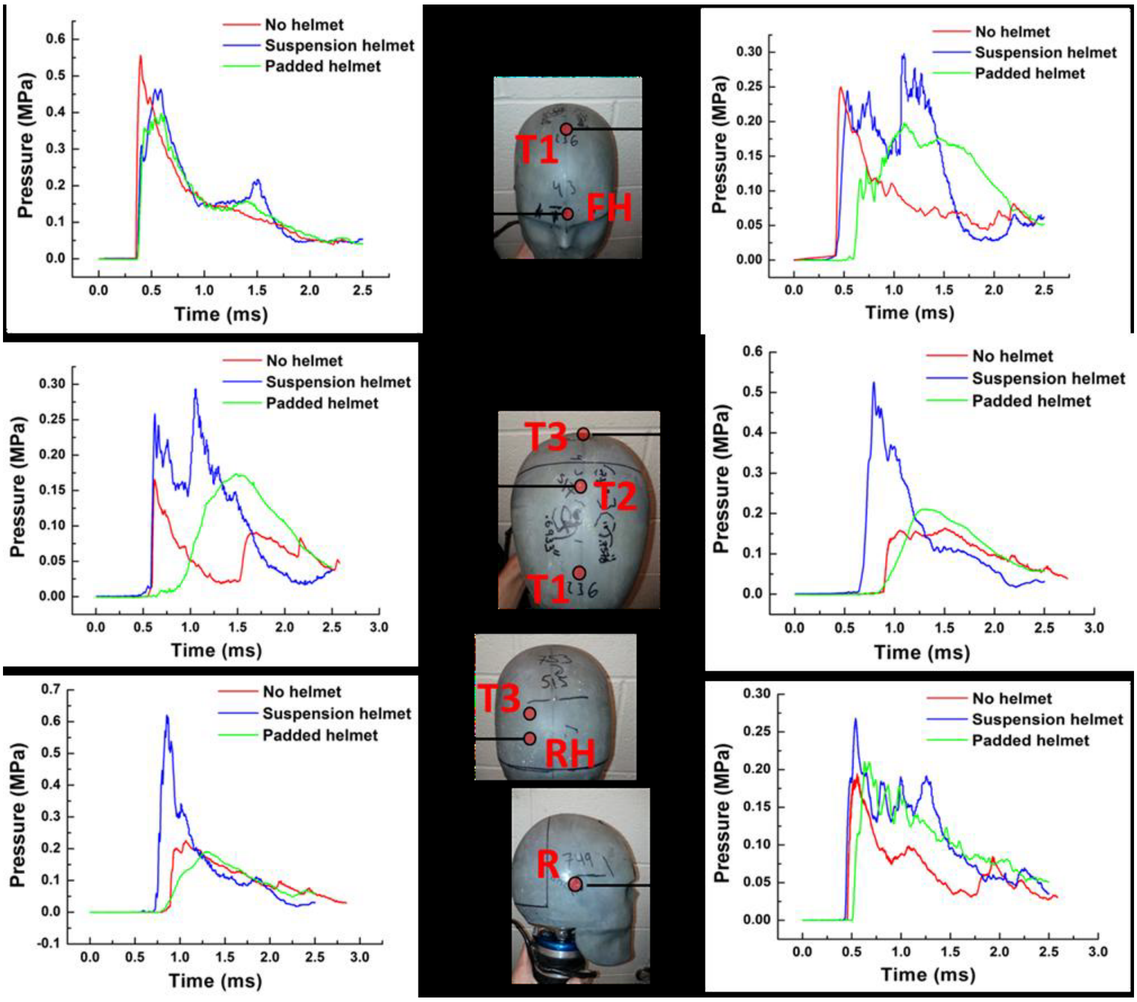

Figure 4.9 Pressure measurements of Ganpule [11]. Comparison between "no helmet", "unpadded helmet" (here called "suspension helmet") and "padded helmet".

In the PMHS experiments the incoming generated blast waves were of amplitudes 70 kPa, 140 kPa and 200 kPa. The human skulls were filled with gelatin and sensors inserted at the locations shown in Figure 4.10.

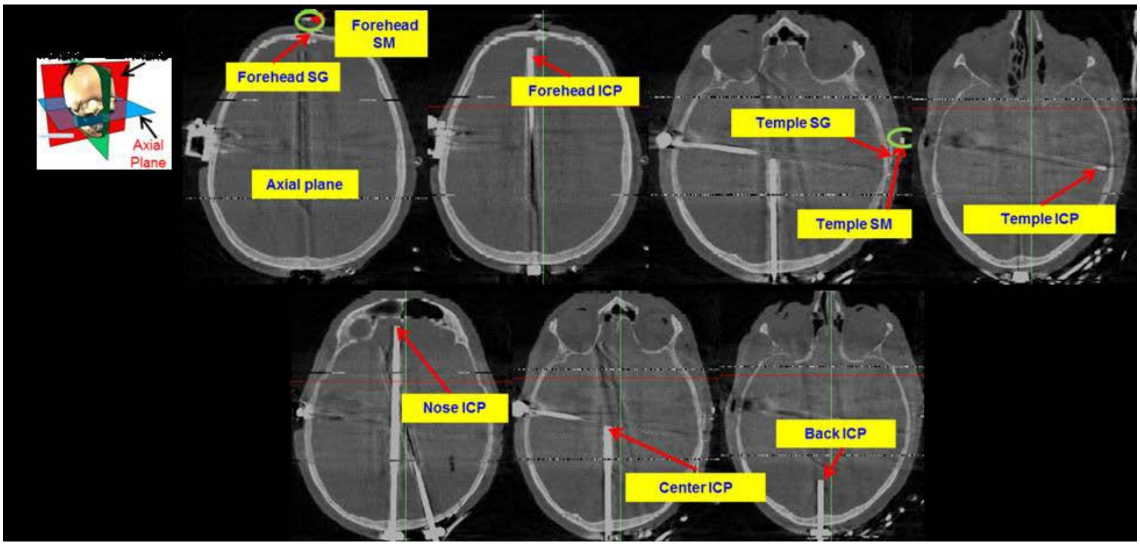

Figure 4.10 Sensor location for PMHS experiments in [11].

Some typical pressure results are shown in Figure 4.11. It is clear that padded helmet performs better than the unpadded helmet in most cases, although there is some variety according to sensor position. However, there is no doubt that a padded helmet is better than no helmet.

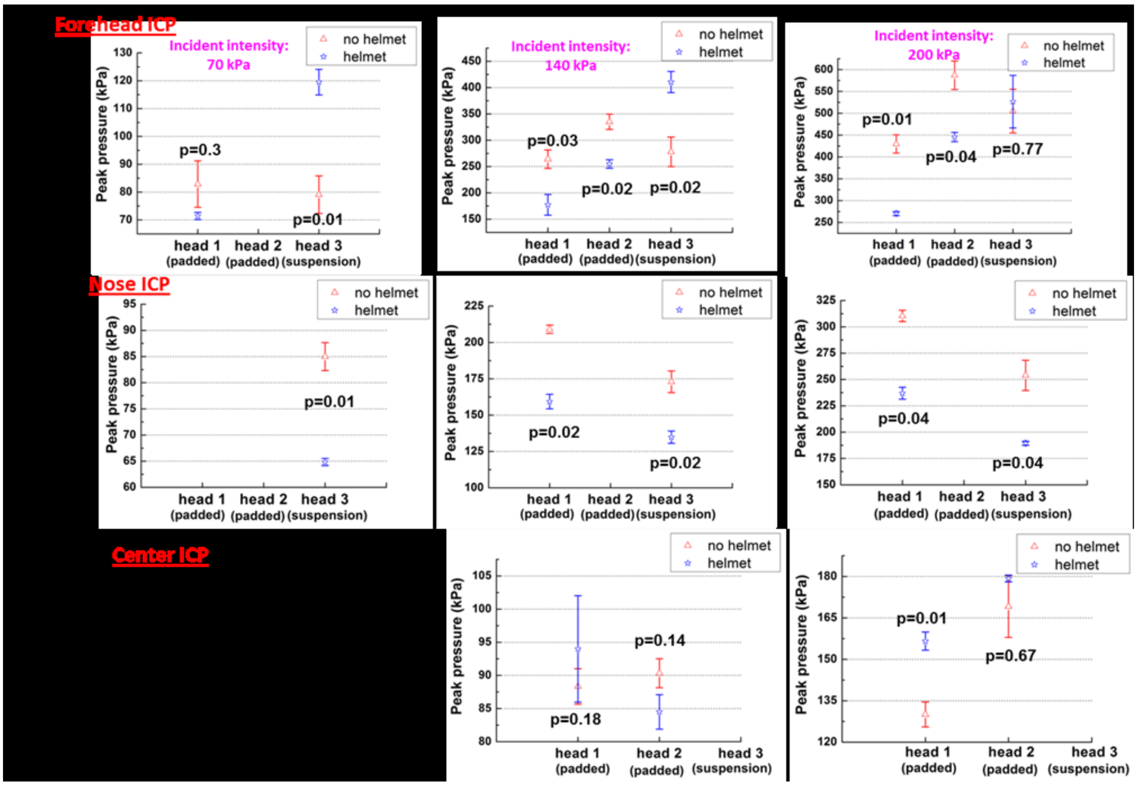

Figure 4.11 Results for PMHS experiments in [11].

4.5 Summary of experimental studies

The results from the experimental studies clearly indicate that wearing an unpadded helmet looks likely to be worse than being unprotected. However, wearing a padded helmet might possibly improve the situation compared to an unprotected head, although the effect does not seem to be very significant. There are also indications that including goggles could improve the situation further.

5 Numerical studies

In this chapter we review the numerical studies which have been performed on the topic of helmets and blast waves, again in chronological order.

5.1 Moss et. al. (2009)

The earliest relevant numerical study, which we are aware of, was performed by Moss et al. [12]. Their main objective was to examine blast wave propagation through the skull and into the brain, but they also included some helmet simulations. For this they used the ALE3D code (an Arbitrary Lagrangian-Eulerian code) with relatively simple generic geometries for both head and helmet. The charge was 2.3 kg C4 at 4.6 meter distance from the head, corresponding to a non-lethal blast. Two helmet cases were studied: padded and unpadded helmet, shown in Figure 5.1.

Unfortunately, no qualitative results are given in the article, but it is stated that without padding the clearance gap between helmet and head leads to an “underwash” effect (Figure 5.2) that amplifies the pressure acting directly on the skull. Without padding this underwash is inhibited, though they warn that it may possibly more strongly couple the helmet motion to the head, which might increase mechanical loads.

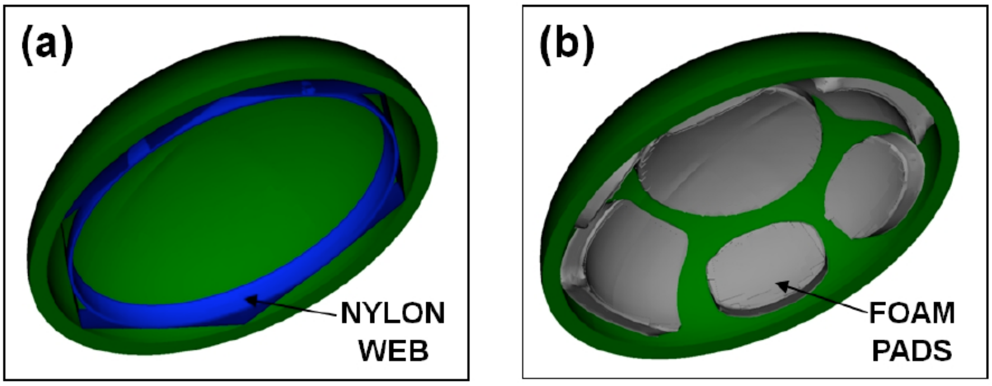

Figure 5.1 Numerical helmet of Moss et. al. [12].

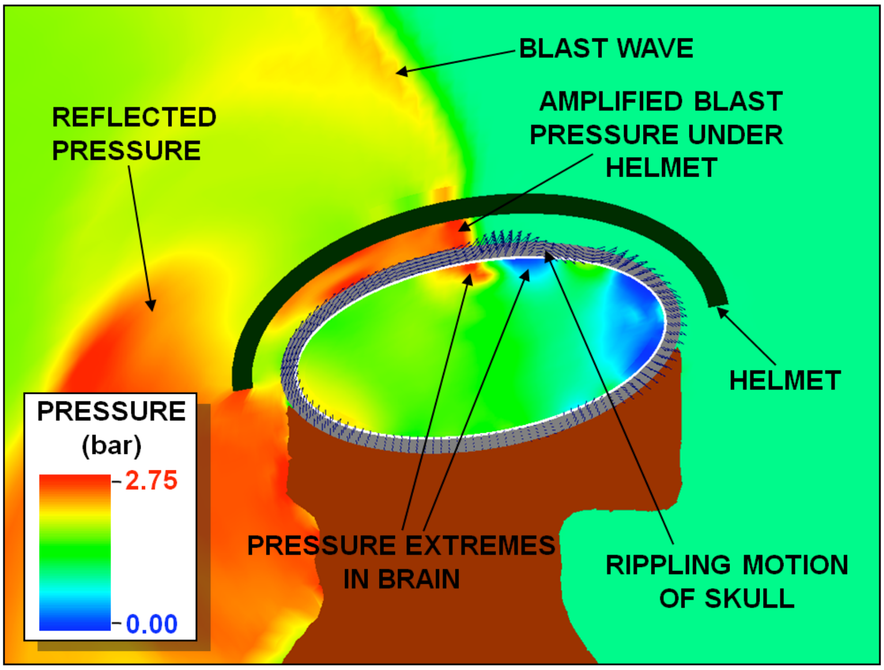

Figure 5.2 Simulation in [12] showing the "underwash" effect for an unpadded helmet.

5.2 Panzer et al. (2010)

Panzer et al. [13] performed 2D-simulations of a head exposed to a blast wave, both unprotected and with an ACH. Their numerical code was LS-DYNA and their setup is shown in Figure 5.3.

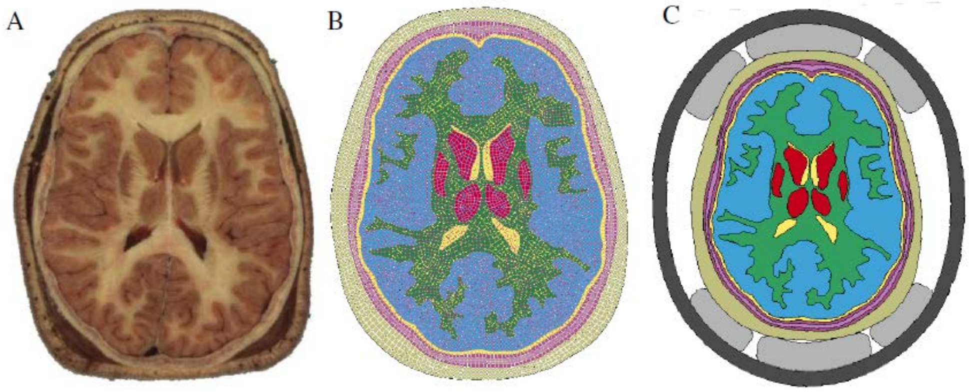

Figure 5.3 Head slice (left), Numerical head model from [13] with and without helmet.

It is very important to note that although the head geometry may look complex, their model is actually in 2D with planar symmetry. This means that the geometry is in no way similar to a real head, and for example, the shock wave can only enter the head by propagating through the helmet. Thus, any “underwash” effect can not be studied using this approach.

A number of simulations were performed with incoming pressure waves corresponding to explosive charges in the range 0.29 kg - 41.8 kg at distances ranging from 1.09 m to 7.65 m. Several different types of padding materials were also examined in each case.

Some of the results are summed up in Figure 5.4, which shows peak brain pressure for the helmet case (different paddings) as a function of peak pressure for an unprotected head. This means that the data points falling below the straight line correspond to reduced pressure when a helmet is worn. We see that most points fall in this category, thus indicating that wearing a helmet is better than being unprotected. However, there seem to be some exceptions for the weakest shock waves. We also see that the type of padding material in the helmet can have a large influence.

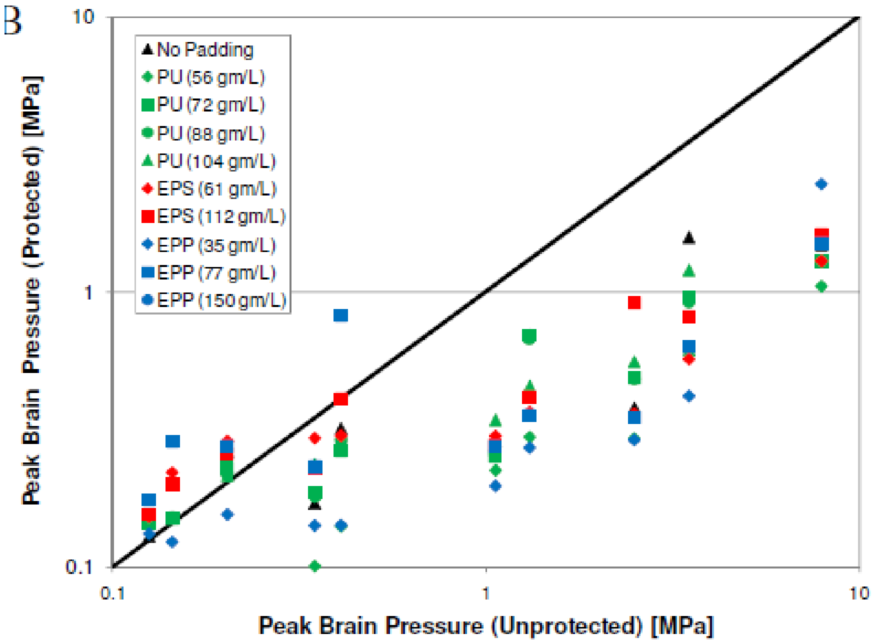

Figure 5.4 Results of Panzer et al. [13].

5.3 Nyein et al. (2010)

In [14], Nyein et al. looked specifically at the ACH using numerical simulations. Their code was “an extension of Virtual Test Facility VTF”, apparently an in-house numerical package at MIT. However, their choice of scenario was quite peculiar: a tiny 3.16 g TNT charge detonated at 12 cm distance. The article does not explain why such a small charge was decided on, only mentioning that the scenario was selected to be above the threshold for blast injury given by the Bowen curves [15].

Three different simulations were performed: unprotected head, head with padded helmet and head with padded helmet and face shield. Their numerical model is shown in Figure 5.5.

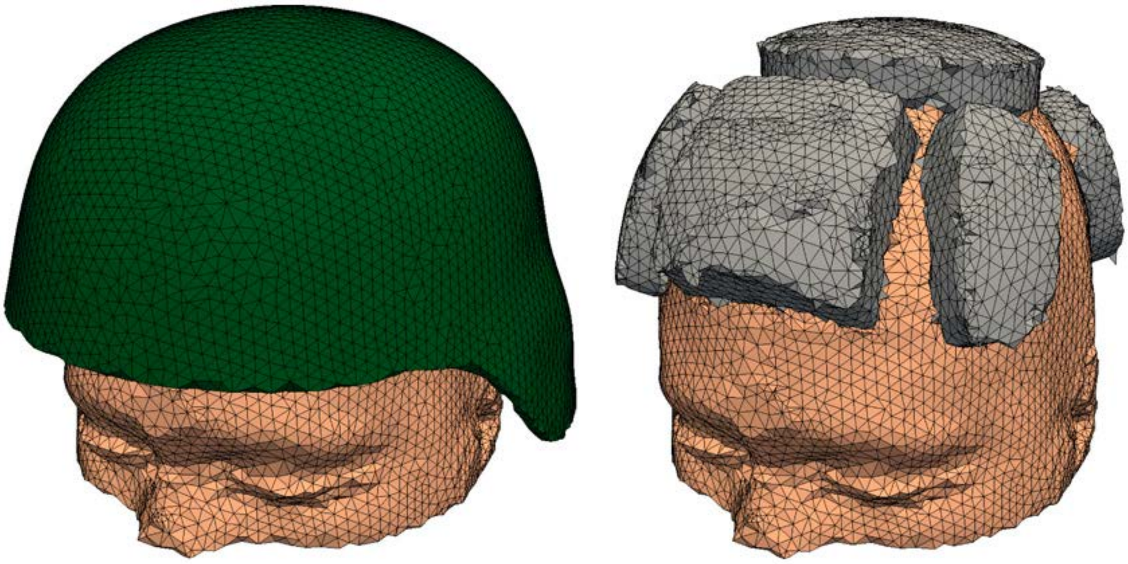

Figure 5.5 Numerical model of Nyein et al. [14], showing ACH helmet model (left) and padding (right).

Numerical sensor gauges were inserted to monitor the pressure at different positions, as shown in Figure 5.6, together with the obtained results. We note that the results depend on location of the gauge. For the two points B and C which are inside the actual brain, it is clear that the maximum pressure amplitude is slightly lower for the case with (padded) helmet than for an unprotected head, although the difference is not very large. However, by far, the biggest pressure reduction is found by including a face shield.

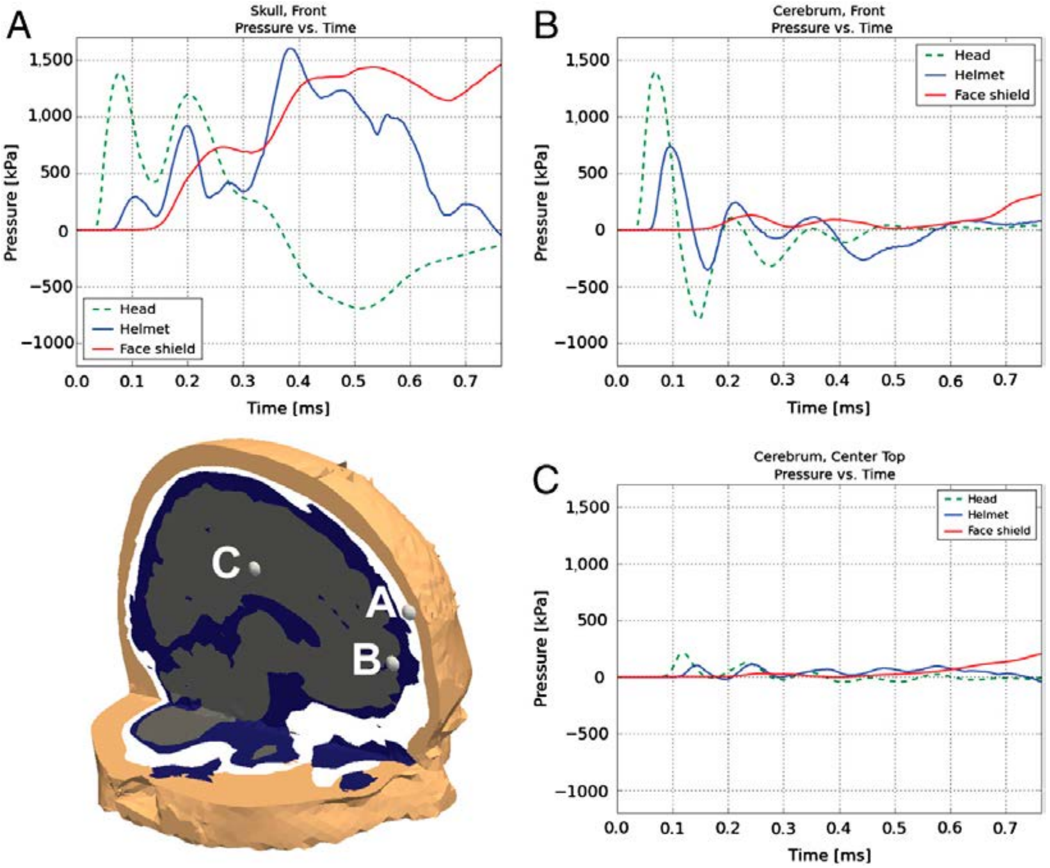

Figure 5.6   Position of numerical gauges and some results from Nyein et. al. [14].

5.3.1 Follow-up on Nyein et al.

The article by Nyein et al. [14] was heavily criticized by Moss et al. in a letter to the journal editor [16] titled “*Distinguishing realistic military blasts from firecrackers in mitigation studies of blast-induced traumatic brain injury*”. Their main objection was that Nyein et al. had used a charge that was too small to be relevant for military applications, something which they claimed might have had an influence on the results. Further, they claimed that, in any case, the results in [14] were nothing new and just confirmed their own previously obtained results in [12], something which had been ignored by Nyein et al.

In another letter to the journal editor [17], Nyein et al. responded to the criticism by Moss et al. in [16]. They claimed that the size of the charge was irrelevant and that a small charge had been used to make it easier to verify the numerical results experimentally at an in-door laboratory. Regarding the second accusation, Nyein claimed that the model in [12] was ignored due to it being allegedly so simplistic in geometry and material models that no conclusions could reasonably be made from it.

5.4 Grujicic et al. (2010)

The numerical study by Grujicic et al. [18] had a slightly different scope than most other studies on helmets and blast waves. Their focus was on how the type of padding material inside the ACH influenced the wave that was ultimately transmitted to the brain, in particular whether the use of polyurea (a class of elastomeric co-polymers) instead of the current elastomeric foam-like material (EVA) would help attenuate the wave.

Their study was performed using Abaqus and the components of their numerical model are shown in Figure 5.7. Two different charge sizes were considered: 6.98 g TNT and 324.0 g TNT at 0.6 m distance.

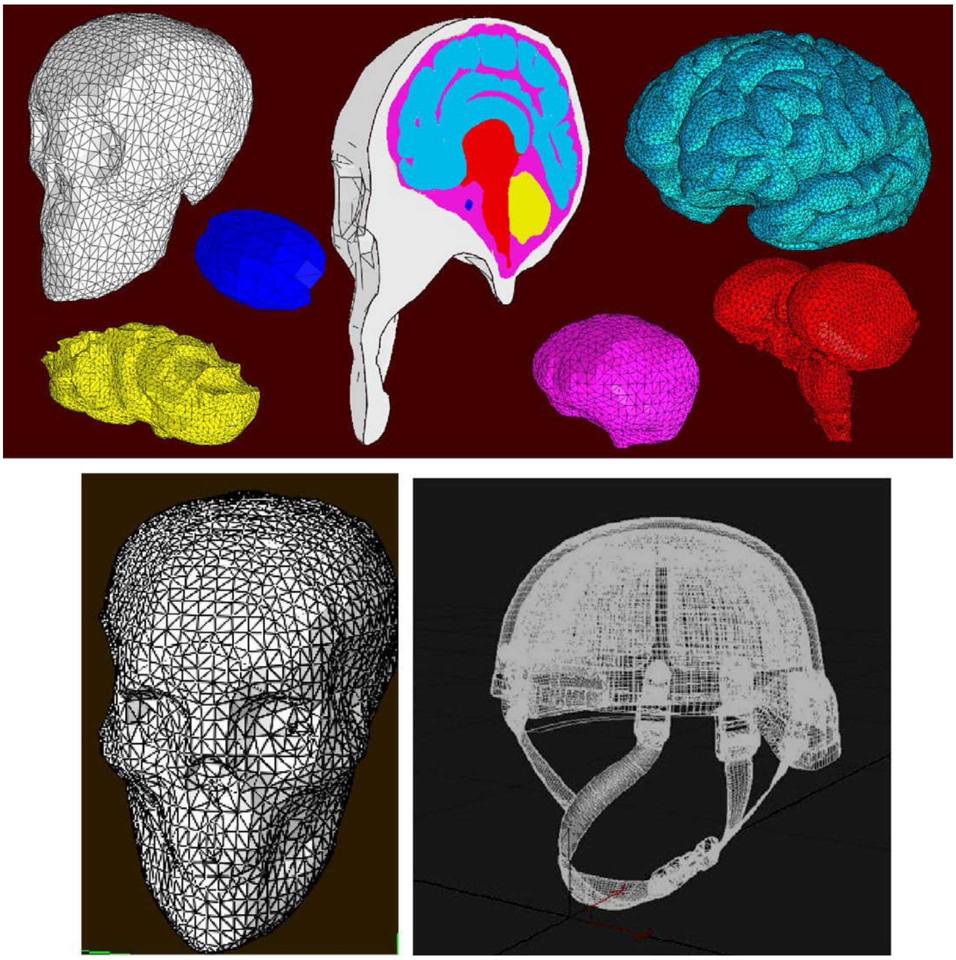

Figure 5.7 Numerical model of Grujicic et al. [18].

Results for stress inside the brain for the two padding materials are shown in Figure 5.8. We note that for the small charge, there was not much difference in amplitude for the padding two materials, whereas for the larger charge the polyurea material gives a substantially lower stress (around a factor of 3). The paper contains an interesting discussion on why the results are dependent on charge size. It is related to the EVA material being very porous and the effect is in fact the same phenomenon explained and discussed in [19].

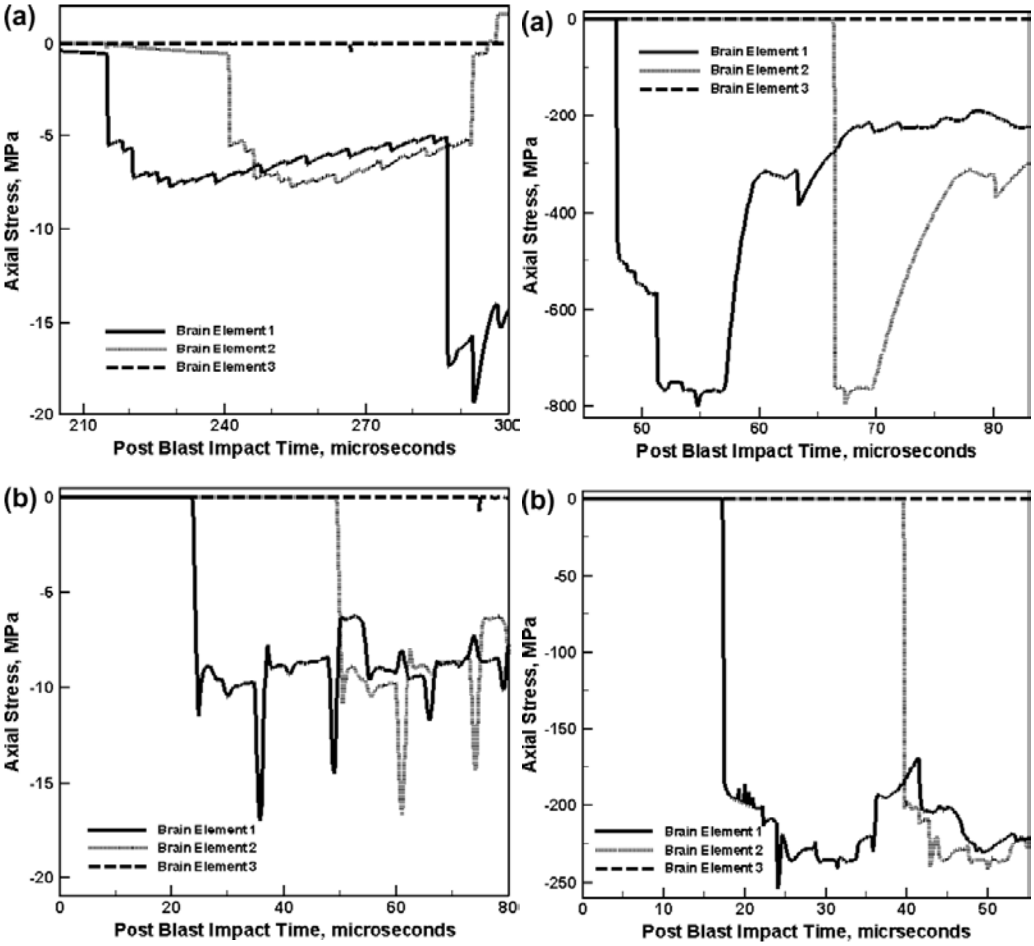

Figure 5.8 Numerical results from Grujicic et al. [18]. New Polyurea (below) and old EVA material (above). Small charge (left column), big charge (right column). (Note the different axis scale in the right column).

5.5 Ganpule et al. (2011)

In [20], Ganpule et al. used Abaqus to numerically examine how wearing an ACH affected the pressure on the skull surface from an incoming shock wave. A shock tube scenario was used with three different loadings of 180 kPa (0.65 ms duration), 350 kPa (duration not given) and 520 kPa (duration not given). Three different geometries were examined: unprotected head, head with unpadded helmet (and various gaps between head and helmet) and padded helmet. The scenario is shown in Figure 5.9.

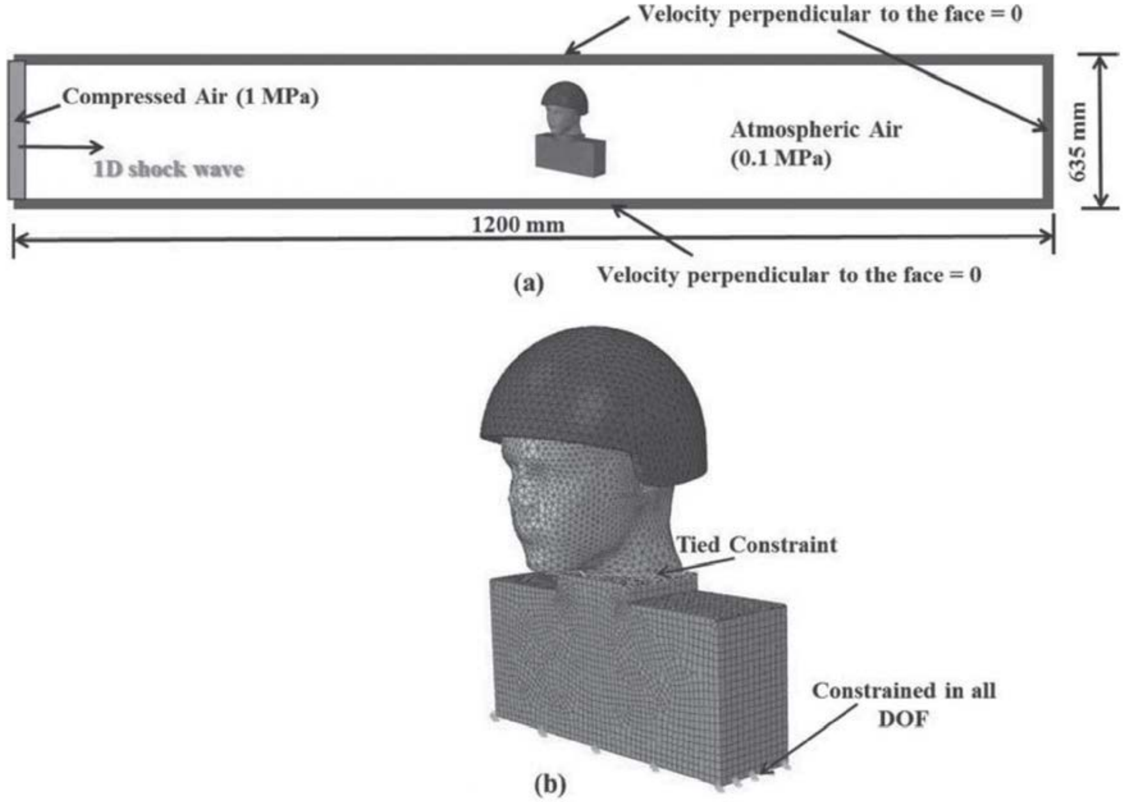

Figure 5.9 Numerical setup of Ganpule et al. [20].

The main results are reproduced in Figure 5.10. It is quite clear that a padded helmet gives the lowest pressure on the skull surface. Further, an unprotected head is actually better than a helmet without padding.

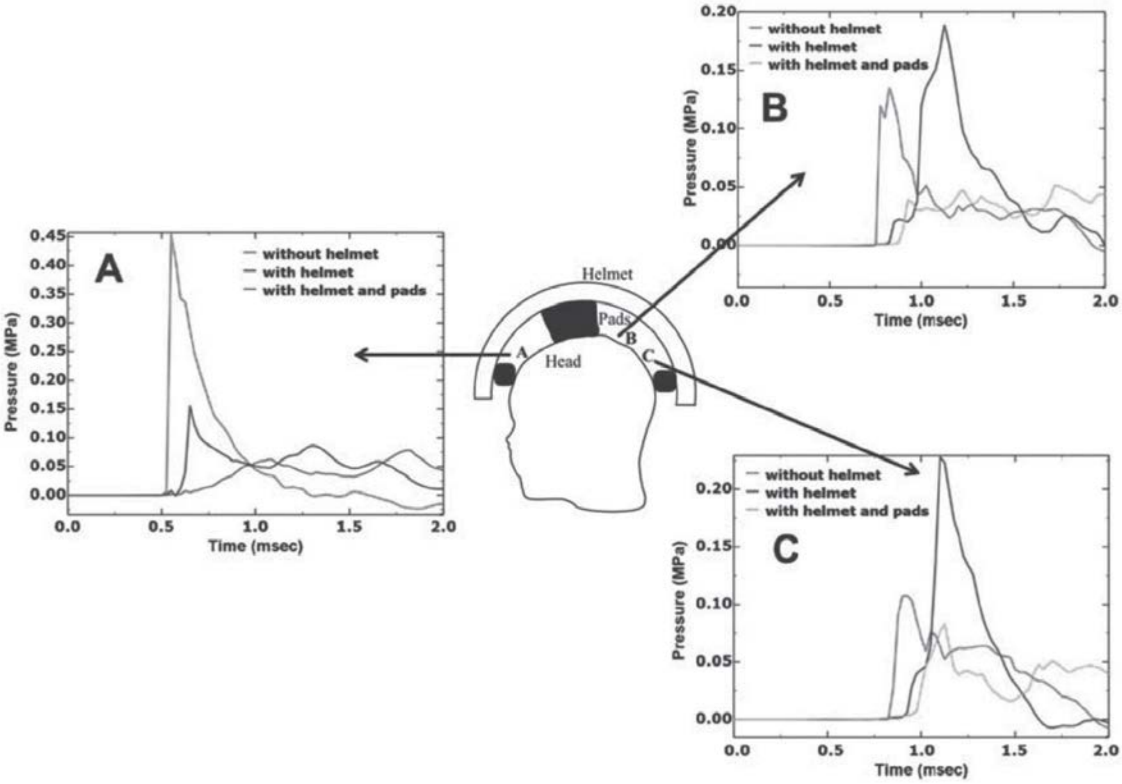

Figure 5.10 Numerical results from Ganpule et al. [20].

5.6 Mott et al. (2012)

In [21], Mott et al. used numerical simulations to expand on their previous experimental work [5], reviewed in Chapter 4.1. Strangely, their paper does not mention which numerical code was used. The study was actually done for two different helmets (LWH and ACH), but the results showed no difference.

In their scenario a 5 kg C4 explosive was detonated at a distance of 3 meters, as shown in Figure 5.11. The geometry of their padding material is shown in Figure 5.12 and was modelled as totally rigid (thus, very different from the padding studied by Grujicic in [18]). The head was also modelled as rigid and pressure inside the brain could therefore not be measured. Pressure was instead logged at many different locations on the skull surface using numerical gauges.

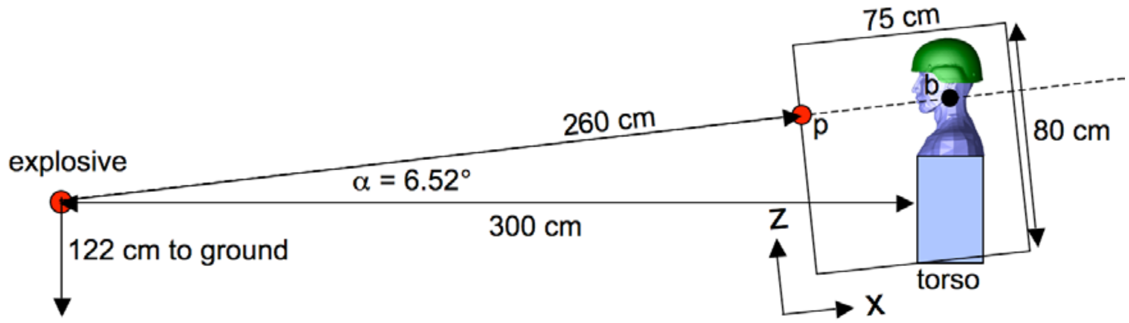

Figure 5.11: Numerical scenario in [21].

Figure 5.12 Padding design used in [21].

Typically the maximum pressure was lower for padded helmets than unpadded helmets, as shown in Figure 5.13 for one gauge point. This is confirmed in Figure 5.14, which shows an overview of the maximum pressure at different locations with and without padding.

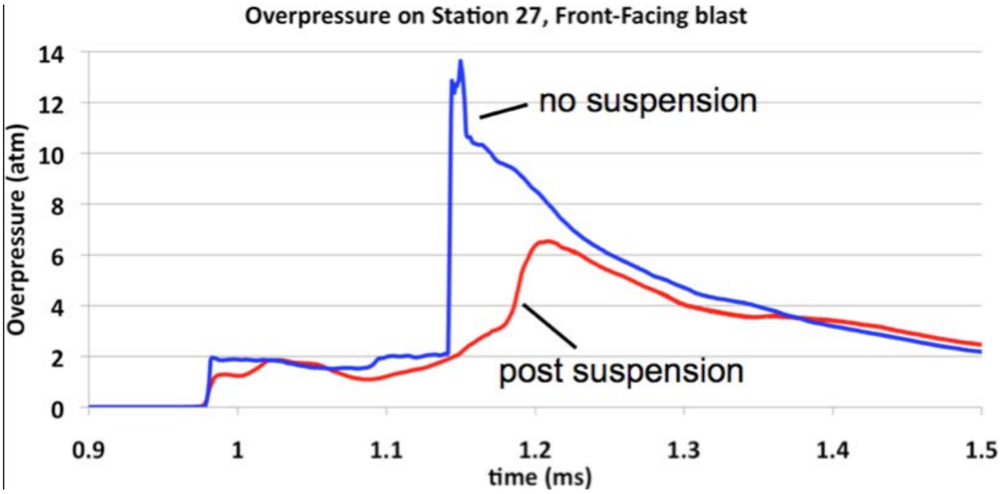

Figure 5.13 Typical results in [21] for helmets with and without padding (here called “suspension”).

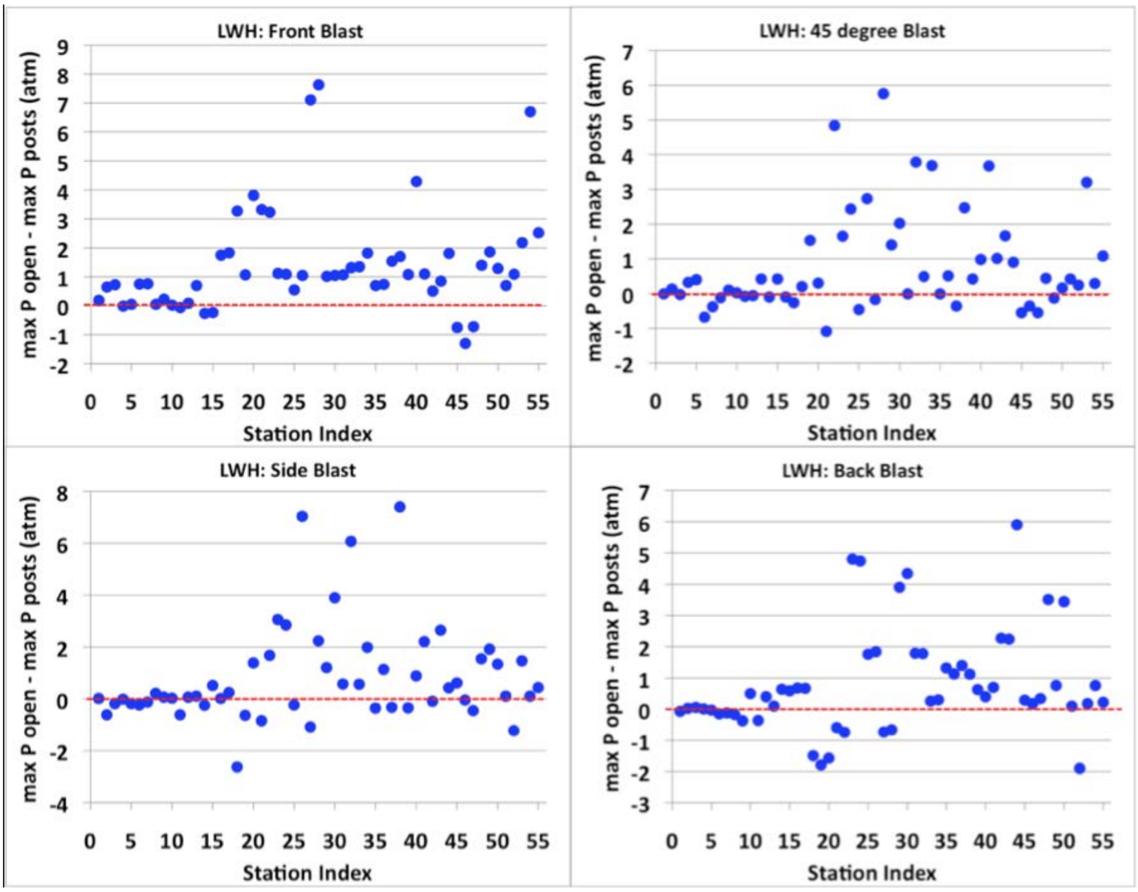

Figure 5.14 Comparison in [21] of maximum pressure at different locations on skull surface for padded and unpadded helmet.

Finally, they added different protective elements to the helmet configuration. The results with regards to pressure are reproduced in Figure 5.15. We note that there might be a slight improvement with added elements, but typically a reduction in pressure in one location seems to lead to an increase in pressure somewhere else.

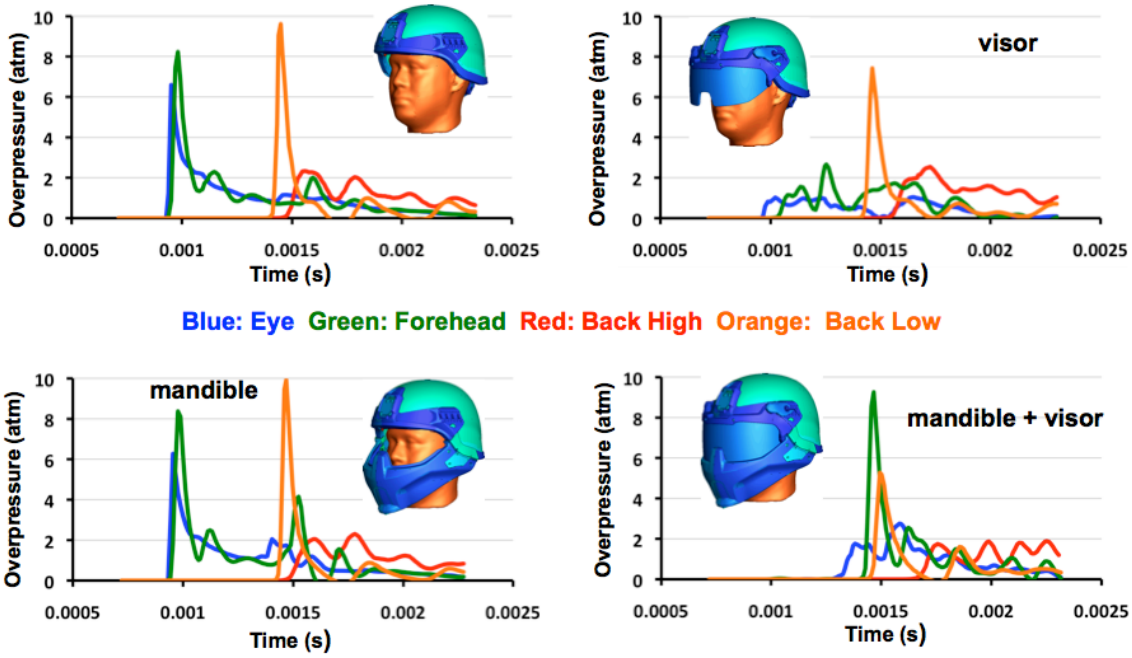

Figure 5.15 Pressure results on skull from [21] with different protective elements added to the helmet configuration.

5.7 Sharma et al. (2013)

Sharma et al. [22] performed numerical simulations on the ACH (padded) using LS-DYNA. For the head geometry they used their own model WSUHIM, shown in Figure 5.16. A total of 15 different materials were used in the head model, which had earlier been validated against the cadavar impact tests of Nahum et al. [23].

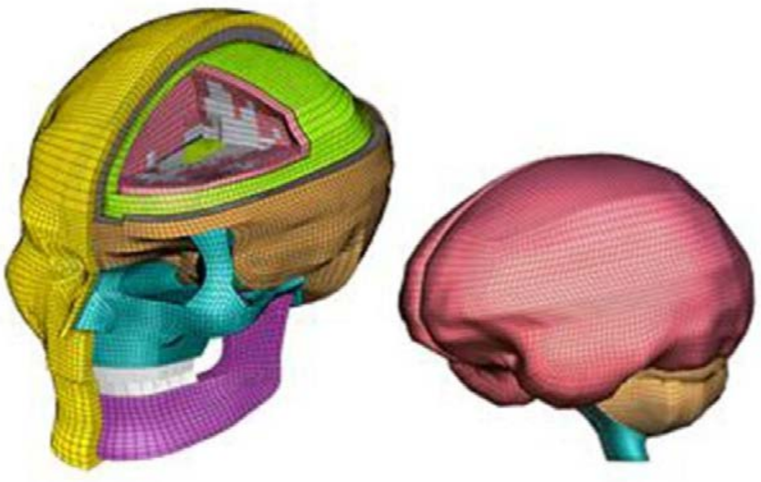

Figure 5.16 Numerical model of Sharma et al. [22].

The head model was placed in a shock tube with incoming shocks of 71 kPa, 170 kPa and 300 kPa (duration not given). Simulations were run with and without padded helmet and the pressure was measured at four different locations inside the brain. The results for different numerical sensors are shown in Figure 5.17 for the 71 kPa incoming shock.

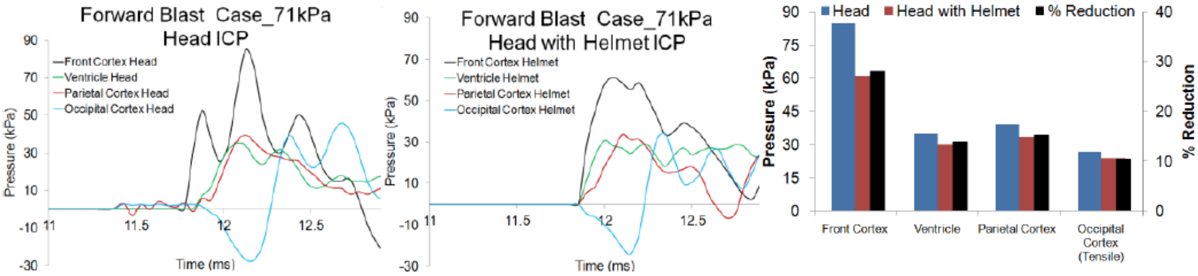

Figure 5.17 Results from [22] for intracranial pressures at different locations inside the brain with and without helmet (71 kPa).

We see that a padded helmet leads to a reduction of the pressure at all the sensor points inside the brain.

The results were similar for all shock strengths, as is summed up in Figure 5.18. The same was also the case if the shock impacted the head sideways.

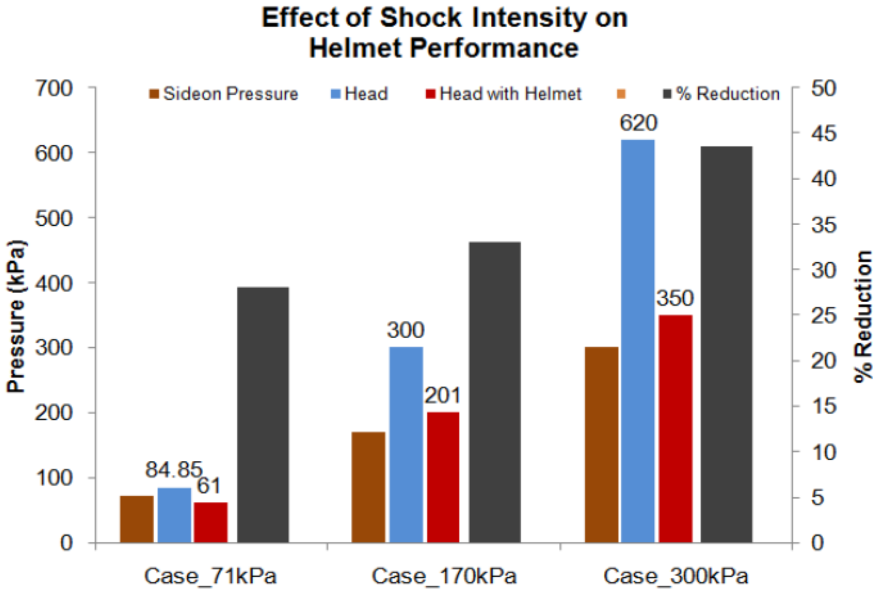

Figure 5.18 Summary of results from Sharma et al. [22].

5.8 Zhang et al. (2013)

Zhang et al. [24] also examined the situation of padded and unpadded helmets interacting with a blast wave. The helmet under study was the ECH (Enhanced Combat Helmet). LS-DYNA was used in the simulations, but the blast wave was not modelled and instead output from Conwep was used as a boundary condition for the pressure on the head/helmet. The padding was modelled using a foam material model. The numerical model is shown in Figure 5.16.

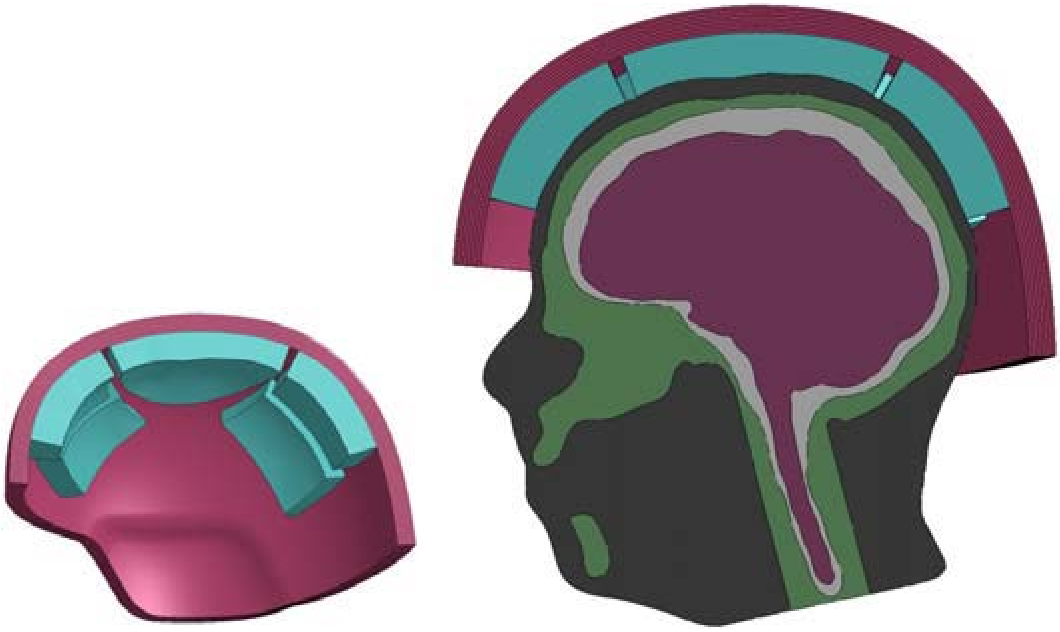

Figure 5.16 Numerical model of Zhang et al. [24].

Their scenario was a charge of 3.2 kg TNT detonated at a distance of 3 meters from the head. Some representative results for pressure on the skull surface are shown in Figure 5.17. We see that the pressure amplitude is much higher without the foam.

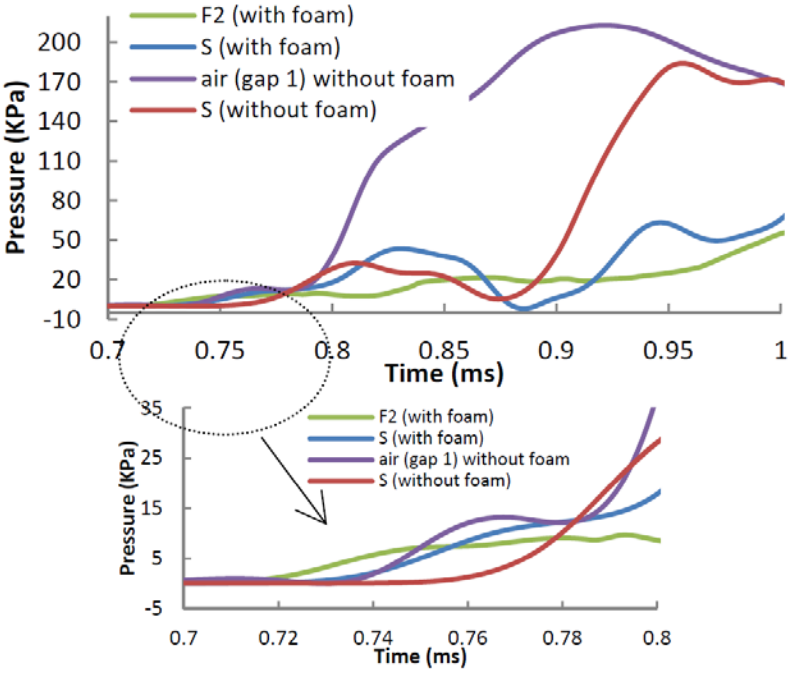

Figure 5.17 Numerical results from Zhang et al. [24]. The Air (gap 1) and F2 sensors are roughly the same location, but F2 are inside the foam and Air (gap 1) is in the air (since no foam).

5.9 Ganpule (2013)

We have already reviewed the experimental results of Ganpule [11] in Chapter 4.4. His PhD thesis also contained several numerical results which are presented here.

Numerical simulations using Abaqus were performed of the experiments described earlier (head in shock tube). The numerical model is shown in Figure 5.18.

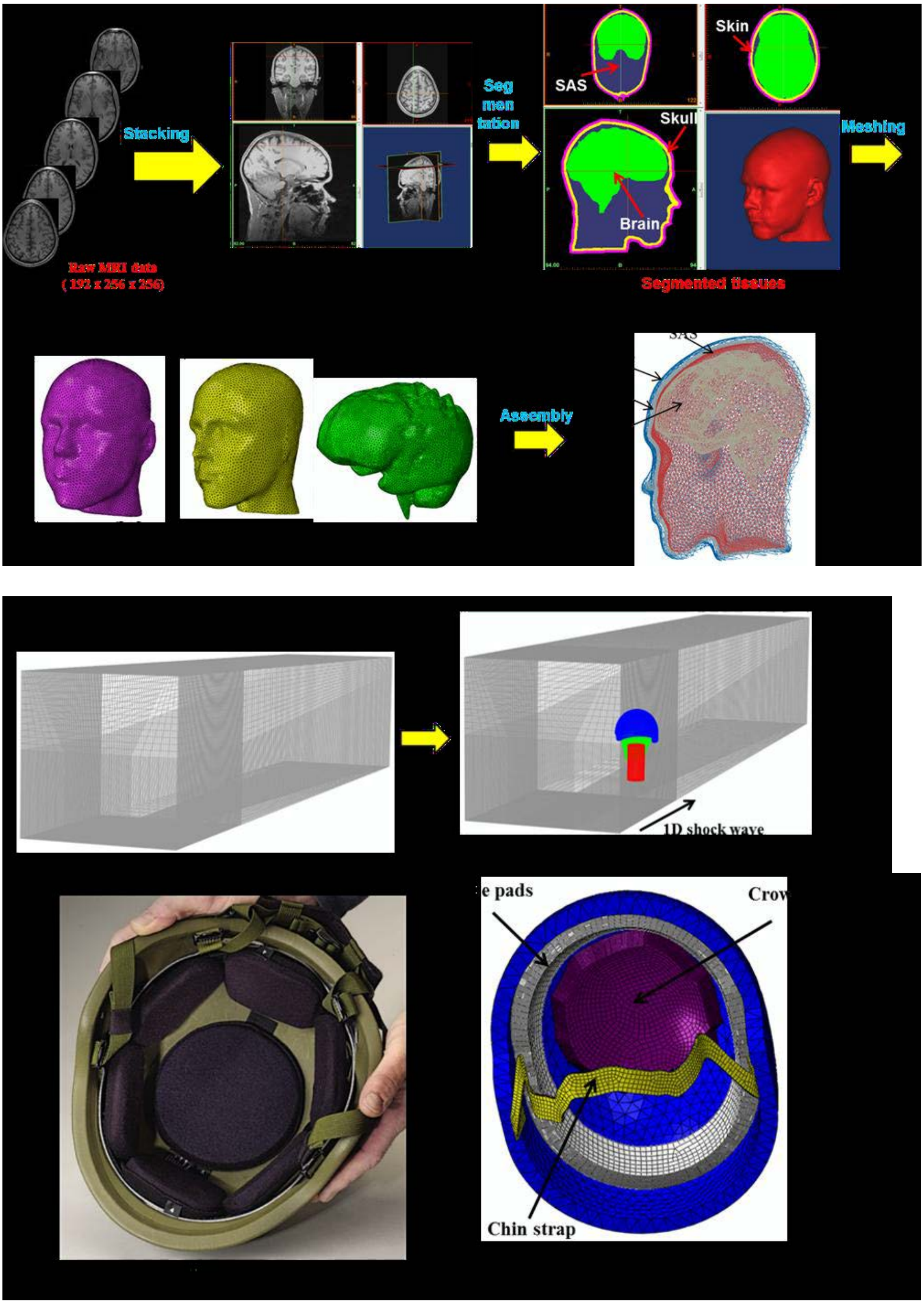

Figure 5.18 Numerical model of Ganpule [11].

The numerical simulations were compared with the experiments both for an unprotected head, unpadded helmet and padded helmet. The results are shown in Figures 5.19-5.21.

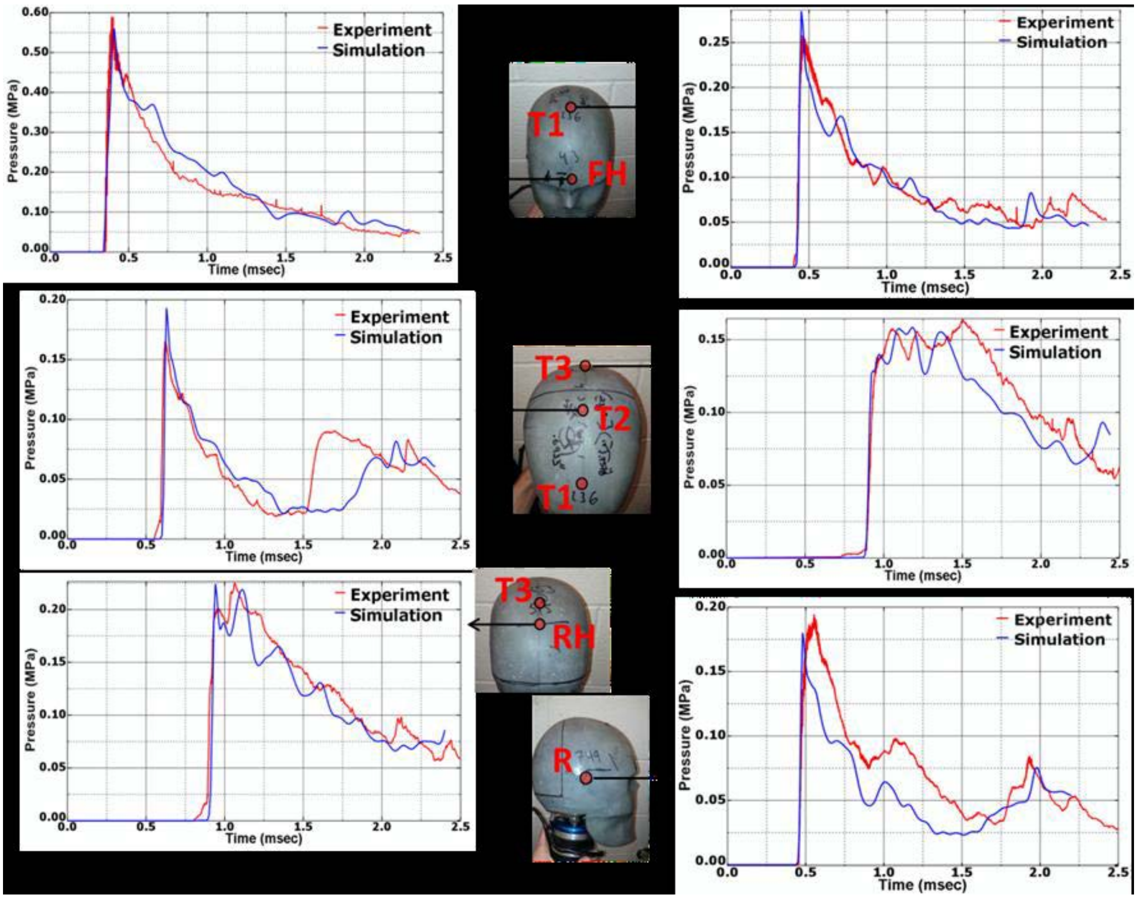

Figure 5.19 Comparison between experiment and simulation for an unprotected head. (Ganpule [11]).

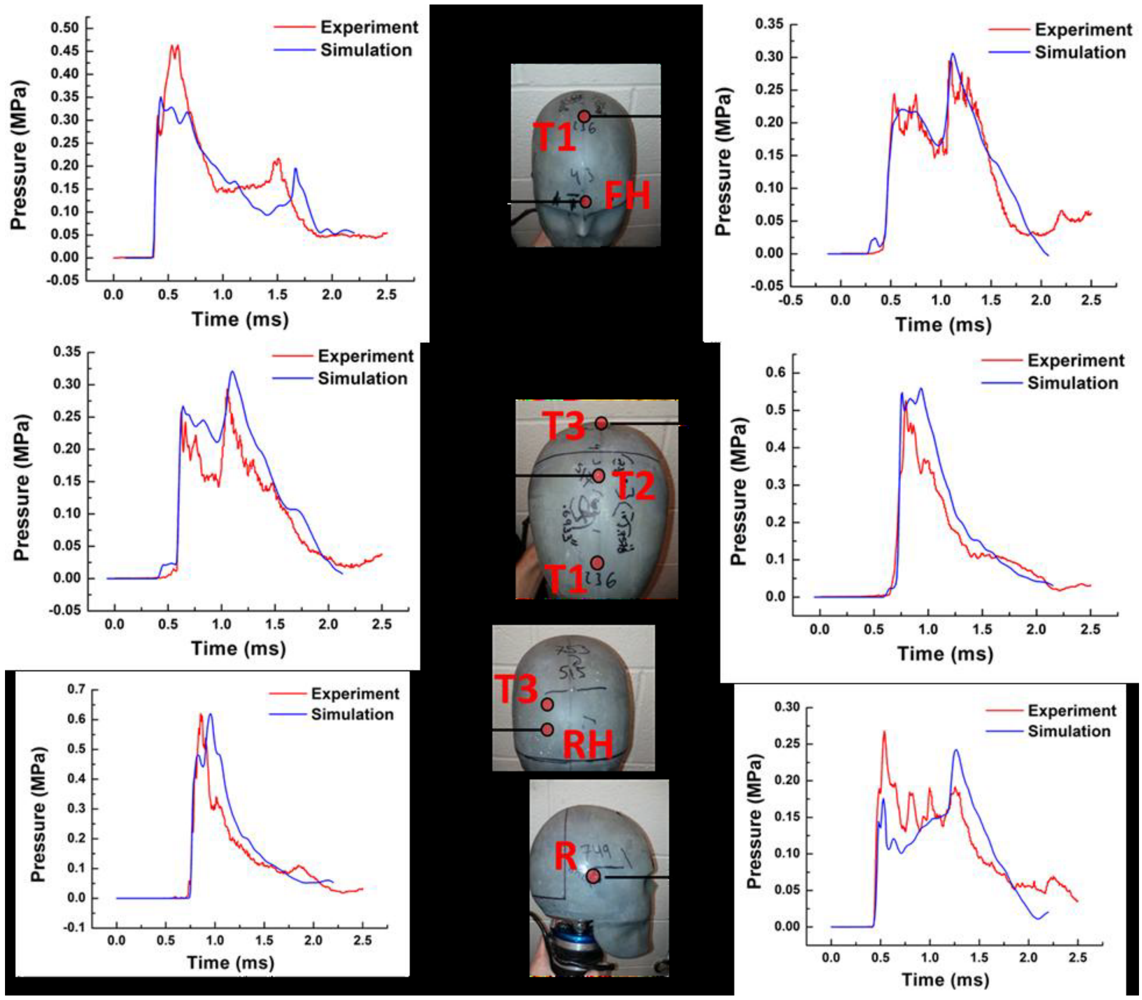

Figure 5.20 Comparison between experiment and simulation for an unpadded helmet. (Ganpule [11]).

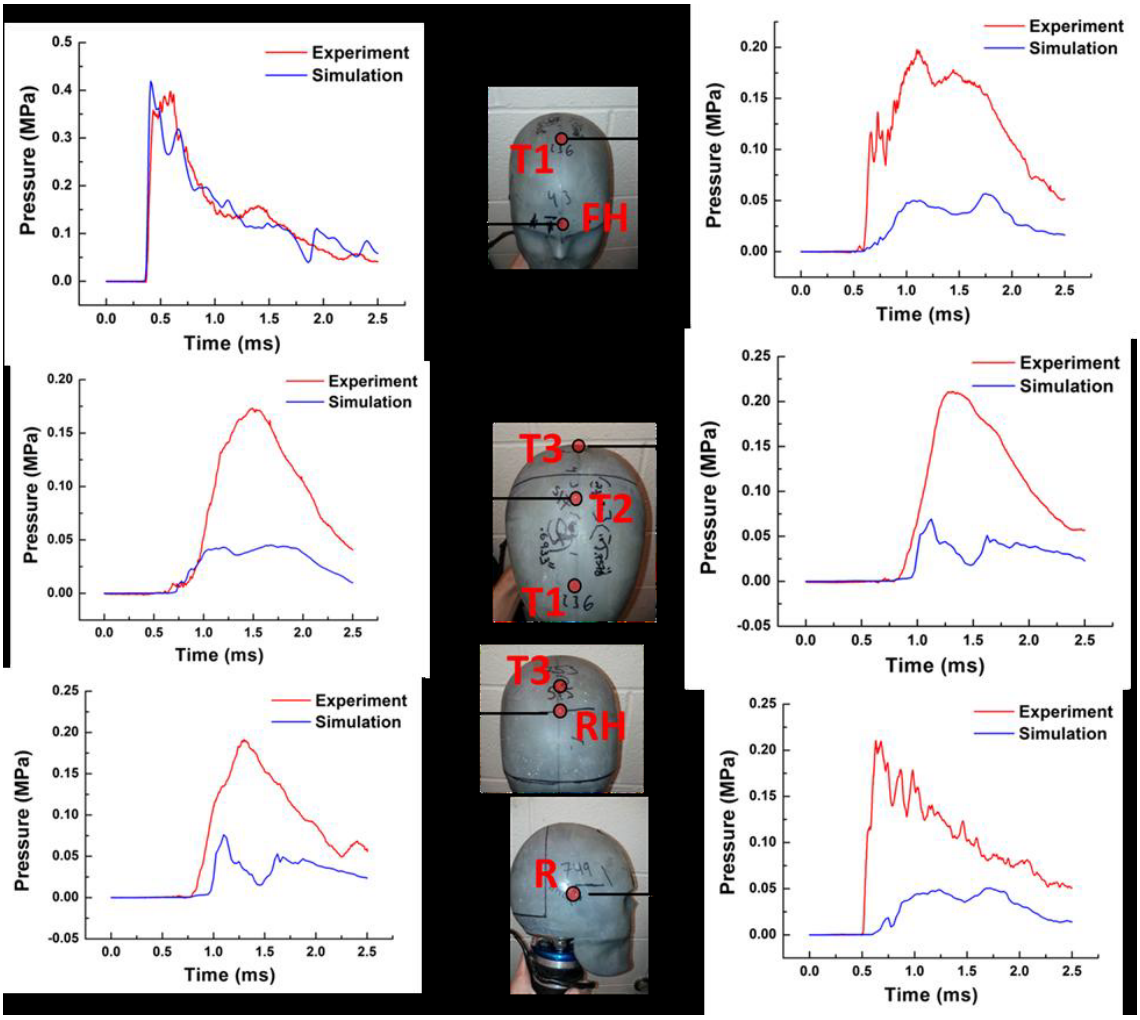

Figure 5.21 Comparison between experiment and simulation for a padded helmet. (Ganpule [11]).

We note that there is very good agreement (Figure 5.19-5.20) between simulations and experiments for the unprotected head and for the case of an unpadded helmet. However, for the case of a padded helmet the agreement is quite bad (except for the point on the forehead which is outside the helmet). In this case, the simulation gives much lower pressure on the head surface than what was actually measured. Ganpule has no credible explanation for the disagreement.

Keeping this in mind, it is still interesting to compare the numerical peak pressure for the different cases of unprotected head, unpadded helmet and padded helmet. This is shown in Figure 5.22. We see that the results vary with location of the sensor and impact angle of the blast wave, but typically the padded helmet gives the lowest pressure and the unpadded helmet (here called “suspension helmet”) the highest pressure.

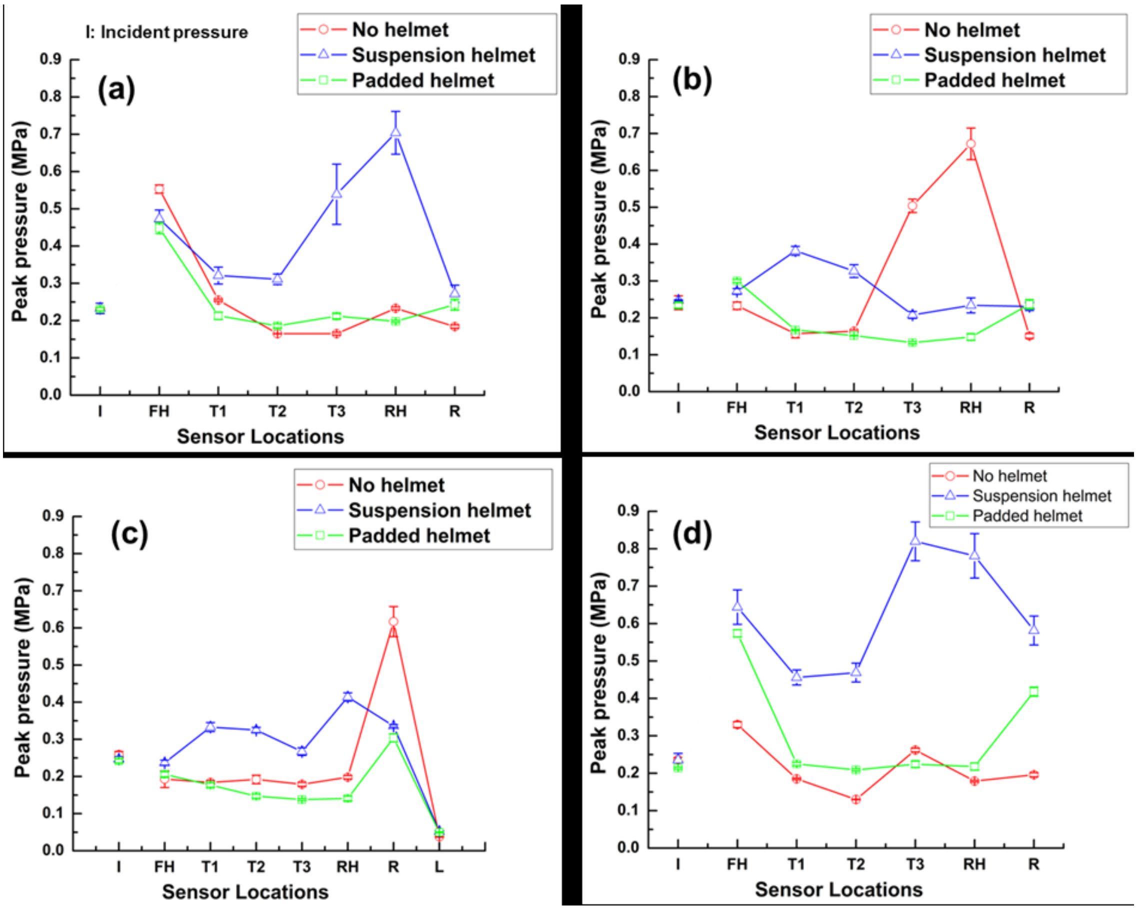

Figure 5.22 Numerical peak pressure from Ganpule [11] for different impact angles: front, back, side, 45 degrees.

Finally, Ganpule performed some numerical simulations with the skull protected by an additional face shield. The results are shown in Figure 5.23, where the face shield is shown to lead to a large reduction in pressure.

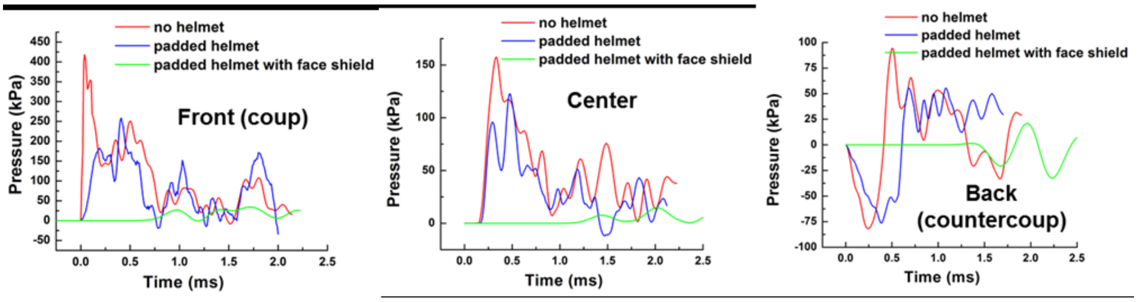

Figure 5.23 Simulation results from Ganpule [11] including a face shield.

5.10 Summary of numerical studies

The results of the numerical studies are very clear. Wearing a padded helmet is better than being unprotected, which again is better than wearing an unpadded helmet.

6 Summary

Here we summarize the results from the scientific literature in Tables 6.1 and 6.2. For easy comparison the charge weights and distance has been converted to pressure amplitude and duration using Håndbok for Våpenvirkninger [25].

Experimental results				
Study	**Method**	**Set-up**	**Helmet**	**Results**
Mott et al. (2008)	Hybrid III	Charge: 380 kPa, 1.1 ms	LWH (padded)	Padded helmet better than unprotected head.
Rafaels et al. (2010)	Hybrid III + PMHS	Shock tube: 145 kPa, 0.66 ms 228 kPa, 0.93 ms	ACH (padded)	Padded helmet mostly better than unprotected head.
Merkle et al. (2012)	Human Surrogate Head Model	Charge: 250 kPa, 2.2 ms	Different helmets (all padded)	Little difference between unprotected head and padded helmet. Goggles + helmet decreased pressure further.
Ganpule PhD (2013)	Dummy + PMHS)	Shock tube dummy: 230 kPa, ? Shock tube PMHS:	PASGT and ACH (both padded). No difference	Dummy: Unprotected head better than unpadded helmet. Padded

		70 kPa, ? 140 kPa, ? 200 kPa, ?	found.	helmet about the same as unprotected head. PMHS: Padded helmet better than unpadded helmet in most cases, though some variety. Padded helmet better than unprotected head.

Table 6.1 Summary of experimental results from the literature.

Numerical results				
Study	**Code**	**Set-up**	**Helmet**	**Results**
Moss et al. (2009)	ALE3D	Charge: 68 kPa, 3.9 ms	Generic (unpadded)	Unprotected head better than unpadded helmet
Panzer et al. (2010)	LS-Dyna (2D)	Charge: Many configurations	ACH (padded, unpadded, different types of padding)	Helmet usually better than unprotected head. Padding usually better than no padding.
Nyein et al. (2010)	Extension of Virtual Test Facility	Charge: 1500 kPa, 0.21 ms	ACH (padded)	Padded helmet mostly slightly better than unprotected head. Face shield + helmet usually even better.
Grujicic et al. (2010)	Abaqus	Charge: 400 kPa, 0.69 ms	ACH (two different types of	Polyurea padding better than current elastomeric foam-

		1300 kPa, 1.1 ms	padding)	like padding for big charge. No difference for small charge.
Ganpule et al. (2011)	Abaqus	Shock tube: 180 kPa, 0.65 ms 350 kPa, ? 520 kPa, ?	ACH (padded, unpadded)	Unprotected head better than unpadded helmet. But padded helmet even better than unprotected head.
Mott et al (2012)	Code not mentioned.	Charge: 300 kPa, 3.1 ms (120 kPa, 2.8 ms in study of extra protective elements.)	LWH and ACH (padded and unpadded). No difference found.	Padded helmet better than unpadded helmet in most locations on the head surface. Extra protective elements maybe even slightly better.
Sharma et al. (2013)	LS-Dyna	Shock tube: 71 kPa, ? 170 kPa, ? 300 kPa, ?	ACH (padded)	Padded helmet better than unprotected head.
Zhang et al. (2013)	LS-Dyna	190 kPa, 2.8 ms	ECH (padded, unpadded)	Padded helmet better than unpadded helmet.
Ganpule PhD (2013)	Abaqus	Shock tube: 230 kPa, ?		Unprotected head better than unpadded helmet. Padded helmet even better than unprotected head. Including face shield gives more protection.

Table 6.2 Summary of numerical results from the literature.

To sum up there has been quite a significant body of work done on this topic, both experimentally and numerically, and for different scenarios with regards to strength and duration of the incoming blast wave. In total the results point to a very clear conclusion: Using a padded helmet will generally decrease the intracranial pressure compared with an unprotected head. Especially the numerical simulations point to a very strong effect here, whereas the experiments indicate an effect that is much smaller. However, wearing an unpadded helmet (which, in practice, nobody does today) could, in some cases, be worse than being unprotected with regards to shock wave propagation into the brain, and is definitely worse than wearing a padded helmet.

The main function of a military helmet is to protect against penetration. This review of the literature has shown that it will also, to some degree, protect against blast waves. It is therefore recommended to wear a helmet during military operations. No more research is needed to establish this.

However, one unsolved question is why the numerical results indicate that padded helmets give much more protection than the experiments show. Answering this question might also help in optimising the padding material for shock attenuation. This could be a topic for future research. The potential benefits of adding extra protective elements (visor, mandible etc) to the helmet system might also be looked further into.

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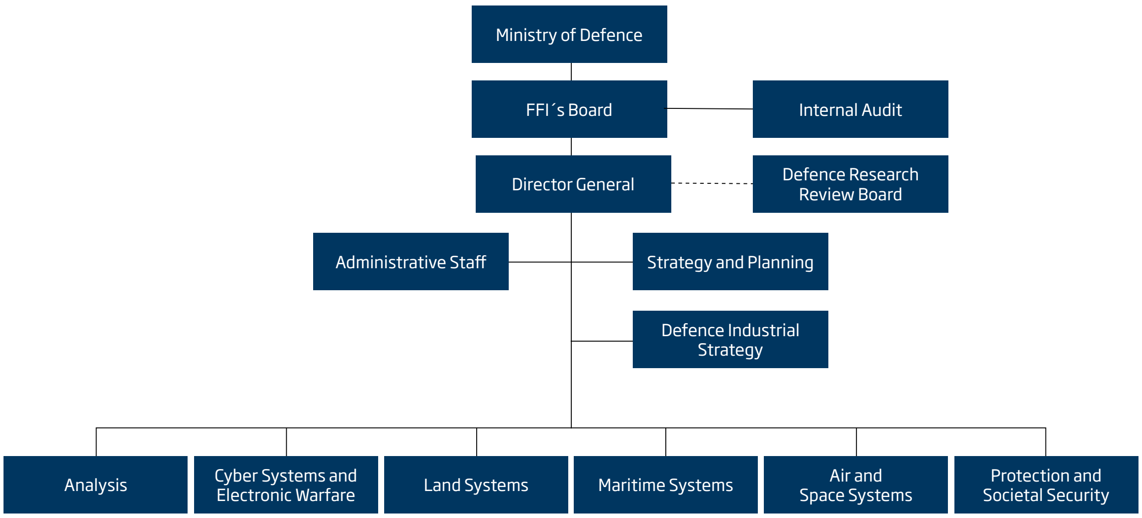

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