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Guidelines to inform the generation of clinically-relevant and realistic blast loading conditions for primary blast injury research

Abstract

Introduction

'Primary' blast injuries (PBIs) are caused by direct blast wave interaction with the human body, particularly affecting air-containing organs. With continued experimental focus on PBI mechanisms, recently on blast traumatic brain injury, meaningful test outcomes rely on appropriate simulated conditions.

Methods

Selected PBI predictive criteria (grouped into those affecting the auditory system, pulmonary injuries and brain trauma) are combined and plotted to provide rationale for generating clinically-relevant loading conditions. Using blast engineering theory, explosion characteristics including blast wave parameters and fireball dimensions were calculated for a range of charge masses assuming hemispherical surface detonations and compared to PBI criteria.

Results

While many experimental loading conditions are achievable, this analysis demonstrated limits that should be observed to ensure loading is clinically relevant, realistic and practical. For PBI outcomes sensitive only to blast overpressure, blast scaled distance was demonstrated to be a useful parameter for guiding experimental loading regime design as it permits flexibility for potential experimental setups. This analysis revealed that blast waves should correspond to blast scaled distances $1.75 < Z < 6.0$ to generate loading conditions found outside the fireball and of clinical relevance to a range of PBIs. Blast waves with positive phase durations (2-10ms) are more practical to achieve through experimental approaches, while representing realistic threats such as IEDs (i.e. 1-50kg TNT equivalent).

Conclusions

These guidelines can be used by researchers to inform the design of appropriate blast loading conditions in PBI experimental investigations.

Keywords

Blast injury criteria, primary blast injury, shock tube, guidelines, loading conditions, exposure levels

Key messages

- At present, there are no guidelines specifically for the design or specification of appropriate blast wave parameters within experimental primary blast injury (PBI) studies.
- Through analysis of PBI criteria and theoretical blast wave calculations, zones of blast parameters are proposed to guide experimental designs.
- The range of blast conditions of relevance to PBI research is limited, prompting reason for researchers to consider whether loading conditions are appropriate.
- While many experimental loading conditions are achievable, this analysis demonstrated limits that should be observed to ensure loading is clinically relevant, realistic and practical.
- To simulate loading conditions found outside the fireball and of clinical relevance to PBIs, generated blast waves should correspond to blast scaled distances $1.75 < Z < 6.0$.
- Blast waves with positive phase durations (2-10ms) are typically more practical to achieve, while representing realistic threats such as IEDs (i.e. 1-50kg TNT equivalent).

1. Introduction

Blast injuries are a complex type of physical trauma resulting from direct or indirect exposure to an explosion, caused by a combination of mechanisms (shock wave transmission, penetrating fragments and blunt impacts etc.). So-called 'primary' blast injuries (PBIs) are those specifically caused by exposure to blast overpressure.[1] PBIs particularly affect air-containing organs such as the lungs, gastro-intestinal tract and ears due to rapid pressure gradients induced within tissues.[2] Recent PBI research has focussed on blast traumatic brain injury (bTBI),[3] and despite the diagnostic ambiguities, bTBI has been described as the 'signature injury' of the wars in Iraq and Afghanistan.[4]

PBI studies typically replicate injuries in the laboratory using *in vitro* and *in vivo* models exposed to blast waves generated by explosive testing or simulated conditions using laboratory equipment. Explosive testing is expensive and traditionally involves full-scale arena trials at specialist facilities, so researchers often simulate blast using equipment such as shock tubes.[5]

Blast injury is predominantly a clinically-driven field although evidence suggests it would benefit from engineering input to ensure the conditions applied are realistic and clinically relevant.[6] Blast loading for PBI research is simulated experimentally using ultrasound (i.e. shock wave lithotripsy),[7] microwaves [8] and lasers [9], but the resulting shockwaves do not replicate the physical properties of a blast or the injury features observed in people exposed to real-life blast events.[10] Furthermore, even when considering more conventional blast simulation methods (e.g. shock tubes), different setups and incomplete reporting of blast wave parameters hinder comparison between studies.[11]

Current guidance includes pressure instrumentation setup, the importance of pressure sensor calibration, data acquisition and interpretation of measured pressure-time profiles.[6,11] Recognising the experimental issues in this field, "reproducing blast exposures in the laboratory" was specifically defined as a work package by the NATO Human Factors and Medicine Research Task Group.[12] This resulted in guidelines to describe common blast-wave generation platforms, blast measurement best practice and reporting standards.[5] However, at present there is no guidance to inform ranges of blast wave parameters that are appropriate for PBI experiments. As a result, prior studies demonstrate limited rationale for the explosion context such as scale and proximity to the fireball, with generated blast conditions influenced by facility and equipment capabilities.

For clinical relevance, blast conditions should correspond to predictive PBI criteria to ensure pressures initiate the injury without causing certain fatality. While multiple combinations are possible, current guidance does not specify appropriate ranges of blast wave parameters for PBI research. Existing criteria to predict injury and fatality from PBIs are fragmented, contested,[13] and limited to specific anatomical regions. This makes it challenging to understand the range of blast conditions responsible for the full spectrum of possible PBIs (e.g. mild hearing loss through to severe lung injury or risk of fatality). With a vast range of potential explosive scenarios and loading conditions achievable in laboratories, broad comparison between PBI criteria is needed to establish appropriate ranges of blast pressures.

Considering realism, generated blast conditions should also correspond to explosive threats or battlefield operational conditions, while considering proximity to the fireball. The fireball contributes a significant thermal injury hazard, with temperatures estimated between 2000-4200K following detonation of TNT.[14] Importantly, the medium inside the fireball is multiphase (air and detonation products) so the shock structure and loading profile is

complex to characterise, sensitive to the charge shape, blast wave curvature and difficult to measure.

Considering practicality, testing such ‘near-field’ loading conditions remain challenging to predict and exhibit low repeatability, and therefore considered a non-ideal regime to conduct controlled blast testing.[5] The fireball dimensions therefore have important practical implications for experimental studies when specifying stand-off distances.

Without rationale or guidance, there is the potential for unrealistic loading regimes to be generated leading to less meaningful clinical interpretations of PBI research. Overall, there is a need for more robust guidance on the range of blast parameters appropriate for PBI studies, acknowledging both the clinical relevance and blast physics of the equivalent explosive threat being simulated. This article presents the development of guidelines to inform the generation of appropriate experimental blast loading regimes for PBI research.

2. Methodology

Theoretical PBI guidelines were developed by combining two main methodologies:

- a) compilation of existing PBI criteria affecting the ear, lung and brain;
- b) calculation of explosion characteristics including air blast wave parameters and maximum fireball radius for a range of idealised surface burst detonations.

Primary Blast Injury (PBI) Criteria

A range of PBI criteria have been developed and contested since the 1960s. For this study, PBI criteria take the form of blast overpressure thresholds and overpressure-duration curves assuming human exposure to idealised blast waves. PBI criteria selected for this study were informed by a separate review,[13] and grouped into: (1) auditory system; (2) pulmonary injury & lethality; and (3) brain-related PBI (Table 1).

Table 1: Summary of primary blast injury criteria analysed with respect to idealised blast wave parameters.

Blast Injury Area	Criteria Description
Auditory System (Ears)	<p>Peak Overpressure Thresholds</p> <ul style="list-style-type: none"> • 35 kPa [15] - Threshold for eardrum rupture • 103 kPa [15] - 50% probability of eardrum rupture • 202 kPa [16] - 100% probability of eardrum rupture
Pulmonary Injury & Lethality	<p>Peak Overpressure-Positive Phase Duration Functions</p> <p>Bowen curves [17] for pulmonary (lung) blast injuries assuming a 70kg man stood near a wall, including:</p> <ul style="list-style-type: none"> • Threshold for pulmonary blast injury • 1%, 50% and 99% probability of fatality from pulmonary blast injury
Brain-related PBI	<p>Peak Overpressure Thresholds</p> <ul style="list-style-type: none"> • 144 kPa [18] - 50% risk of mild brain haemorrhage

For the auditory system, PBI criteria include blast overpressure levels to predict the onset (threshold) and probabilities (50% and 100%) of eardrum rupture (Table 1; Fig. 1, grey lines).

Pulmonary injury criteria utilise the Bowen overpressure-time curves,[17] including the threshold (onset) and probabilities (1%, 50% and 99%) of fatality (Table 1; Fig. 1, red lines).

Overpressure levels for lung injury and lethality have been proposed by some researchers although these were not included as dependence on the blast duration has been demonstrated [17,19,20]. Due to a lack of consensus on how to extend Bowen's pulmonary injury criteria to an open-field scenario, [13] this analysis considered a 70kg person stood near a reflective wall (Table 1; Fig. 1, red lines).

Brain-related PBI criteria were developed more recently than other injury areas; this study analyses an overpressure threshold representing the 50% risk of mild brain haemorrhage criteria developed by Rafaels et al. [18] (Table 1; Fig. 1, black line). Moderate brain haemorrhage and risk of fatality were excluded as overpressure-time functions exceed the 99% probability of fatality from pulmonary injury.

Calculating Blast Characteristics

Following an explosive detonation, a violent expansion of gases force surrounding air outwards at supersonic speeds, forming a layer of propagating, compressed air known as a blast wave. Blast waves are characterised by an instantaneous increase in pressure to the 'peak overpressure' (above atmospheric), which decreases over a time known as the 'positive phase duration' (t^+) (Fig. 2). In an ideal scenario, blast waves propagating in unobstructed, free-air theoretically exhibit a waveform known as the Friedlander function [21]:

$$P_i(t) = P_i \left[1 - \frac{t - t_a}{t^+} \right] \exp \left[\frac{-A(t - t_a)}{t^+} \right] \quad (1)$$

where $P_i(t)$ is the incident overpressure at time t (kPa); A is the decay coefficient (dimensionless); and t_a is the arrival time (ms).

At a given point, blast wave overpressure and duration depend on the mass of the explosive charge, W (kg) and the distance from the detonation, or 'stand-off distance', R (Fig. 2). Blast wave parameters also depend on position of the detonation relative to the ground. When explosions occur at the ground surface, incident and reflected shock waves merge effectively instantaneously, forming a single hemispherical shock front with approximately twice the energy of a spherical above-ground detonation (Fig 2). Many real-world explosions occur at the ground so can be modelled as surface bursts.

Due to differing explosive materials, it is common practice in blast engineering to relate the stored energy of any explosive charge/threat to an equivalent mass of Trinitrotoluene (TNT) based upon the ratio of the energy densities of the explosive materials (Table A - supplementary information).

Blast Wave Calculations

Extensive air-blast experimentation has been used to derive equations to calculate blast wave properties. In this study, incident blast wave parameters were calculated assuming idealised surface detonation scenarios involving hemispherical charges of TNT for a range of charge masses scenarios to compare with PBI criteria (Fig. 2). P_i and t^+ were calculated as a function of stand-off distance, R using the Kingery and Bulmash [22] equations using ConWep software [23]. Calculations were performed for regular intervals of charge masses ranging from 10g-1000kg, examining different scale explosive threats (i.e. landmines to truck bombs) and representing different blast testing capabilities (Table B1-B5 - supplementary information).

Blast Scaling

With multiple possible combinations of stand-off distances and charge masses, blast scaling is an important concept. Hopkinson-Cranz scaling [24] is based on geometrical similarity and

can be applied to physical experiments or simulations at different scales. Two explosions are expected to produce identical blast waves at distances which are proportional to the cube-root of the respective energy release. The scaled distance of a blast event is defined as:

$$Z = \frac{R}{\sqrt[3]{W}} \quad (2)$$

Importantly, for a given blast scaled distance Z the peak overpressure is constant, making it a useful parameter to describe blast conditions arising from different mass charges while considering the relative distance from the explosion. Hopkinson-Cranz scaling was used to calculate peak blast overpressures at regular blast scaled distances $Z=0.5-6.0$ to examine how they relate to PBI criteria and to further specify appropriate loading conditions.

Fireball Radius

A semi-empirical model proposed by Gilbert et al. [25] was used to calculate the maximum fireball dimensions resulting from the detonation of different masses of high explosive:

$$D = 3.5\sqrt[3]{W} \quad (3)$$

where D (m) is the maximum fireball diameter and W is the equivalent mass of TNT (kg). While the growth of a fireball evolves in stages, this model predicts maximum fireball diameter as a hemisphere on the ground and is applicable to any high explosive [14]. The maximum fireball radius, R_f can be expressed as eq. 4 and, through rearrangement and inspection of eq. 2, the maximum fireball radius corresponds to a constant blast scaled distance of $Z=1.75$ (eq. 5):

$$R_f = 1.75\sqrt[3]{W} \quad (4)$$

$$\frac{R_f}{\sqrt[3]{W}} = Z = 1.75 \quad (5)$$

For each charge mass considered, peak overpressure and duration were calculated at stand-off distances such that $Z=1.75$, thus calculating blast wave parameters expected at the maximum fireball radius, permitting analysis with PBI criteria.

3. Results

Inspection of combined injury criteria in Fig. 1 suggests that the 99% risk of fatality from pulmonary injury represents an upper bound blast conditions for PBI investigation. While current PBI criteria do not support a definitive minimum threshold, comparison between different criteria (Fig. 1) supports zones of clinically-relevant loading regimes.

Calculated blast wave parameters were plotted as a series of curves for each charge mass, mapping combinations of peak overpressure and positive phase durations experienced at different stand-off distances, with the selected PBI criteria overlaid (Fig 3). Curves representing the 100g and 10kg charge masses were labelled with stand-off distances at regular intervals, showing that as charge mass increases, blast waves with higher positive phase durations are generated at injury-relevant peak overpressures. Larger scale explosions therefore have the potential to inflict relatively more serious lung injuries as tolerance to pulmonary injury reduces with increasing positive phase duration (Fig. 3).

The spatial variation of expected PBIs at different stand-off distances for different explosive charge masses can also be analysed through plotting PBI criteria with blast wave parameters (Fig. 3), with examples provided in Table 2.

Table 2: Expected PBIs as a function of stand-off distance for 100g and 10kg TNT charge masses.

Charge Mass, TNT equivalent	Stand-off Distance, R	Expected Primary Blast Injury
100g	R=0.75m	~1% risk of fatality from pulmonary blast injury
	R=1.5m	No lung injuries expected (below pulmonary injury threshold) ~50% risk of ear drum rupture
	R=3.0m	No PBIs expected*
10kg	R≤3.5m	~99% risk of fatality from pulmonary injury
	3.5m<R<9.0m	Varying risk of pulmonary injury
	R≥12.0m	No PBIs expected*

*In the absence of minimum threshold exposure levels for mild brain-related PBI.

Analysis of Fig. 3 shows that larger charge masses and explosive threats inflict PBIs over a larger distance compared to smaller charges. However, for smaller charge masses (i.e. 100g TNT), the range of stand-off distances where PBIs are of interest is relatively small (i.e. 0.5-2m) (Fig. 3).

Zones of blast wave parameters corresponding to realistic explosive threats are plotted against PBI criteria in Fig. 3. based on reported TNT equivalent charge mass (Table A; supplementary file), and suggests there is limited relevance in generating blast waves with:

- positive phase durations below 0.4ms as this corresponds to either very small explosive threats (<10g TNT) or larger threats at very close stand-off distances that would cause fatality; or
- positive phase durations over 20ms, as this effectively models very large explosions (>100kg TNT equivalent), which occur rarely.

Analysis of Fig. 4 indicates that loading conditions in PBI experiments should correspond to scale distances of $1.75 < Z < 6.0$, to ensure simulation of conditions found outside the fireball while generating peak overpressures of sufficient magnitude to induce the lowest reported threshold for PBI (i.e. threshold for eardrum rupture).

4. Discussion

As expected, an increased probability and severity of PBI or fatality correlates with decreasing stand-off distances due to exposure to higher peak overpressures, consistent with casualty and forensic reports. Loading from small charge mass detonations have a relatively narrow range of stand-off distances such that overpressures are clinically-relevant to the injury type of interest, and therefore require careful experimental design. Beyond $\approx 10\text{kg TNT}_{\text{eq}}$, pulmonary blast injury criteria converge and intersect with the selected ear and brain injury criteria, suggesting different PBIs could occur simultaneously for blast waves with increased durations.

Understanding the expected PBIs at different stand-off distances for a known charge size is useful when designing explosive arena tests. The importance of fully reporting both peak overpressure and duration parameters was highlighted, as this has implications for the scale

of the equivalent explosive threat being simulated, and the nature and severity of PBIs expected.

When injury criteria are sensitive to only overpressure, blast scaled distance is a useful parameter as it is applicable to a broad range of experimental setups (various charge mass and stand-off distance combinations) and research facility capabilities. For example, scaled distances $Z=2.0-3.0$ approximately correlate to a 50% probability of mild brain haemorrhage, irrespective of the blast duration or charge mass.

Analysis of positive phase durations in Fig. 3 can help inform the experimental approach required (e.g. shock tube or conventional blast testing). Generating blast waves with long positive phase durations (with sufficient peak overpressures to cause PBIs) presents several experimental challenges. As an example, blast waves with positive phase durations $>10\text{ms}$ and peak overpressures capable of causing PBIs ($>34\text{kPa}$), requires charge masses of $>100\text{kg}$ TNT (Fig. 3). In context, this represents relatively large explosive threats such as vehicle-borne IEDs (Fig 3, Table A). Experimentally, large charge masses (100kg TNT) would require targets positioned at relatively large stand-off distances ($>9\text{m}$ to avoid 99% risk of fatality), thus requiring access to large test sites and potentially unfeasible testing costs. Likewise, laboratory-scale shock tubes typically cannot simulate blast wave durations over 10ms; higher durations are achieved by increasing the volume of driver gas and length of the driven section, requiring additional infrastructure and space. Constrained by facility capabilities and expense, positive phase durations $<10\text{ms}$ are more practical to achieve, while still representing realistic threats such as IEDs (Fig. 3).

While many experimental loading conditions are achievable, collective analysis of Figs 3-4 demonstrated that there are limits to ensure that loading is clinically relevant, realistic and practical. As such, for PBI research, it is recommended that generated blast wave conditions: equate to blast scaled distances $1.75 < Z < 6.0$ with positive phase durations from 2-10ms (i.e. charge masses of 100g-50kg TNT_{eq}, predominantly IED-scale threats). These blast conditions are operationally relevant and can be adjusted to be in the range of a broad spectrum of potential PBI types and injury thresholds. Experimentally, these conditions are also practical considering the required size for test sites and common laboratory shock tube capabilities, while balancing testing practicalities such as the fireball size and stand-off distances.

Limitations

This study is limited to the assumption of highly-idealised, hemispherical charge surface burst detonations. Spherical detonations above ground and different shaped charges will give rise to modified blast parameters. Furthermore, while the air-blast calculations adopted in this study have been shown to be accurate for geometrically simple 'far-field' scenarios,[26] definitive experimental validation data is lacking in the extreme 'near-field'. Hence, there is considerable uncertainty on the exact form or magnitude of the blast loading profile close to the source of an explosion, which often manifests as low repeatability within experiments.[5] The guidelines do not apply to blast scenarios involving obstructions, reflections and confinement as these greatly modify loading and lead to complex waveforms. Despite the inherent limitations of idealised blast wave assumptions, current experimental approaches generally simulate such blast waveforms, so this analysis remains of utility to the blast injury research community.

These guidelines are restricted to predictions of PBI following whole-body exposure to idealised blast waves and cannot predict localised injury associated with small charges at small stand-off distances. For example, while landmine victims are effectively exposed to "extreme near field" blast loading ($Z < 1.0$), they typically experience traumatic amputation

(rather than fatality) due to localised injury to the limbs. For PBI research, a minimum blast scaled distance of $Z=1.75$ is advised to examine conditions found outside the fireball, which also avoids conditions that lead to localised injury effects.

Reported PBI criteria analysed in this study assume un-protected human exposure to idealised blasts, specifically 70kg males in the case of the Bowen injury criteria. Importantly, experiments involving animal models require scaling of blast parameters; in particular, the positive phase duration must be compatible with the size and type of target being tested.[6] The influence of protective equipment and armour should also be considered where necessary. At present, there is no definitive minimum blast exposure threshold for PBI although researchers suspect that relatively low, or repeated, blast exposure can contribute to mild bTBI. Until more is understood, the minimum reported PBI threshold remains to be ear injury at an overpressure of 34kPa.

While the proposed guidelines are not definitive, new analysis presents 'zones of interest' to guide and inform the generation of blast loading conditions that are clinically-relevant (to the PBI of concern), realistic (corresponding to real-world threats) and practical from a testing perspective. Analysis presented in this paper encourages broader, multi-disciplinary understanding, raising awareness of how generated blast loading parameters correspond to different PBI types, and spatially, where such conditions occur by consideration of equivalent idealised blast threats.

5. Conclusion

With a continued research focus on bTBI and injury studies involving shock wave generation, it remains important that simulated blast loading is appropriate to ensure meaningful outcomes. Analysis presented in this paper demonstrates the implications of generated loading regimes and provides information to guide appropriate design of loading conditions within blast injury studies. Specifically, the resulting guidelines can:

- Help the community to generate valid, clinically-relevant loading conditions based on existing PBI criteria.
- Acknowledge different scale blasts considering real-world threats, proximity to the fireball and typical experimental capabilities.

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