ESTIMATING BLAST EXPOSURES FROM THE 2020 BEIRUT EXPLOSION AND EXAMINING CORRELATION WITH BLAST INJURIES

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ABSTRACT

On 4th August 2020, approximately 2750 tonnes of Ammonium Nitrate stored in the port of Beirut ignited, causing a huge explosion that damaged large parts of the city, causing more than 200 deaths and over 7,000 injuries. Injured victims' locations at the time of the explosion were previously unreported and unknown due to improper documentation. Without such knowledge, a victim's degree of blast exposure cannot be estimated, preventing further understanding of how blast loading contributed to injury outcomes.

As a large, city-scale explosion, a victim's blast exposure will have been significantly influenced by their location, including distance from the port detonation, their elevation, and proximity to buildings. In the absence of pressure measurements, engineering models can estimate and provide useful insight into the blast conditions likely to have occurred at different distances from the blast epicentre.

This paper reports on findings from a first-of-kind forensic study of the 2020 Beirut port explosion that aimed to investigate the relationship between victims' blast injury patterns and predicted blast exposure based on their location. Patients were selected from existing Beirut blast injury databases and invited to participate in this study. Over 300 participants completed a structured interview administered by telephone which acquired information on the participants' exact location at the time of the blast, their circumstances, and self-reported injuries alongside clinical records from prior injury databases. Participant locations were determined as precisely as possible and recorded using Google My Maps to obtain corresponding latitude and longitude coordinates. For each location, estimated blast loading parameters were calculated assuming an idealised, hemispherical surface detonation at the port using equivalent charge mass estimates in the literature. Estimated blast loading conditions were analysed against participants' injury severity scores and reported injury patterns to examine correlation between loading intensity and injury outcomes.

Results from this study highlight the capacity and limitations of blast modelling approaches for injury prediction through examination of a real-world urban blast case study. New knowledge can be used to inform disaster management and guide the protection of civilians exposed to urban blasts.

INTRODUCTION

On 4th August 2020, approximately 2750 tonnes of Ammonium Nitrate stored in the port of Beirut ignited, causing a catastrophic explosion that damaged large parts of the city. The explosion caused at least 218 fatalities, injured more than 7,000 and left an estimated 300,000 people homeless [1]. With the increasingly urbanised nature of explosive violence and the high proportion of casualties being civilian [2], the Beirut explosion offers an opportunity to gain deeper understanding of the relationships between blast loading exposure and blast injury outcomes.

Blast injuries are a complex type of physical trauma resulting from direct or indirect exposure to an explosion, caused by a multitude of mechanisms including shock wave transmission, penetrating fragments, and blunt impacts, among others. Traditionally, these mechanisms have been classified into distinct categories ranging from primary to quinary blast injury mechanisms [3], [4]. Notably, primary blast injuries (PBIs) have received considerable research attention [5], and are caused by exposure to blast overpressure [4]. PBIs particularly affect air-containing organs such as the lungs, gastro-intestinal tract, and ears due to rapid pressure gradients induced within tissues [6].

Previous investigations into the injury patterns resulting from the Beirut blast have consistently noted a substantial prevalence of secondary blast injuries, primarily attributed to extensive failure of glazing [7]–[10]. However, these earlier studies lack accurate documentation of victims' locations at the time of the explosion. Such limitations stemmed from either inadequate documentation or the presumption that victims' residential addresses corresponded to their locations during the explosion. For instance, while Yamimine et al. [8] reports the absence of any correlation between the victims' locations and the severity of their injuries, the method employed to ascertain patient locations in the study remains unclear, and the distances were categorised into wide-ranging zones. Consequently, a comprehensive exploration of the link between injury patterns, injury severity, and the victims' proximity to the Beirut blast epicentre remains unachieved.

Given the scale of the explosion, an individual's blast exposure, and consequently their risk of injury, are strongly dictated by two critical factors: their distance from the blast epicentre and their proximity to nearby buildings. In the absence of blast pressure measurements, engineering models can provide useful insight into the blast conditions likely to have occurred at different distances from the blast epicentre.

This paper presents preliminary findings from a wider study investigating blast injury victims' exact locations and other contextual information at the time of the 2020 Beirut explosion. Using accurate location data, injury patterns and severity were mapped as a function of distance from the blast epicentre and analysed alongside estimated blast loading conditions.

METHODOLOGY

Data Collection Methodology

Data were collected using structured telephone interviews to acquire new information as part of a larger study investigating the spatial and contextual factors that contributed towards the Beirut blast injuries. This prospective research study was approved by the American University of Beirut Institutional Review Board (BIO-2022-0152).

Participants were contacted using details from compiled injury databases of patients who had previously agreed to be contacted for future research under the protocol (BIO-2020-0357). Selected patients were contacted by the study team to explain the study's objectives, risks, benefits and to obtain their oral consent to be surveyed. As an appreciation for their time, respondents received compensation upon completing the survey.

The structured interview contained a series of questions to determine participants' exact location at the time of the explosion, the nature of their blast injuries and various other contextual and environmental information at the time of the disaster. The interviews were administered by telephone in both English and Arabic by researchers at the American

University of Beirut. Interview responses were assigned with unique study identification numbers and recorded in an electronic form linked to a shared spreadsheet.

A key component of the interview involved asking participants to describe their exact location at the time of the blast, including whether they were inside or outside. Locations were identified and recorded with place markers using Google My Maps [11] (Figure 1). Locations were determined as accurately as possible (≈10m), enabled by interviewers' local knowledge and two-way conversation with participants referencing nearby local landmarks to verify locations.

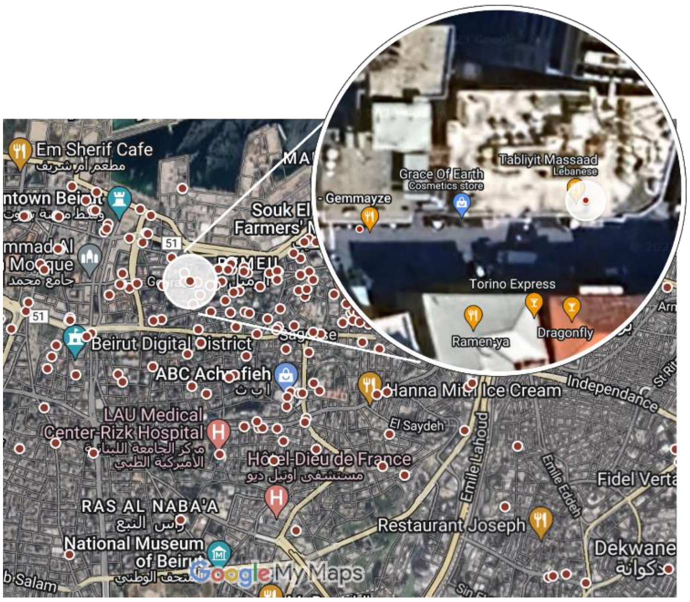


Figure 1: Victim's locations were recorded in Google My Maps [11] as accurately as possible through interviewers' extensive local knowledge and reference to nearby landmarks.

Following the interviews, all records were verified that they met the study inclusion criteria; participants were included only if they experienced an injury as a direct and immediate consequence of the Beirut blast and those with injuries caused during the response or clean-up operations were excluded.

Injury severity scores (ISS) from existing datasets were matched to a total of 187 participants within the study cohort. ISS is an anatomical scoring system that provides an overall score (ranging 0-75) for patients with multiple injuries to multiple regions of the body [12]. ISS is one of the most widely used scoring systems in the trauma literature and correlates well with several important trauma outcomes such as mortality and duration of hospitalisation [12].

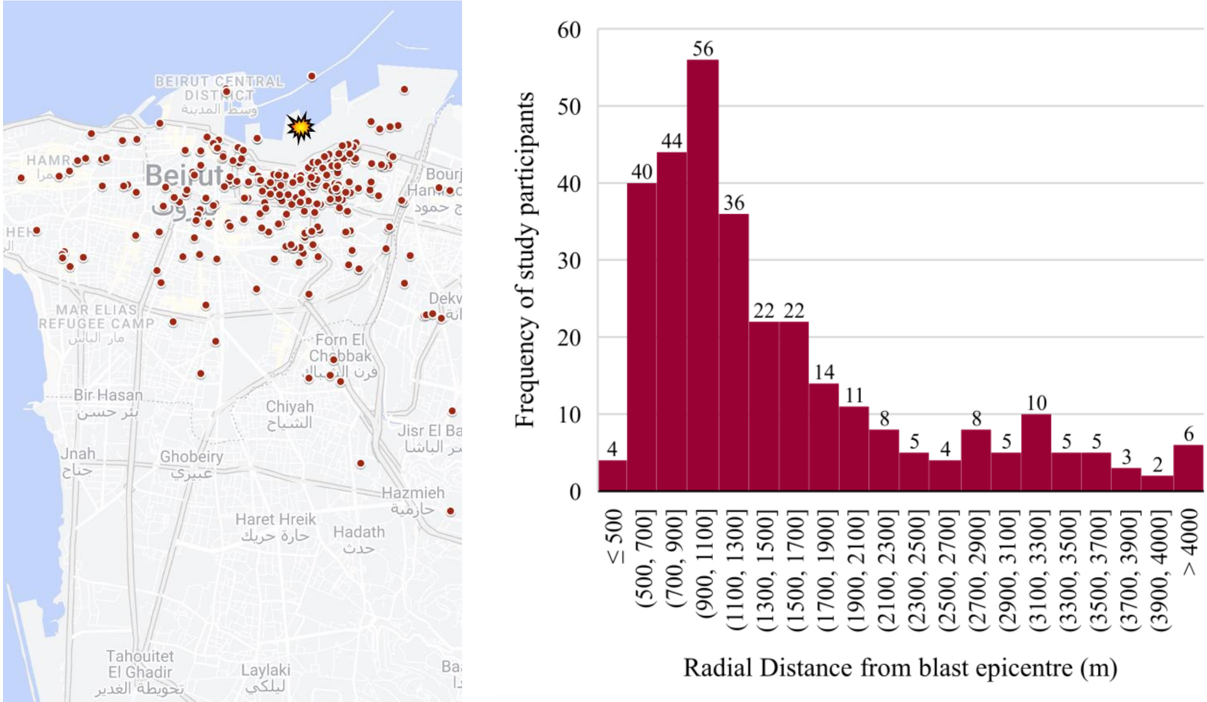
Estimating Victims' Blast Exposure

For this analysis, the Beirut explosion was modelled as an idealised, hemispherical surface burst detonation with the blast wave assumed to propagate unhindered in a free-field environment without obstacles. Participants' location at the time of the blast were recorded in Google My Maps and latitude and longitude coordinates were used to calculate their radial distance from the blast epicentre (Figure 2a). Blast loading parameters were calculated as a function of radial distance from the blast epicentre using the ConWep spreadsheet tool [13], based on the empirical models presented by Kingery and Bulmash [14]. An equivalent charge mass of 0.5kt TNT was assumed, based on the best estimation by Rigby et al.[15] and median value proposed by Dewey [16].

RESULTS & DISCUSSION

Spatial Data

The study cohort comprised a total of 310 participants. The closest and furthest participants were 472m and 7832m from the blast epicentre respectively (Figure 2a,b). Most participants were located 500-1700m from the blast epicentre with a generally decreasing number at further distances (Figure 2b). Very few (N=4) participants were located within 500m of the blast due to the large port area surrounding the blast epicentre and very few injuries were survivable within this region. A total of 250 participants (81%) stated that they were located inside at the time of the blast and 60 (19%) located outside.



(a) (b)

Figure 2: a) Study cohort (N=310) locations in Beirut at the time of the explosion and b) radial distance of participants from the Beirut blast epicentre.

Blast Injury Patterns & Injury Severity

Participants in this study typically reported multiple injury types. Injuries were grouped into seven main blast injury patterns; the frequency of each reported injury pattern is presented in Figure 3. Laceration and penetrating injuries (‘secondary blast injuries’) were the most common injury pattern reported (N= 276; 89%), followed by soft tissue injuries (N=145; 47%) and musculoskeletal injuries (N=70; 23%), the latter two representing ‘tertiary’ blast injuries. The high incidence of laceration injuries aligns with previous studies on the Beirut injuries [7], [10], which can be attributed to people being close to their windows to watch or film the initial fire before the blast [17]. Very few participants reported having ‘internal injuries’ (N=11) with a total of four reporting tympanic membrane (eardrum) rupture.

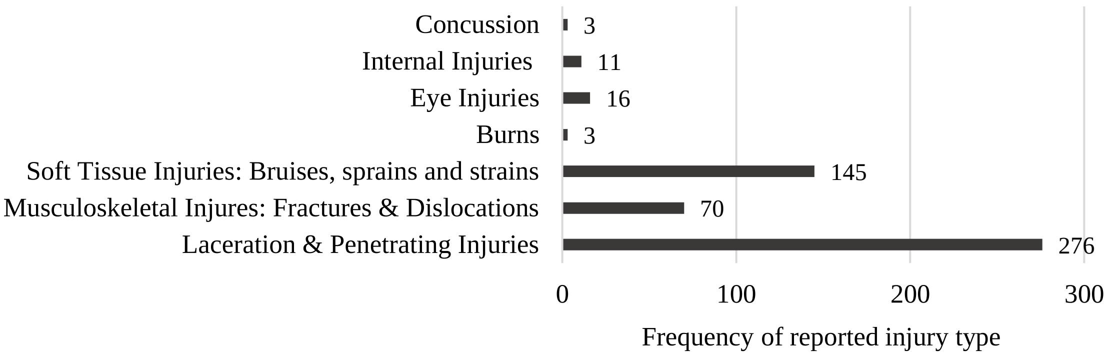


Figure 3: Frequency of reported injury patterns within the study cohort.

The three most common blast injury patterns (lacerations & penetrating injuries, soft tissue injuries and musculoskeletal injuries) are plotted as a function of distance from the blast epicentre in Figure 4. Laceration and penetrating injuries had high prevalence at all distances from the blast epicentre (Figure 4). This suggests blast loading was sufficient to cause secondary blast injuries from projectiles including glazing fragments and other debris even at significant distances (>4km). Musculoskeletal and soft tissue injuries had notably increased prevalence at distances closer to the blast epicentre (<1.5km), with relatively few reported further afield.

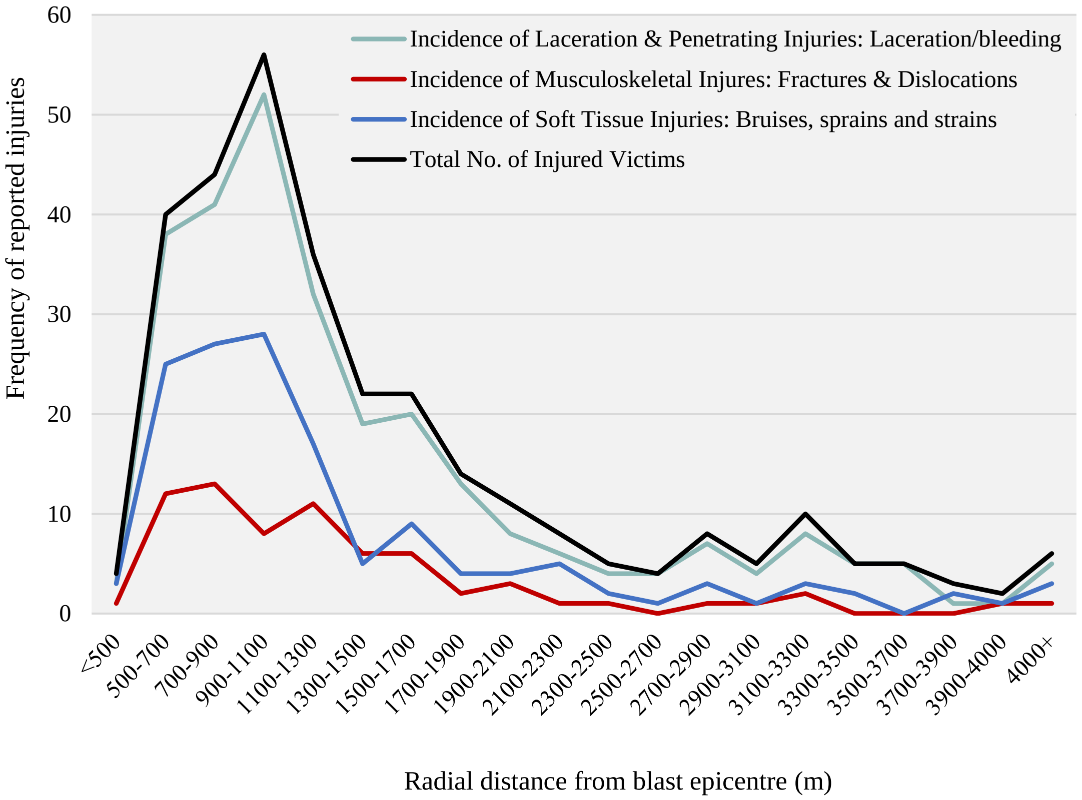


Figure 4: Distribution of injury patterns with distance from the Beirut blast epicentre.

The majority (70%) of the study cohort had ‘minor injuries’ (ISS<8) with a total of 25 (13%) classified as ‘major trauma’ (ISS>15). ISS within the study cohort clearly show correlation with participants’ distance from the blast (Figure 5). Generally, the most severe injuries (higher

ISS) occurred closer to the blast epicentre, with a notable cluster of ‘severe’ and ‘very severe’ injuries at radial distances 600-1400m (Figure 5). Minor injuries occurred at all distances from the blast epicentre with some isolated cases of severe injuries further from the blast. These findings suggest that some injury patterns (musculoskeletal and soft tissue injuries) and injury severity correlate with distance from the blast, and therefore, are likely to have been influenced by blast loading exposure.

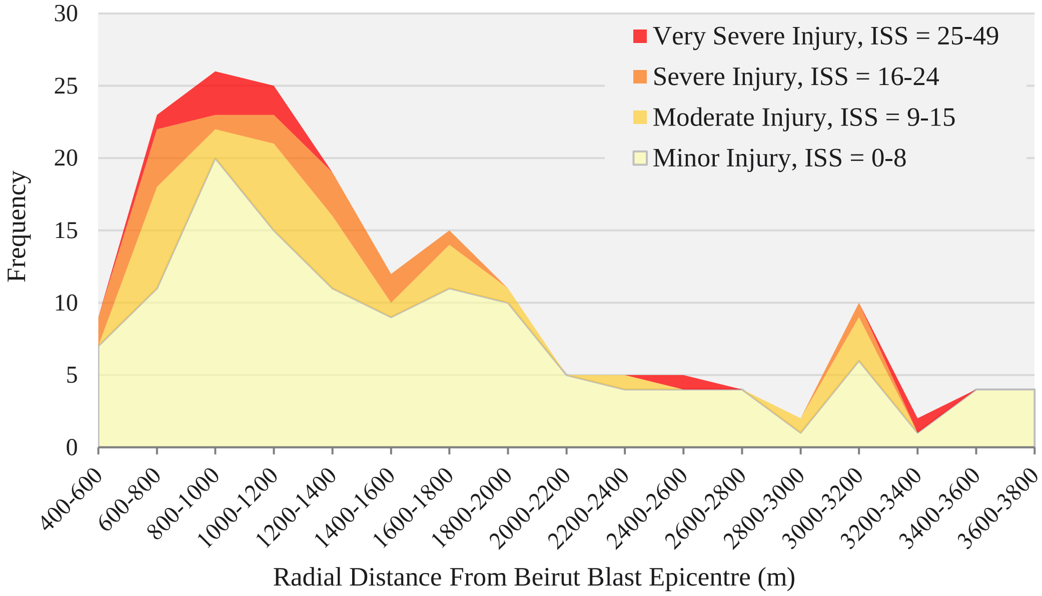
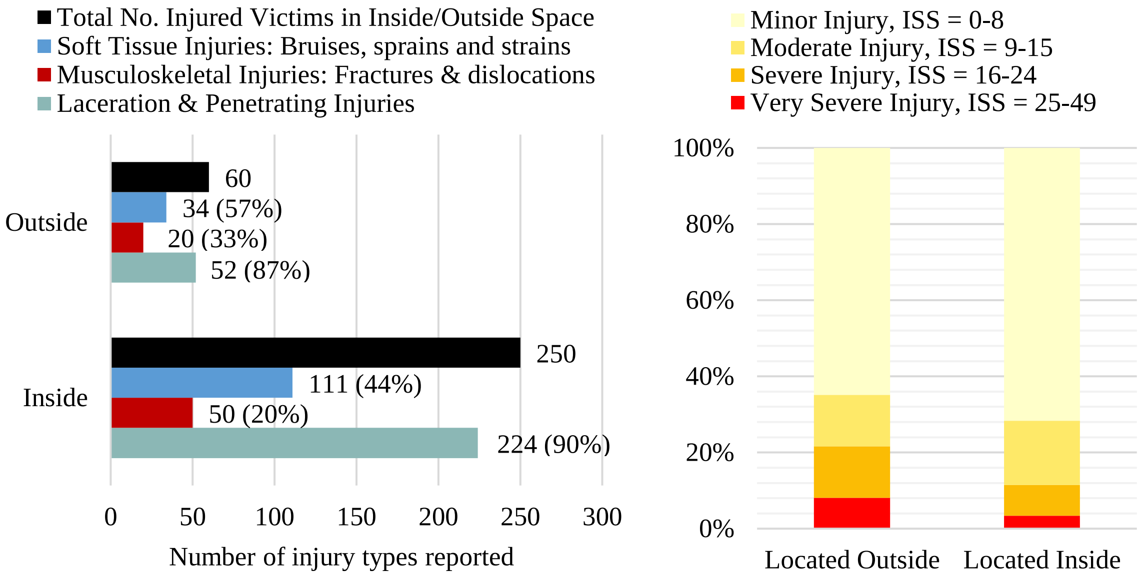


Figure 5: Distribution of injury severity (ISS) with distance from the Beirut blast epicentre.



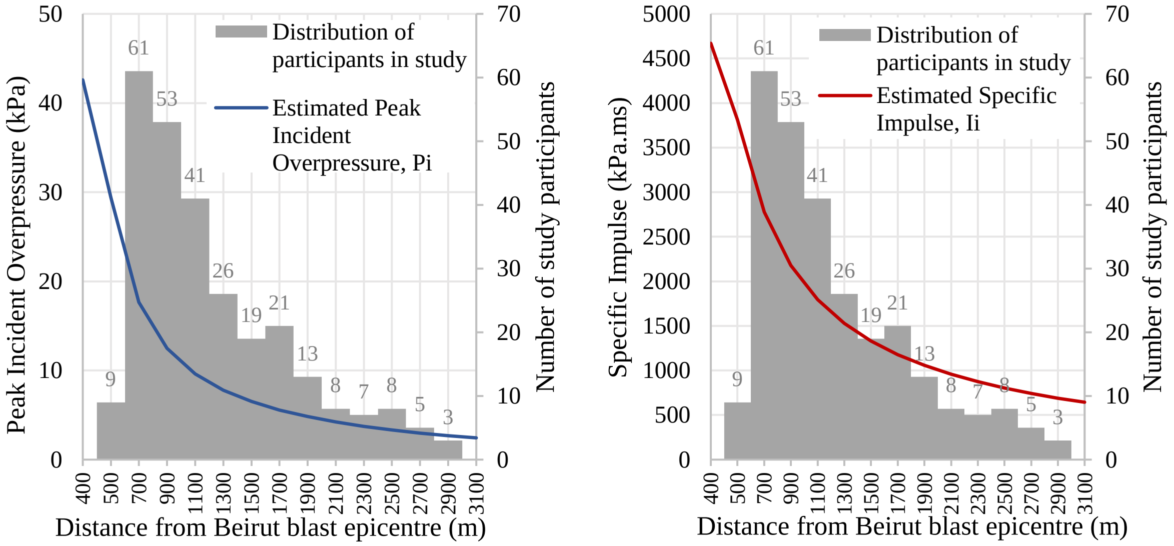
a) Injury patterns b) Injury severity (ISS)

Figure 6: Injury patterns and injury severities (ISS) for inside and outside spaces.

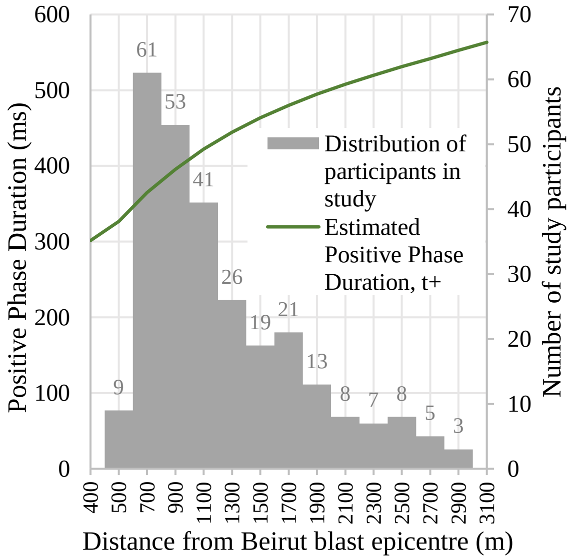
The incidence of laceration and penetrating injuries were similar for both outside and inside spaces (87%; 90%) (Figure 6a). However, a relatively higher proportion of musculoskeletal injuries and soft tissue injuries occurred in outside spaces in comparison to inside spaces (Figure 6a). A higher proportion of the most severe injuries (major trauma ISS>15) occurred for participants located outside (21%) compared to those inside (11%) (Figure 6b). These findings could be due to higher exposure to blast winds in outdoor spaces, increasing the likelihood of falls and impacts with surfaces.

Estimated Blast Loading

Idealised (free-field) blast loading parameters were calculated using ConWep to estimate blast wave peak overpressures, specific impulses, and positive phase durations as a function of stand-off distance from the Beirut blast epicentre to a distance of 3km, as plotted in Figure 7.



a) Incident peak overpressure (kPa) b) Specific impulse (kPa.ms)



c) Positive phase duration (ms)

Figure 7: Estimated blast wave parameters as a function of distance from the Beirut blast epicentre assuming a free-field 500T TNT detonation.

Study participants located closest to the epicentre were exposed to the highest incident peak overpressures, estimated to be p_i=29 kPa at a radial distance of 500m. Peak incident overpressures and specific impulses decrease with distance from the blast epicentre, whereas the positive phase duration increases with increasing distance (Figure 7). Positive phase durations are at a minimum closest to the blast, with an estimated duration of t^+=327 ms at a 500m stand-off, increasing to t^+=558 ms at 3km. Specific impulses decrease from a maximum of I_i=3814 kPa.ms at a radial distance of 500m to 666 kPa.ms at 3km. Estimated blast conditions exhibited 'long-duration' blast wave characteristics, namely high impulses and positive phase durations, which indicate non-trivial drag loading.

Analysis of blast wave parameters reveals that most study participants were exposed to peak incident overpressures below 20 kPa. This is far below the established predictive injury criteria thresholds for all PBIs [18], including the lower bound/most sensitive indicator, tympanic membrane (eardrum) rupture (=35kPa). Given that PBIs typically occur close to the blast epicentre, the large stand-off distance (>500m) of participants explains the low incidence of PBIs. As noted by other researchers, survivable PBIs following explosive events are relatively rare as those located close enough to sustain injuries from blast overpressure are often killed by fragmentation [19].

The large positive phase durations (t^+>100ms) and impulses are indicative of a 'long-duration' blast wave [20] (Figure 7). This type of blast wave is characterised by powerful drag loading resulting from non-trivial dynamic pressures (blast winds). These blast winds significantly contributed towards the extensive secondary blast injuries, propelling glass and debris as airborne projectiles that cause lacerations and penetrating injuries. The higher impulses and stronger drag loading found closer to the blast epicentre and in outdoor locations may account for the relatively higher prevalence of tertiary injuries. This is because winds were sufficient to cause people to be thrown against/fall on hard surfaces, leading to fractures and blunt trauma. Consequently, it is plausible that the higher magnitude loading conditions found closer to the blast epicentre contributed to more severe injuries (Figure 5).

Limitations

Blast loading estimates in this analysis are greatly limited by the assumption of free-field blast wave propagation, and therefore, loading conditions are assumed to be perfectly radially symmetric. In reality, blast wave interaction within Beirut's urban landscape will have modified the magnitude and distribution of loading conditions. Blast wave propagation in urban environments is complex to characterise and can both amplify and reduce loading through multiple reflections, channelling, and shadowing effects due to blast wave interactions with structures [21].

In such cases, computational fluid dynamics (CFD) can be used to develop more advanced models of blast wave propagation in urban environments, potentially offering more accurate predictions for key blast wave loading parameters, relevant for PBI predictions. However, for scenarios such as Beirut, where peak incident overpressures were relatively low (p_i<35kpa) and where secondary and tertiary blast injury mechanisms were dominant, such improvements in accuracy may have relatively limited benefit from an injury prediction perspective. Further work should examine the extent that blast wave interaction with Beirut's urban landscape modified the magnitude and distribution of loading conditions throughout the city to determine whether such modifications are significant from an injury risk perspective.

Some further limitations to the study are to be considered. The relatively small cohort size of 310 participants may not fully reflect the injury patterns of the whole injured population. However, injury patterns observed in the present study generally have close agreement with prior injury studies [7]–[10]. Furthermore, the present study does not consider levels of structural damage that occurred at the site of the participant. This will have also contributed towards tertiary blast injuries due to structural collapse, as found with the Oklahoma City bombing [22].

CONCLUSION

This paper reports preliminary findings from a larger study investigating the spatial and contextual factors that influenced the nature of blast injuries caused by the 2020 Beirut blast. Findings showed that injury patterns and severity correlated with distance from the blast epicentre.

Preliminary results from this study highlight the capacity and limitations of blast injury prediction methods through examination of a real-world, urban blast case study. While the accuracy of blast loading estimations can be improved through more advanced modelling techniques such as CFD, findings highlight the need for robust predictive injury criteria that can account for secondary and tertiary blast injury mechanisms, with the capability to distinguish between inside or outside spaces.

New knowledge from the wider study and improved methods to predict blast injury patterns and severities can help to inform and prioritise emergency responses (disaster management) and the protection of civilians exposed to urban blasts.

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