Area of coverage and sizing definitions of personal armour for UK Armed Forces personnel

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Abstract. Personal armour is worn by Armed Forces personnel and aims to prevent or mitigate the damage caused by projectiles to structures that are likely to result in death or life-changing long-term morbidity. Such injuries remain the leading cause of potentially survivable deaths on the modern battlefield. Defining anatomical coverage is necessary to enable objective comparisons between body armour designs and ensure Armed Forces personnel are sufficiently protected. Historically, protection has generally been provided to cover the whole population, as insufficient evidence existed to justify the coverage that should be provided for a given individual. This paper aims to summarise recent work that has been undertaken to define anatomical coverage for all areas of the body for hard armour plates and soft armour. Coverage was grouped into distinct areas that require coverage:

- Head and face
- Neck
- Torso (thorax and abdomen)
- Upper arm/axilla
- Thigh/pelvis

A systematic review of the literature was undertaken to identify those anatomical structures that, if damaged were highly likely to result in death or life-changing long-term morbidity. Anthropometric landmarks were identified for each area and Computed Tomography (CT) scans were utilised to determine how the internal anatomical structures corresponded to anthropometric landmarks and to define variation in the population. In addition, the lower borders of coverage for the upper arms and legs were related to the application of tourniquets. This is the first time that the medical area of coverage has been defined for personal armour for UK Armed Forces personnel. This paper also describes how the area of coverage is defined to industry and how coverage is compared between potential suppliers. Finally, plans for future studies using Magnetic Resonance Imagery (MRI) scans to determine 3D positions of structures in supine and upright positions is outlined; which will enable high fidelity coverage and modelling studies.

1. Introduction

Historically, protective equipment was designed to prevent death, but there is an increasing recognition that prevention of those injuries causing significant long-term morbidity is also required [1][2]. For example, ballistic eyewear has been worn for many years, but more recently pelvic protection was introduced due to the long- term morbidity from genital injuries [3]. However, any protective system will be a compromise, between the degree of protection and the encumbrance or 'burden' on the wearer. A programme to procure new body armour for UK Armed Forces personnel is currently underway and part of this programme is to optimise the anatomical coverage of the armour, which can subsequently be modified by factors such as tactical considerations on the ground, weight restrictions and equipment integration. This paper summarises this coverage work in its entirety; it is built upon numerous other papers that have been published for each body region [4-10]. For more insight into the rationale for each area the reader is encouraged to read the specific papers. Protection levels of armour should be selected to correspond to the prevalent threat that will be encountered, within the constraints of acceptable human factors considerations, however, this is outside the scope of this paper.

1.1 Methodology

The exact medical coverage requirements for UK body armour have not been openly published until recently, making objective comparisons between designs more difficult; Breeze *et al.* [4] introduced the terms *essential* and *desirable* structures to enable such comparisons. The essential and desirable medical coverage provided by a particular element of body armour are medical judgments and should be independent of the ballistic protective protection and material used. Essential medical coverage is the

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minimum coverage that should be provided to all Armed Forces personnel, although in reality, this will be subject to a degree of modification due to human factors considerations such as equipment integration and interoperability. The boundaries of the soft armour will be eventually determined by the 'trade-offs' in the requirements for mobility and acceptable thermal burden, and for all other areas a suitable level of basic armour should be used.

1.1.1 Essential medical coverage

Those anatomical structures that, if damaged would likely lead to death prior to definitive surgical intervention being available, for example, bleeding from the thorax that cannot be compressed and requires surgical access (thoracotomy) to arrest it. In recent military operations such as Afghanistan, it is recommended that damage control surgery be performed within 60 minutes [*].

1.1.2 Desirable medical coverage

Those anatomical structures potentially responsible for mortality which, if damaged, would cause morbidity necessitating lifelong medical treatment or that result in significant disability. This includes physiological disability as well as psychological disability, for example, damage to the lower parts of the spinal cord (lumbar or sacral parts) may result in significant loss of function of limbs, or damage to the genitalia may result in psychological trauma.

1.2 Vulnerable structures

A review of the medical literature was undertaken in order to ascertain those structures within the thorax and abdomen likely to lead to death or significant long-term morbidity. Using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) methodology, PubMed, ProQuest, Web of Science and Google Scholar were searched. Four limited-access sources (Ministry of Defence online library, the Barrington digital library at Cranfield University, the Dstl Athena electronic library and the proceedings of the Personal Armour Systems Symposia conferences) were also interrogated.

Anatomical structures were identified that, if damaged were highly likely to result in death within 60 minutes (essential medical coverage) or would cause death after that period or result in significant long-term morbidity (desirable medical coverage). A time period of 60 minutes from time of injury to arrival at either a Role 2 or 3 Medical Treatment Facility (MTF) capable of performing Damage Control Surgery (DCS) was chosen as this is the target of the UK Ministry of Defence [*] and the US Department of Defense [@]. Strictly defining the time to surgery and not just 'time to medical care' as used in the past is important as surgery is the only means of arresting non-compressible haemorrhage; fluid resuscitation, compression and novel haemostatic agents merely buy time. The essential and desirable coverage structures are defined in the following tables.

Table 1. Anatomical structures comprising essential coverage

Head and Face	Neck	Torso/Abdomen	Arms	Pelvis/legs
Brain	Spinal Cord (C1-C5)	Heart	Axillary Arteries	Iliac Arteries
Brain Stem	Carotid Arteries	Aorta	Brachial Arteries	Femoral arteries
Cerebellum	Vertebral Arteries	Vena Cava		
	Larynx	Liver		
	Trachea	Bronchial Arteries		
		Pulmonary Arteries		
		Pulmonary Veins		
		Spleen		
		Subclavian Artery		
		Subclavian Vein		

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Table 2. Anatomical structures comprising desirable structures

Head and Face	Neck	Torso/Abdomen	Arms	Pelvis/legs
Eyes	Oesophagus	Oesophagus	Median Nerve	Testis
Optic Nerve	Pharynx	Pharynx	Ulnar Nerve	Anus
Nose	Vagus Nerve	Lungs	Radial Nerve	Rectum
Lips	Brachial Plexus	Trachea		Sacral nerve
Ears	Vocal Cords	Kidneys		Femoral nerve
	Spinal Cord (Below C5)	Intestines		Urethra
		Spinal Cord (Below C5)		Ureters
		Spinal Nerves		
		Pancreas		
		Ovary		

Rationale into these definitions is not included in this paper due to brevity, however full details are available in the relevant papers [4-10].

1.3 Protection Levels

This paper focuses on coverage and not the impact on human factors of wearing protective equipment. In an ideal situation, personnel would be protected from every threat from every angle, however this is not feasible and so we define three general types of protection that can be used for coverage:

1. Hard armour has highest impact on human factors as it is often rigid, heavy and bulky;
2. Soft armour has less impact on human factors as it is flexible, but it still restricts movement and comfort;
3. Basic armour material is similar to regular clothing material, so is designed to have minimum impact on human factors, however it offers a low level of protection.

Therefore some compromises are always necessary. These armours are defined as follows.

1.3.1 Hard Armour

A rigid ballistic protective material designed to protect against high velocity bullets. This is currently fulfilled by a ceramic and composite plates.

1.3.2 Soft Armour

A flexible ballistic protective material designed to protect against low velocity bullets and high energy fragments. This is currently fulfilled in most systems by layers of Para-aramid and/or Ultra High Molecular Weight Polyethylene (UHMWPE) but could be comprised of various types of and/or combinations of materials. This can have water repellent treatment and is normally encased in a water repellent and ultra violet resistant cover. Soft armour material can also be pressed into a rigid material, for example, if used as a helmet.

1.3.3 Basic Armour

A flexible material that provides protection against lower energy fragmentation, such as the knitted silk used in the Tier 1 pelvic protection *(ballistic underwear)* currently utilised by the UK armed forces, and the Ultra-high-molecular-weight polyethylene (UHMWPE) used in the neck collar of the Enhanced Protection Under Body Armour Combat Shirt (EP-UBACS). Basic armour should be used in areas of coverage where a hard armour would severely impair mobility and/or comfort.

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2. Coverage definitions by body region

External anthropometric landmarks are identified that define the coverage boundaries of each of the body regions and correspond to the internal anatomical structures. Coverage is further defined as threshold and objective area of coverage

- Threshold coverage are areas that must be covered by a given armour and is associated with a high level of mortality (usually corresponding to the essential structures, subject to human factors considerations);
- Objective coverage are areas where coverage would be advantageous, but may only be achieved by a lower protection level or only used in a scalable system.

2.1 Head and face

The head and face are defined as the area above the base of the skull.

2.1.1 Area of coverage definition

Threshold coverage:

- Helmet coverage to be from the margins of the brain which relate to the nasion, external auditory meatus and superior nuchal line, as shown in Figure 1;
- This coverage only protects against horizontal trajectories (such as 'a' in Fig 1). It is unrealistic to protect from lower angle trajectories (such as 'b' in Fig 1) using a helmet.

Objective coverage:

- All areas;
- This could be achieved using a mandible guard and nape protection, but these should only be employed in roles considered high risk and when not limited by human factors.

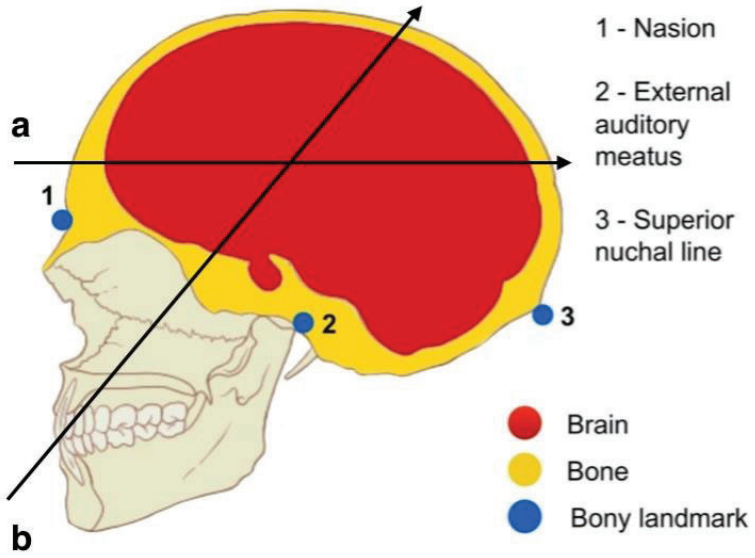

Figure 1. Landmarks for the brain with example trajectories 'a' and 'b'. Reproduced from [6] with permission of BMJ.

2.2 Neck

The neck is defined as the area below the base of the skull and above the suprasternal notch.
2.2.1 Area of coverage definition

Anatomical coverage of the neck according to essential and desired structures alone is not feasible due to human factors considerations. Therefore coverage of the neck is divided into 3 zones as depicted in Figure 2. These are defined as:

- Zone 1: Suprasternal notch to the cricoid cartilage;
- Zone 2: Cricoid cartilage to the lower border of the mandible;
- Zone 3: Lower border of the mandible to base of the skull.

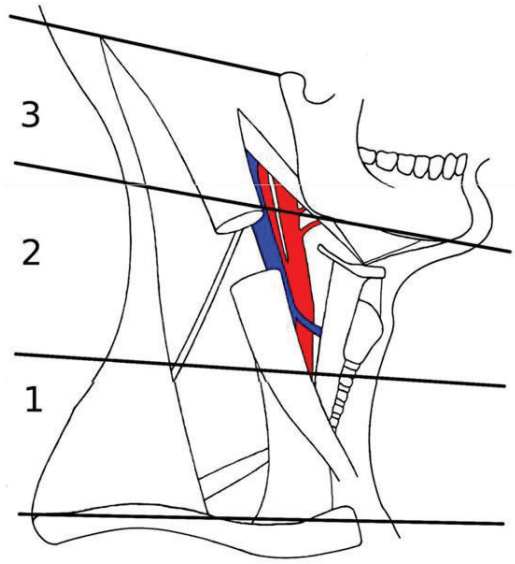

Figure 2. Landmarks of the neck.

Threshold coverage:

- Coverage must be afforded to Zone 1;
- The level of protection should be basic armour at the threshold level.

Objective coverage:

- Coverage to zones 1 and 2.
- Using combination of soft and basic armour.
- It is deemed unrealistic to cover zone 3 using neck protection with current technology.

2.3 Torso

The torso is defined as the area below the suprasternal notch and above the iliac crest; it is bordered laterally by the axillary fold.

2.3.1 Area of coverage definition

Coverage of the torso (thorax and abdomen) is defined from the three landmarks depicted in Figure 3.

1. Suprasternal notch;
2. Lower border of ribcage (10^{th} rib);
3. Iliac crest.

These correspond to the boundaries of the most vulnerable structures that are identified as the aortic arch, heart, liver and spleen, and bifurcation of aorta respectively [5].

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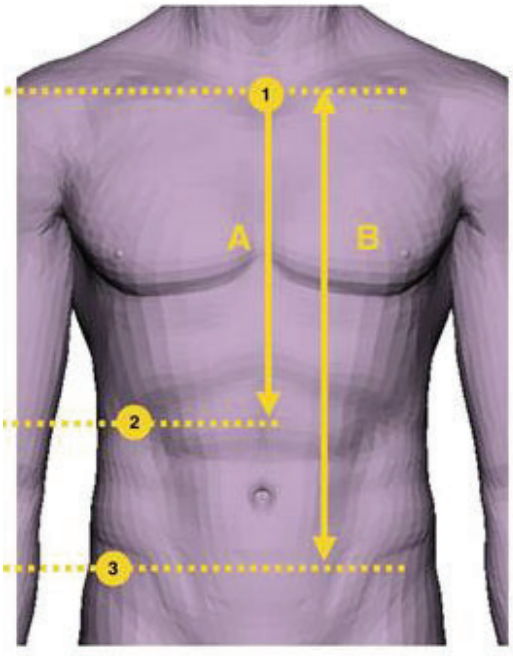

Figure 3. Suprasternal notch (1), lower border of ribcage (2) and iliac crest (3). Threshold height is A, objective height is B.

Threshold coverage:

- Coverage must be afforded from suprasternal notch to the lower border of rib cage.
    - The level of protection in this area should be commensurate to the threat of either small arms or fragmentation (corresponding to hard or soft armour respectively).
    - If hard armour is utilised then a further restriction must be placed upon the width, otherwise no movement would be feasible. This is summarised in Figure 4.
        - The top width must cover the heart
        - The bottom width must cover the liver and spleen.
- Coverage of all areas by basic armour that are not covered by hard or soft armours.

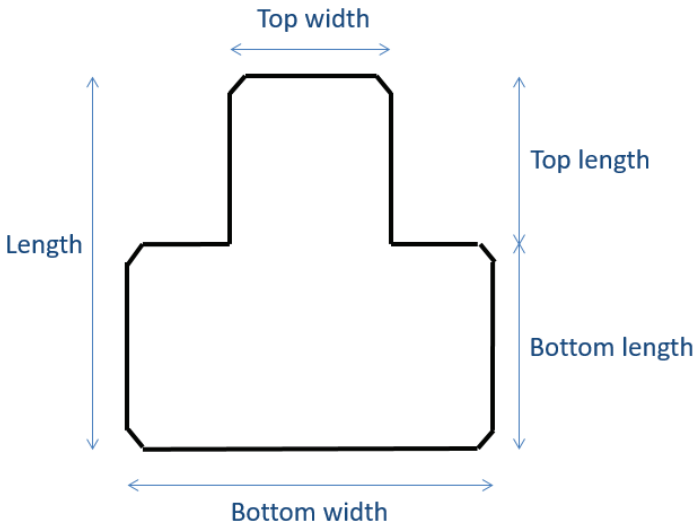

Figure 4. Definition of hard plate widths.

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Objective coverage:

- Coverage of all areas by soft armour.
- This should only be achieved up to a level suitable to human factors needs.

2.4 Upper arm/axilla

The Upper arm/axilla is defined as the areas lateral to the axillary fold, extending to the elbow.

2.4.1 Area of coverage definition

Coverage of the arm is defined from the three landmarks depicted in Figure 5.

1. Acromion;
2. Axillary fold;
3. Deltoid insertion.

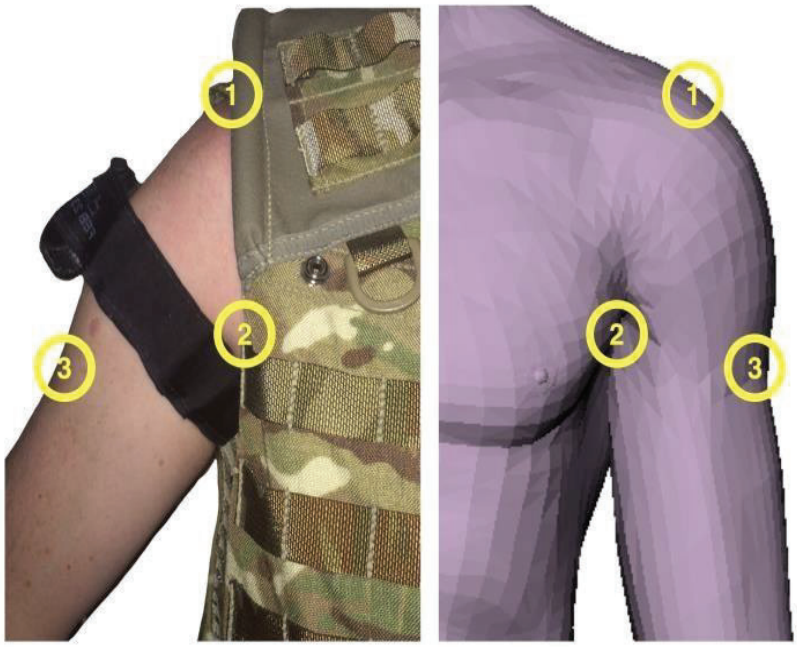

Figure 5. Landmarks of the arm/axilla, with example of application of tourniquet (left).

Threshold coverage:

- Coverage must be afforded to a sufficient distance below the deltoid insertion so that a tourniquet remains in place and is effective.
  - For the UK Armed Forces a distance of 40 mm below the deltoid insertion [9] was selected.
- Basic armour level of protection.

Objective coverage:

- Threshold area of coverage, but with soft armour level of protection.

2.5 Thigh/pelvis

The thigh/pelvis is defined as the area below the iliac crest, extending to the knee.

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2.5.1 Area of coverage definition

Coverage of the thigh/pelvis is defined from the two landmarks in Figure 6.

1. Iliac crest;
2. Ischial tuberosity.

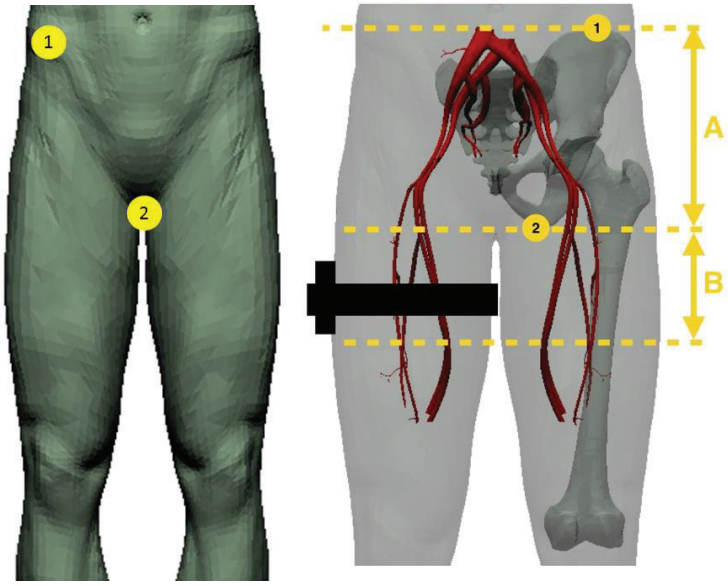

Figure 6. Landmarks of the thigh/pelvis (left). Example of application of tourniquet (right).

Threshold coverage:

- Coverage must be afforded to a sufficient distance below the ischial tuberosity so that a tourniquet (or two adjacent tourniquets) remain in place and are effective.
    - For the UK Armed Forces a distance of 100 mm below the ischial tuberosity was selected [10].
- Coverage at the threshold level is only required for the front, underneath and rear. Protection of the sides of the leg/pelvis area is not required.
    - This level was determined as it is commensurate with the current protection offered to UK Armed Forces personnel, which is deemed to be acceptable from a human factors perspective.
- Basic armour level of protection.

Objective coverage:

- Threshold area of coverage, but with soft armour level of protection.
- Coverage to a sufficient distance below the ischial tuberosity (so that a tourniquet remains in place) and is effective from all directions by basic armour.

3. Comparison of armours

When multiple armour solutions exist that achieve the threshold requirements, there is a requirement to objectively compare the coverage they offer so that decisions can be made on the best armour solution to procure or use. It is vitally important that the human factors performance is also assessed during this process so that an optimum solution is used and not just the one that offers the most coverage. There are two tools available to UK MOD for this purpose [11]:

- Coverage of Armour Tool (COAT)
    - COAT is a simple shotline tool. Geometrical elements that model the armour and body are represented. Vulnerable structures from Tables 1 and 2 are selected, the tool then calculates the percentage of coverage from azimuths and elevations that are selected by the analyst. An example grid is shown in a screen shot of the tool in Figure 7;

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- The percentage coverage of different armour solutions for areas of the body can then be objectively compared;
- This method assumes that all vulnerable structures are equally important and that uncovered shotlines pass through the entire body.

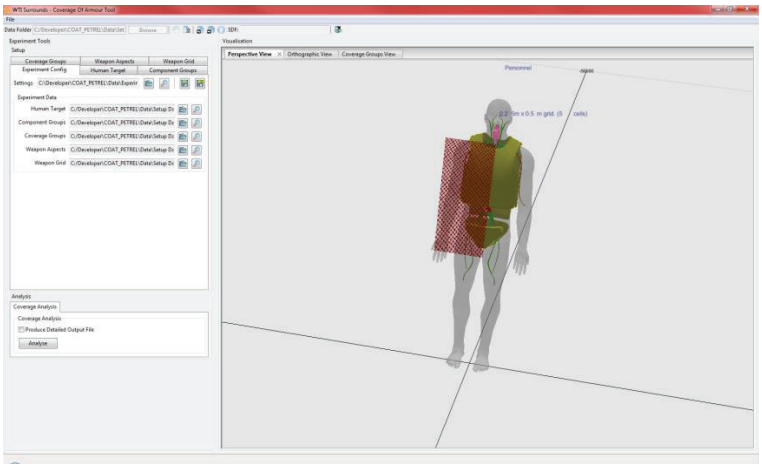

Figure 7. Screen shot of Coverage of Armour Tool.

- Weapon Target Interaction (WTI)
  - WTI is a terminal effects vulnerability model. It simulates the penetration through a human geometry, determines the volume of damaged tissue and outputs injury scores that are commensurate with the Abbreviated Injury Scale [12];
  - The injury scores for grids of shotlines, from user defined azimuths and elevations, can be calculated. The scores can then be weighted for different levels of injury to determine an objective coverage score;
  - Examples of a hard plate of the threshold dimensions from 0° and 20° azimnuth both at 0° elevation is shown in Figure 8.

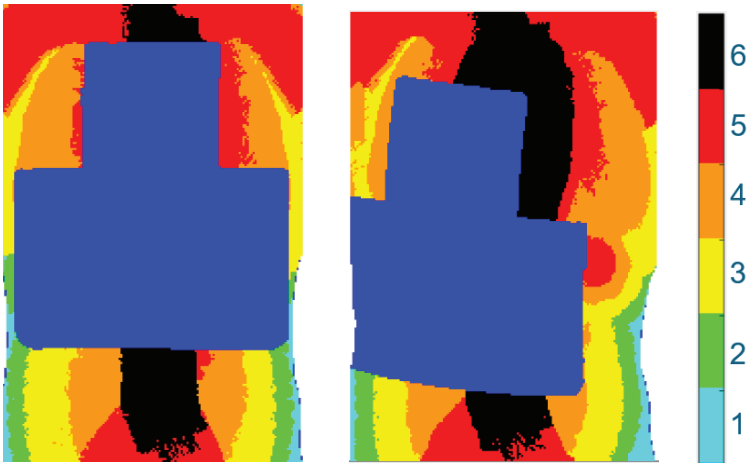

Figure 8. Example of output from WTI model. The blue area represents shotlines being stopped by the hard plates, the other colours correspond to AIS 1-6 as shown in the scale.

4. Future direction

The sizing for UK personal armour coverage is currently based on a range of measurements of the previously described anatomical boundaries from a variety of anthropometric data sources [13] and interrogation of anonymized Computed Tomography (CT) scans of injured military personnel undertaken at the Queen Elizabeth Hospital, Birmingham [5][9][10]. Whilst these represent the best data

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set available at the time, there are limitations such as the small amount of measurements of females and the lack of 3D geometry on which to assess ranges of sizes of armour. Currently all assessments using COAT and WTI are undertaken on the Zygote® geometry, which is close to a 50th percentile UK serviceman and STANAG 4512 target so allows for comparison, but there is no account taken on the effect of posture and it has been shown that the Zygote® geometry has many inaccuracies [14].

To address these shortcomings, a study to conduct MRI scans on a range of male and female subjects that represent the UK Armed Forces population is underway in association with the Sir Peter Mansfield Imaging Centre at the University of Nottingham. Subjects will be scanned in supine and upright positions, with major organs segmented to create representations of 3D geometry. From these scans the aim is to create an atlas of geometries that will cover all sizes of males and females of the population in a range of postures. In addition, the subjects will also be scanned wearing the current UK VIRTUS body armour system in the upright position to determine the current level of coverage as worn. When complete, this work will allow assessments of all sizes of body armour in a range of postures.

Finally, a medical area of coverage Defence Standard is in preparation from the recommendations in this paper which will form the basis of future UK body armour procurement.

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