Journal of Forensic and Legal Medicine 32 (2015) 77–83

Contents lists available at ScienceDirect

Journal of Forensic and Legal Medicine

journal homepage: www.elsevier.com/locate/jflm

Original communication

Refrigeration and freezing of porcine tissue does not affect the retardation of fragment simulating projectiles

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ARTICLE INFO

Article history:
Received 14 October 2014
Received in revised form
10 February 2015
Accepted 4 March 2015
Available online 13 March 2015

Keywords:
Gelatin
Ballistic
Penetration
Military

ABSTRACT

Explosively propelled fragments are the most common cause of injury to UK service personnel in modern conflicts. Numerical injury models to simulate such injuries utilise algorithms based upon gelatin and animal tissue testing but data is limited on many fragment simulating projectiles and these simulants cannot represent human anatomy. Testing with post mortem specimens may overcome this limitation but no information exists about how post mortem tissue changes and storage conditions in humans or animals may affect projectile penetration.

Two chisel nosed cylinders (0.49 g and 1.10 g) and a 0.51 g (5 mm) sphere were fired into three groups of porcine tissue (fresh, refrigerated and frozen then refrigerated) and compared to 20% gelatin. Depth of projectile penetration was ascertained with the assistance of computed tomography and kinetic energy absorption by tissues measured using Doppler radar and high speed photography.

No difference in depth of penetration was found between porcine tissue stored in the different manners compared with 20% gelatin by impact velocities less than 100 m/s. Insufficient numbers of projectiles were retained in tissue at higher velocities for statistical analysis to be undertaken. Energy absorbed per millimetre of tissue ranged between 0.42 and 0.98 J/mm for different porcine tissue despite differing storage.

This pilot study would suggest that the effect of refrigerating or freezing porcine tissue followed by thawing has no effect on its ability to retard these projectiles. Further research is required to ascertain if these results occur at greater velocities and for other types of projectile.

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1. Introduction

Explosively propelled fragments are the most common cause of injury to UK service personnel in modern conflicts.[1,2] Models capable of reproducing the penetration of these projectiles into human tissues improve analysis of causative mechanisms of injury.[2,3] Such models should ideally reflect the differences in retardation caused by different tissues within a particular type of anatomical structures as well as the shapes and boundaries of those structures. Traditionally such injury models have utilised tissue simulants and animal surrogates, but clear limitations exist with both.[2,4–6] Although animals can represent the tissue properties of a human, with the exception of primates none can adequately reflect true human anatomy.[2] In addition the 'biological variation' produced by penetration into heterogenous tissues means that large numbers of shots need to be undertaken to achieve any statistical conclusions.[4,7] In the past tissue penetration could only be measured by using a rod or dissection, resulting in potential distortion of the tissue architecture[8,9]; Computed Tomography (CT) has recently been used to supplement such information but as yet has only been used to scan samples after firing.[9] Gelatin is the most commonly used physical tissue simulant for ballistic testing. It is homogenous in nature and relatively cheap, enabling high volumes of testing to be undertaken.[5,6,10] However gelatin cannot simulate

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http://dx.doi.org/10.1016/j.jflm.2015.03.003
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the complex anatomical relationships between structures nor the mechanical properties of tissues other than muscle.

Numerical simulations of injury are likely to represent the future of injury modelling and considerable effort has already been invested in their development.[2] These simulations are desirable as they do not require the use of physical tissue simulants, with the potential to reduce costs, and prevent the requirement for animal testing. They can also represent the underlying anatomy in great detail, with the option of overlaying any design of body armour.[2] However the complex algorithms defining projectile penetration into different tissue types required to populate these numerical models in most cases does not yet exist.[2,7] These values can only be derived from mechanical testing of the representative biological tissues and it is likely that these will realistically take many years to produce.[2] In the interim it is proposed that algorithms of penetration based upon 20% gelatin will be used, with bespoke algorithms for each individual tissue type consecutively introduced with each generation of the model.

Ballistic testing utilising Post Mortem Human Subjects (PMHS) is a potential method for ascertaining the effect of human anatomy on projectile penetration that cannot be assessed using animal or tissue simulants. The use of PMHS in this regard has to date been extremely limited, predominantly revolving around testing of whole legs subjected to explosive blasts.[11] Historically PMHS have been used extensively in the automotive industry for crash testing,[12] and are still used by leading institutions in the US and UK to develop or validate combat injury models, particularly those of the leg and spine.[13] A trial utilising penetration of projectiles into the neck components of PMHS is currently planned as part of validation for the high fidelity finite element model of the neck project.[2] These specimens will be stored and transported in strict conditions post mortem to preserve their quality (Box 1).

Box 1
Anticipated storage conditions of PMHS specimens for future ballistic experimentation.

Preservation of post mortem subjects (PMHS) generally begins 2–3 h post mortem by refrigeration at 1 °C. Refrigeration continues for 24–48 h prior to dissection. Following dissection, specimens can either remain refrigerated or may be frozen and can be transported in either condition to their final location. Specimens are transferred to a refrigerator for 24 h prior to testing if frozen.

The effects of tissue changes that occur post mortem as well as the storage conditions on projectile penetration have never to our knowledge been described in the literature. Such storage conditions may affect the material properties and thus performance of animal tissue post mortem and this must be considered before PMHS are more widely used. It is generally agreed that freeze thawing results in cellular changes that significantly alter the mechanical properties of muscles[14–18] and arteries,[19] although the effects on tendons and ligaments are more contentious.[20–24] However while the post mortem effects on the tissue properties of skeletal muscle are substantial, it is not clear to what extent tissue response, especially failure properties, may be affected by preservation methods.

It is recognised that the advanced age (most are >60 years old at death) of many of these specimens may further affect the material properties and thereby measures of projectile penetration. In general the ultimate strength and elastic moduli of anatomical structures reduces with increasing age[16,17] and material properties are also known to be significantly affected by the method of storage of post mortem. Yamada's[16] classical experiments suggested that the best way to maintain material properties was to soak the specimen post mortem in physiological saline followed by refrigeration. However to our knowledge this is not the method in which human cadavers commercially available to UK organisations for research are stored post mortem.[11] Therefore the aim of this trial was to ascertain whether we could mimic those storage conditions that a PMHS would likely be subjected to with an animal surrogate and then compare the results of projectile penetration to that of a fresh subject using representative fragment simulating projectiles.

2. Method

2.1. Fragment simulating projectiles

Testing was undertaken using three FSPs each based upon the limited available open source information as to what are the most representative types produced by explosive weaponry in current conflicts.[8,9,25] Two sizes of chisel nosed (CN) cylinder were tested (0.49 g and 1.10 g) in conjunction with a 0.51 g (5 mm) sphere. FSPs were constructed in stainless steel utilising specifications described in the NATO Standardisation Agreement STANAG 2920.[26]

2.2. Firing, velocity and depth of penetration testing apparatus

FSPs were fired from a split polymeric sabot placed in a 7.62 × 51 mm cartridge case producing muzzle velocities up to 300 m/s (Fig. 1). Projectile impact velocities were measured using a W-700 Doppler radar (Weibel Scientific, Copenhagen, Denmark) and depth of penetration (DoP) was measured using a 2 mm diameter metal rod and a steel ruler. Penetration was defined as a projectile passing completely through the surface of the gelatin or through all layers of skin. Non-penetration was defined as a projectile bouncing off the gelatin surface or passing through less than the full thickness of skin. The term perforation was used to describe passage of a projectile through all layers of skin or a skin substitute.[8] High-speed photography was undertaken with a Phantom V12 high speed camera (Vision Research, New Jersey, USA; 6240 frames/second) to map velocity within the specimen and measure exit velocity, if applicable (Fig. 1).

2.3. Gelatin preparation and testing

Gelatin testing was undertaken using 5 mm spherical FSPs. Four 20% (by mass) type 3 photographic grade gelatin (Gelita UK Ltd, Crewe, UK) blocks were manufactured in 250 mm × 250 mm × 500 mm moulds and left to set at room temperature (18 °C). Twenty-four hours after manufacture, the blocks were conditioned for a further 24 h at 10 °C. Gelatin blocks were placed 3 m from the end of the barrel and forty eight 5 mm diameter spherical FSPs were fired into the ends with an equal distribution among blocks. This was used in combination with previous results of testing with 0.49 g and 1.10 g chisel nosed cylindrical FSPs that utilised a similar 20% concentration and method of preparation.[8,9] Each gelatin block was individually calibrated using the following protocol which is standard in our institution: a 4.5 mm steel sphere at 180 ± 4.5 m/s had to result in a depth of penetration of 38.1 ± 6.4 mm.

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