Preliminary Estimate for Injury Criterion to Immediate Incapacitation by Projectile Penetration

D. Bourget[1], S. Dumas[2] and A. Bouamoul[2]

[1]*Defence Research and Development Canada – Valcartier, 2459 Pie-XI Blvd North Québec (Québec) G3J 1X5, Canada, Daniel.Bourget@drdc-rddc.gc.ca*

[2]*Defence Research and Development Canada – Valcartier, 2459 Pie-XI Blvd North Québec (Québec) G3J 1X5, Canada*

Abstract: Immediate incapacitation is part of the requirements for many small arms acquisition programs around the world. The characterisation of the lethality of bullets and fragments against the protected human body can be performed using ballistic gelatine. A lethality criterion, based on the wound profile, is then applied to the wound track left by the penetrating projectile. The criterion includes the size of the cavity as well as the depth at which different features of the cavity occur. Ballistic gelatine (e.g. 10% at 4ºC and 20% at 10ºC) is a homogenous material that is calibrated to simulate human skeletal muscle but the actual target, that is, a protected human being, is composed of a variety of tissues with different mechanical properties. The questions then arise: How representative of the real target is ballistic gelatine and how does the observed depth of penetration in ballistic gelatine correspond to the actual depth of penetration in a real target? Assuming that immediate incapacitation occurs if a projectile hits the spine with sufficient energy to affect the spinal cord, how deep should a projectile penetrates a block of gelatine to be representative of a spinal impact on a real target?

To answer those questions, we compared ballistic gelatine (10% and 20%) and the actual target, i.e. a human torso, using the ComputerMan software. Based on anthropometric data, the human torso model size was changed and the depth of penetration of a typical fragment at varying velocity was computed. The characteristics of different tissues composing the human torso and their resistance to penetration are discussed herein. Based on our data, the probability of reaching the spinal cord with sufficient energy to cause immediate incapacitation is computed and discussed. The results of the simulation are compared to the injury criteria found in the literature regarding the distance of penetration (i.e. 30-45 cm).

1. INTRODUCTION

1.1 General

Canada is currently revisiting his small arms fleet and through a combination of phased upgrades and acquisitions will modernize his fleet by 2025. DRDC is engaged in a R&D program to support those upgrades and acquisitions. One of the requirements states that the weapon system should be improved such that its performance increases the probability of immediate incapacitation. In order to do that, disruption of the central nervous system (CNS) should occur. For a torso impact, this means being able to hit the spinal cord. There is currently no agreed upon criteria for assessing the probability of immediate incapacitation. The FBI and other researchers [1, 2] are using the 30 to 45 cm (12 to 18 inch) rule of thumb to specify if the projectile has penetrated deep enough to incapacitate a target. This rule of thumb is believed to be based on the observation that to hit critical organs (the CNS as well as the heart and large arteries), 30 to 45 cm of tissues (human or animal) has to be penetrated.

Ammunition and armour tests done in laboratories are executed on ballistic gelatine (NATO or Fackler's) or on ballistic soap, but not on actual animal or human tissues. Therefore, it is believed that the 30 to 45 cm penetration rule might be true for actual human or animal tissues but not for tissue simulant. Furthermore, it is believed that if applicable to tissue simulant, this rule is not valid for immediate incapacitation.

1.2 Objectives

Therefore, the objectives of this paper are to:

a) Assess the validity of the 30 to 45 cm of penetration range for immediate incapacitation
b) Assess how the probability of immediate incapacitation varies with the depth of penetration (DOP) inside ballistic gelatine.

The ComputerMan code was used to evaluate the equivalent thickness of gelatine that corresponds to actual torso penetration and to assess the probability of immediate incapacitation given the DOP in gelatine.

2. METHOD

2.1 ComputerMan software and its retardation algorithm

The ComputerMan software [3] includes a 3D representation of a male subject measuring 1.75 m tall. The representation is divided into 20 horizontal slices, 26 mm thick for the thorax, abdomen and pelvis. Each slice is divided into squares measuring 5 mm x 5 mm. Each cube is assigned one of the 296 different types of tissues (TID) composing the model (i.e. muscles, nerves, bones, etc.). Each cube is also assigned to one of nine generic tissue types. For each tissue type, parameters to calculate penetrating projectile deceleration are available. The generic tissue types are: cartilage (CA), scapula (VR), fat (BN), sternum (ST), rib (RB), lung (LN), liver (LR), muscle (MS), skin and subcutaneous (SK) and finally air (AS).
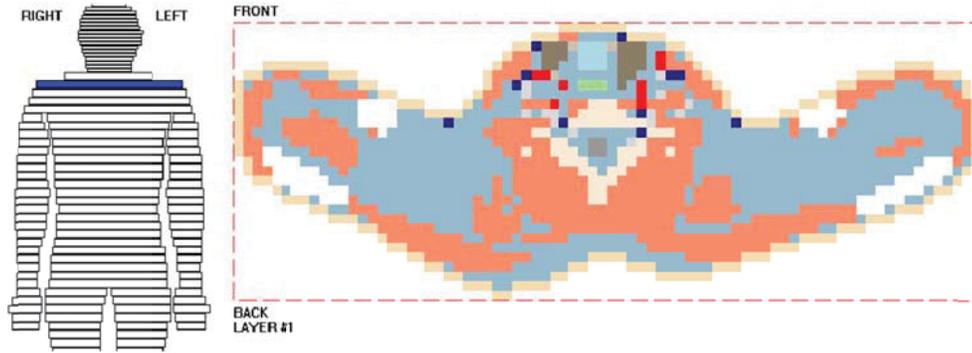
Figure 1 ComputerMan slice structure and details of a representative slice

Figure 1 illustrates the slice structure of ComputerMan. ComputerMan computes the deceleration of penetrating fragments using the following equation of retardation:

$$V = V_s - \left[AV_s + B + \frac{C}{V_s}\right]\frac{\Delta x}{\mu} \qquad (1)$$

Where,

$$\mu = \frac{m}{S_f\left(m/\rho\right)^{2/3}} \qquad (2)$$

In this equation: V_s is the striking velocity; A, B and C are coefficients depending on the tissue type; Δx is the tissue thickness in cm (and must be equal to 0.5 cm due to mesh size); and, μ is a parameter (2) describing the projectile. In Equation (2), m is the mass of the projectile in grams, ρ is the density of the projectile in g/cm^3 and S_f is the dimensionless shape factor of the projectile. In Equation (1), parameter A represents the dynamic pressure exerted by the tissue on the projectile. Parameter B

represents a viscous damping constant. Parameter C represents the tissue stress resistance. Each of these parameter have its relative importance depending on the value of V_s. Equation (1) is used as a relation to compute the deceleration ($\Delta V, (V_s - V)$ for a fixed value of Δx). Consequently, to ascertain the projectile's velocity after a penetration of, say x cm, the equation must be iterated through several Δx up to the value of x cm. Simply inversing Equation (1) produces a result which is not compatible to reality.

Figure 2 shows the depth of penetration of a steel sphere for different generic tissue types as a function of the projectile's striking velocity. As expected, the fat tissue, lungs and liver (BN, LR and LN) being the softest tissues, large amounts of these tissue are required to stop a projectile. Cartilaginous tissues, bones and skin (ST, SK, CA, RB and VR) are much harder. The scapula (VR) is very hard and can stop the projectile within a few centimetre of penetration. The muscle tissue (MS) is situated between those two groups.
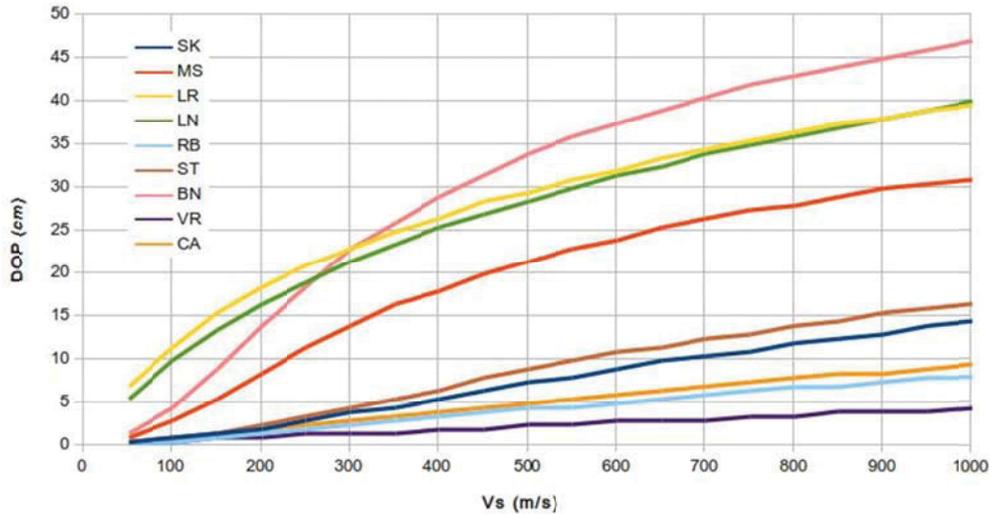

Figure 2 Depth of penetration of a steel sphere (d = 6 mm) for the different tissues in the ComputerMan database versus impact velocity

2.2 Relation between tissue type and equivalent muscle thickness

The muscle tissue (MS) thickness required to achieve the same deceleration as for another tissue T is given by the equivalent MS thickness. The ratio between the deceleration in a tissue T and in MS is given by (3), which is the key to the conversion process to obtain the equivalent muscle thickness. Note that references to the fragment size, shape and density have disappeared from (3).

$$\beta = \frac{A_T V_S + B_T + {C_T}/{V_S}}{A_{MS} V_S + B_{MS} + {C_{MS}}/{V_S}} \tag{3}$$

This ratio changes with the striking velocity, V_s as shown in Figure 3. It peaks around 14 for scapula (VR) at low impact velocities. This indicates that for low V_s values, the type of tissue matters. This is because at low impact velocities, strength of tissue (parameter C of (1)) is of primary importance in the penetration process. For high impact velocities ($V_s > 1,500$ m/s), the ratio reaches constant values (with $\beta \approx 2$ for scapula (VR) at maximum).
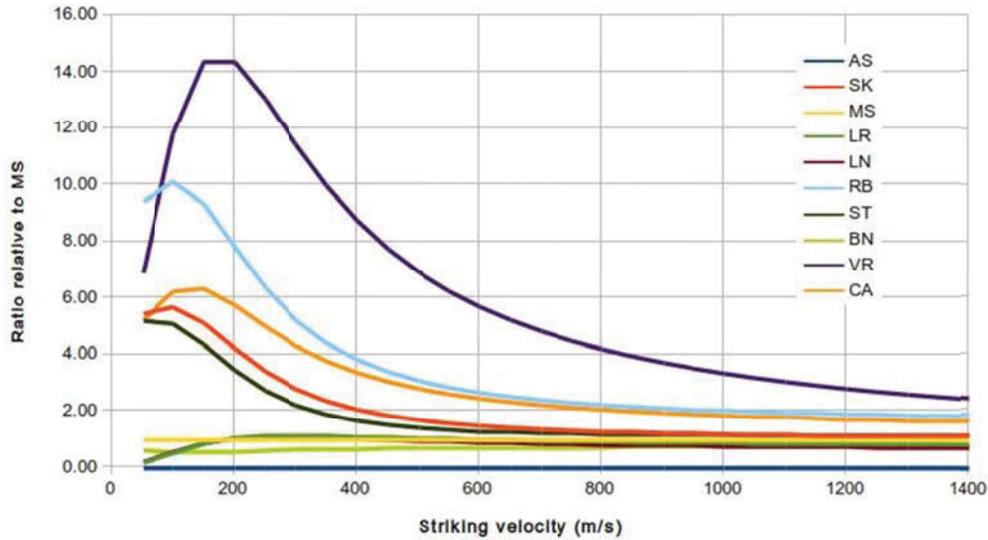
Figure 3 Ratio of retardation $\boldsymbol{\beta}$, following Equation (3) between any given tissue (T) and muscle tissue (MS). Some curve overlap
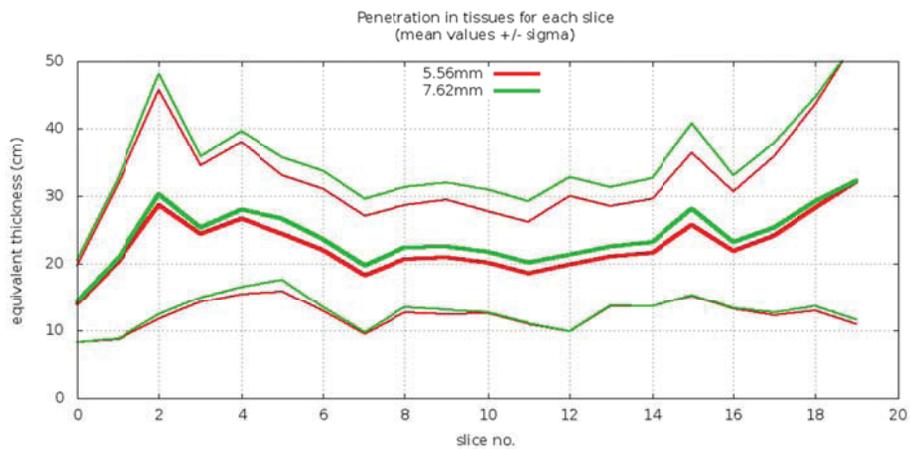
2.3 Computing equivalent muscle thickness

Since immediate incapacitation following disruption of the CNS [4] is the primary objective of this study, equivalent muscle thickness is calculated starting at the spinal cord for each slice. Using iterative backward retardation calculation based on (1) and the equivalent muscle thickness ratio from (3), equivalent muscle thickness is calculated. This calculation is executed for impact velocities at the spinal cord of 0 m/s. It is therefore assumed that the injury criterion for immediate incapacitation is contact of the projectile with the spinal cord which corresponds to an AIS 5 injury [5] in the ComputerMan database. These calculations were done for horizontal shotlines at each 10 degree azimuth all around the ComputerMan torso model and for two different projectile masses corresponding to typical 5.56 mm and 7.62 mm projectiles. For ComputerMan, it is assumed that the projectiles are steel cylinders of diameter 5.56 mm and 7.62 mm weighing 4.0 g and 9.75 g with a length to diameter ratio of 3.8 and 2.7, respectively.

Typical equivalent muscle tissue results are shown for one slice versus impact azimuth (Figure 4) and for different torso region slices (Figure 5). The asymmetry observed in Figure 4 for the MS tissue occurs due to the natural human torso asymmetry. In Figure 5, it can be observed that different slice result in different equivalent MS tissue. Maximums are occurring at slice 2, 4, 15 and 19. Large bony and cartilaginous structures are present in those slices, e.g., slice 2 contains shoulder joints and scapula and slice 19 contains sacrum and wing of ilium. Similarly, minimums are observed at slices 0, 7 and 11. Slice 7 is largely composed of lung tissue and slice 11 is principally composed of fat and liver tissue.
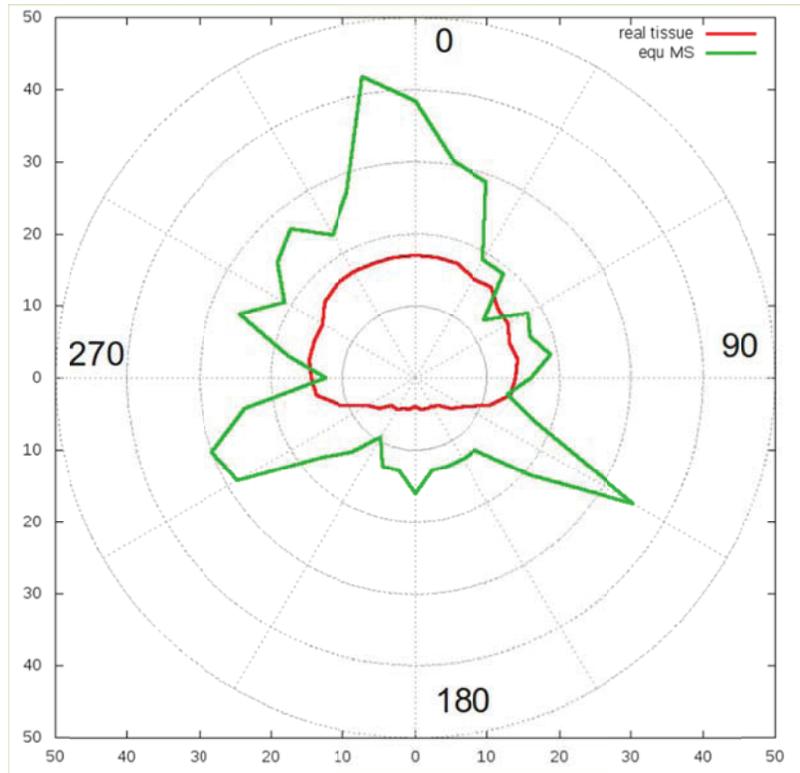
Figure 4 Example of equivalent muscle thickness for a single slice (in the thorax) as a function of the azimuth. 0 degree is the front (top of the page) and -180/180 is the back. Point 0,0 is the center of the spinal cord.


Figure 5 Equivalent muscle thickness statistics for the different section of the torso. Thick lines represent mean values; thin lines represent ± one standard deviation.

3. PENETRATION DEPTH IN 10 %, 4 °C GELATINE

The actual equivalent penetration depth for 10 % gelatine was determined using the process described above. Parameters A, B and C of equation (1) were determined by fitting equation (1) on the ballistic gelatine penetration depth data from [7] . These tests were done independently by France, The Netherlands and Belgium with 5.5-mm steel spheres shot at velocities varying from 175 to 625 m/s against calibrated NATO and Fackler gelatine. Figure 6 presents the fitted curves with the actual

muscle tissue (MS) curve from ComputerMan. This shows that the muscle tissue curve used in ComputerMan is very close to the NATO gelatine values.
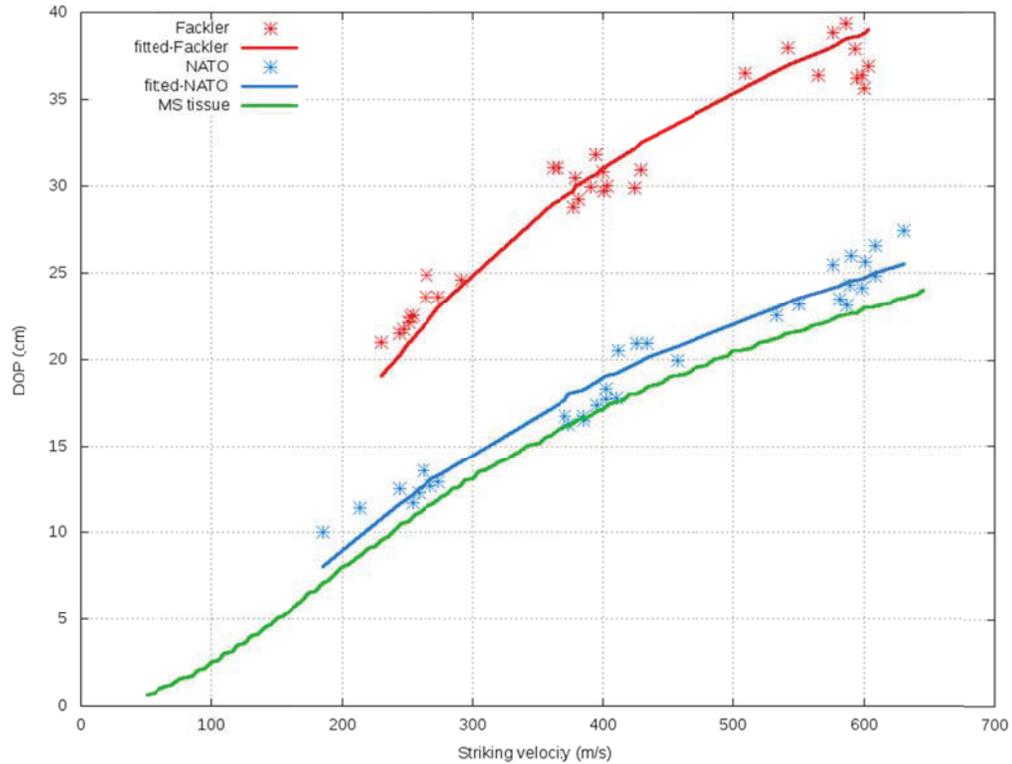
Figure 6 Equation (1) fitted against NATO WG/4 data [7] for Fackler and NATO gelatine

Retardation coefficients as fitted are presented in Table 1.

Table 1 Calculated retardation coefficients

| Data set	A	B	C
NATO	0.265	-4610	8.08e+07
Fackler	0.221	-4174	5.08e+07

4. RESULTS

4.1 General

Based on the calculated equivalent thickness of Fackler's or NATO gelatine that needs to be penetrated in order reach the spinal cord, it is possible to calculate the cumulative probability of causing immediate incapacitation versus the depth of penetration in gelatine. This is calculated by taking the equivalent thickness of gelatine to reach the spinal cord for each shotline and to add the number of occurrence for each centimeter of equivalent thickness. Therefore the cumulative probability of causing immediate incapacitation for a certain DOP in gelatine should be seen as the probability that the spinal cord can be impacted for random impact location over the torso but for shots aimed toward the spinal cord.

4.2 Cumulative probability of causing an immediate incapacitation

Data presenting the cumulative probability of causing an immediate incapacitation (barely touching the spinal cord) versus the depth of penetration are presented in Figure 7 (Fackler's gelatine) and Figure 8 (NATO gelatine) for 4 g, 5.56-mm diameter and 9.75 g, 7.62-mm diameter projectiles. In order to get a feeling of the effect of body size on immediate incapacitation, the original geometry of the ComputerMan was inflated or deflated to fit with the 95th percentile and the 5th percentile male.

Height, width and depth of the torso were scaled up of down following available anthropometric data [6], the original ComputerMan anatomical model fitting closely to the 50th percentile male. Data are presented below are for the 5th, 50th and 95th percentile male.
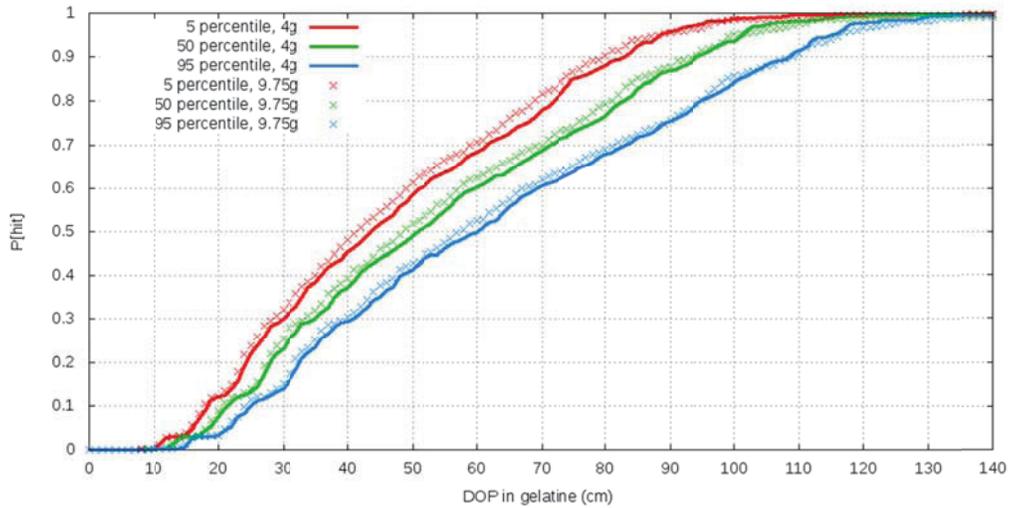
Figure 7 Probability to cause immediate incapacitation (P(hit)) as a function of DOP in 10% gelatine
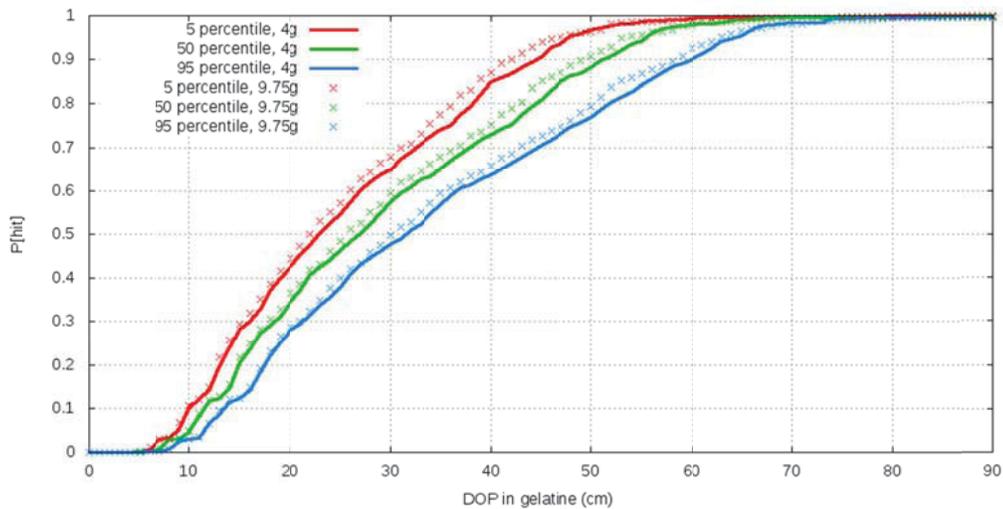
Figure 8 Probability to cause immediate incapacitation (P(hit)) as a function of DOP in NATO gelatine

Data shows that the probability of immediate incapacitation for 5.56 mm and 7.62 mm projectiles are close (approximately 3 cm difference), regardless of the type of gelatine. The difference between 50th and 95th percentile and between 50th and 5th percentile is larger, reaching a maximum of approximately 12 cm. Lastly, the difference between the 10% and 20% gelatine is approximately 25 cm for a 50% probability of immediate incapacitation.

Based on those curves, it would appear that the rule of thumb used in wound ballistic of 30 to 45 cm DOP is not realistic for immediate incapacitation. Much deeper penetration should be attained to reach higher probability of occurrence of immediate incapacitation. For example, a 90% probability of immediate incapacitation is reached after 50 cm of penetration in NATO gelatine and after 94 cm of penetration in Fackler's gelatine. Conversely, the 30 cm DOP value corresponds to a 24% and a 57% probability of immediate incapacitation for the Fackler and NATO gelatine, respectively, the corresponding probability of incapacitation for a 45 cm DOP being 44% and 82%. It is believed that if other critical organs such as the heart and large arteries have been taken into account in the current

study, the DOP required to reach high probability of incapacitation would be reduced. However, incapacitation would be occurring within a much longer timeframe (7 to 10 seconds) since the incapacitation mechanism would change from CNS disruption to circulatory system collapse [4].

4.3 Limitations

The main limitation of our study is that all calculations were done for shotlines aiming at the spinal cord. Therefore, the probability of immediate incapacitation referred to in this paper should be understood as being the probability of immediate incapacitation given that the spinal cord is aimed at. The immediate incapacitation probability presented being a function of the shooter's skills might therefore be overestimated. Another limitation is that the projectiles used to execute the simulation are cylinders made of a single material. Because the drag coefficients of cylinders are different compared to actual bullets, this might result in a different equivalent thickness of gelatine value compared to those presented herein. Finally, other depth of penetration factors like tumbling, fragmentation and bullet construction are not taken into account in the presented calculations.

5. CONCLUSIONS

Numerical simulation was used to evaluate the DOP in ballistic gelatine that is equivalent to the penetration of a human torso such that immediate incapacitation is achieved. The results show an increase in the probability of causing immediate incapacitation versus DOP. They also show that much deeper penetration must occur in Fackler gelatine compared to NATO gelatine to reach similar immediate incapacitation probability. Lastly, it appears that the rule of thumb for penetration in gelatine (30 to 45 cm) is not adequate for assessing immediate incapacitation.

6. REFERENCES

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