Chapter 2 – THE MINE DETONATION PROCESS AND OCCUPANT LOADING

As mentioned in Chapter 1, the HFM-090/TG-25 work focuses on the blast mine threat under vehicles (AP and AT mines). Other types of mines are excluded from the current report. After a blast mine detonation, a shock wave goes through the vehicle. Elastic and also plastic deformation (sometimes even ruptures) together with a global impulse occurs. If the integrity of the vehicle is preserved, predominantly the shock, deformation and global impulse have effect on the occupants inside the vehicle. Otherwise also primary, secondary and miscellaneous blast effects, like overpressure, secondary fragments, toxic fumes and gases, and heat radiation are threats to the occupant.

In Section 2.1, a short introduction to mines is given. In Section 2.2, the process of the effects of a blast mine detonation under a vehicle is described. In Section 2.3, the human body loadings generated by the blast mine effects are discussed.

2.1 INTRODUCTION TO MINES

A large variety of mines exists as mentioned in Chapter 1. These mines can be classified according to target and on damage mechanism:

- Anti-Personnel (AP) mines:
  - Blast mines
  - Fragmenting mines
- Anti-Tank (AT) mines:
  - Blast mines
  - Shaped charge mines

The **AP-mines** are used to injure hostile personnel in order to stop their activities. Most of these mines are activated by a pressure fuse, and they contain a small amount of explosives (up to 250 grams) – enough to cause severe injury to the foot, ankle and leg of someone stepping the mine. Other types of AP mines are activated by a trip wire and cause a blast and a spray of fragments. A special fragmenting type is the bounding mine. First, this mine springs approximately one meter high and then detonates. The fragments are spread 360 degrees around the mine and are very effective in killing or injuring personnel. This mine is also effective against non- or light armoured vehicles as the fragments can penetrate into the vehicle and hit the occupants. The blast load of a detonating AP mine close to a vehicle can also harm the occupants. In some cases fragmentation and blast seem to have cumulative effects.

The **AT-mines** are originally used in mine field barriers to stop the main battle tanks of the enemy. Nowadays they are used in any conflict area and against all types of vehicles. The first generation mines use a pressure fuse activated by loads of more than 200 kg from the vehicle's wheels or tracks. The large amount of explosive (up to 12 kg) causes extreme blast loads resulting in severe damage (at least a mobility kill) to the vehicle. The second generation of AT mines uses tilt rods or magnetic/seismic influence fuses so that they can also detonate under the bottom of the vehicle. These fuses are also used in combination with the shaped charge mines. These mines when detonated form a projectile or a jet (hollow charge mine), which can perforate thick (armoured) plates. A special variant is the Explosively Formed Projectile (EFP) or Self Forging Fragmenting mine (SFF). They form a big slug, which is launched at very high speeds against the target. All these types of AT mines are designed to detonate under the vehicle. The third generation of AT mines are the off-route or the top-attack mines with sophisticated fuses,

but these are out of the scope of this report. The STANAG 4569 decided to focus on the effects of blast mines under vehicles.

2.2 THE EFFECTS OF AN ANTI-VEHICLE BLAST MINE DETONATION

This section describes the four types of effects of the blast mine detonation under a vehicle:

- Local effects;
- Global effects;
- Drop down effects; and
- Subsequent effects.

More background on these effects can also be found in [Dosquet, 2006]. A description of the physics of blast mines in general can be found in [RTO-TR-HFM-089, 2004].

2.2.1 Local Effects

After initiation of the blast mine under a vehicle a shock wave is formed by the detonating explosive. This shock wave hits the bottom plate of the vehicle within approximately 0.5 ms and is subsequently reflected causing an extremely large peak pressure resulting in a local acceleration of the bottom plate. Within approximately 5 ms after the detonation the bottom plate bends in both the elastic and plastic regions depending on the shape, thickness, material and additional stiffeners. Sometimes the bottom plate deformation exceeds the elastic region and causes ruptures and hence, possible overpressure, fragmentation, heat and toxic effects inside the vehicle. The shock wave also causes a mechanical shock in the material of the vehicle structure, which travels with speeds up to 5000 m/s through the whole structure and causes strong vibrations in all vehicle parts. Depending on the boundary conditions, the bending bottom plate may cause deformations in the side walls of the vehicle. All parts mounted on or just above the bottom plate, like torsion bars, can be hit and accelerated in an upward direction.

2.2.2 Global Effects

Due to the reflecting blast wave under the vehicle, a pressure force briefly acts on the complete bottom section of a vehicle. The total impulse load of this pressure force is a measure of the initial vertical velocity causing a jump of the complete vehicle (which follows the impulse law for rigid body motion). The jump height depends on the total mass and, for asymmetric loading, on the moments of inertia around the centre of gravity. In general, it takes about 10 to 20 ms after detonation before the complete vehicle starts moving and 100 to 300 ms before it reaches its maximum jump height.

The time sequence of the mine detonation process and of the local and global effect is presented in Figure 2.1. Some time overlap of the processes is possible.

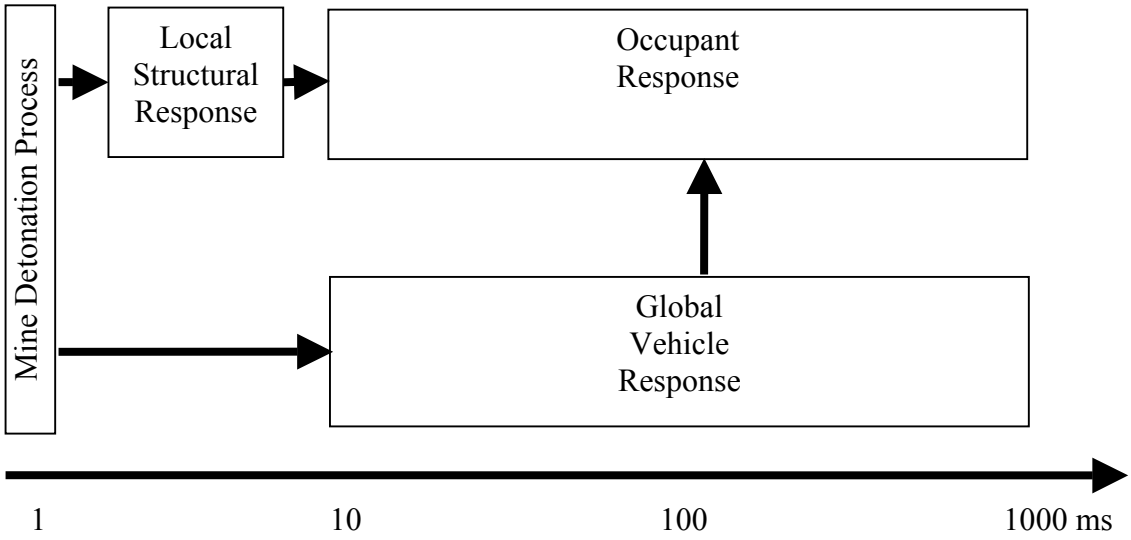

Figure 2.1: Time Sequence of Events during an AV Mine Detonation.

2.2.3 Drop Down Effects

After reaching its maximum jump height the vehicle will fall due to gravity. In actual incidents the vehicle is driving and will not drop down on the original place, whereas in an experimental set-up, the vehicles are tested in a static situation. Therefore, it is possible that the vehicle drops down into its own crater, which can result in higher vertical loadings than in an actual incident. Higher loads can also occur due to elements in the test set-up itself, like steel plates on the drop down surface. Experience in full-scale mine trials showed loadings that were significant during the drop down phase. Most of the time, they were not as important as the ones generated by the initial phase. If the prevention system is damaged during the initial phase, it can result in higher injuries from the impact occurring during the drop down phase.

When testing only the drop down phase, it needs to be taken into account that the initial position of the occupants is not based on the loads of the mine detonation, but on the position the occupants are placed in.

2.2.4 Subsequent Effects

Subsequently, incidents like roll over and frontal crashes after the mine detonation are not considered due to high variation of boundary conditions. This must be considered in crashworthiness investigations.

It should be noted that besides the blast, resulting in acceleration of the vehicle and occupants, other effects for the occupants can also occur, especially when an EFP mine or a shaped charge mine results in penetration of the vehicle. For these cases the resulting fragments, toxic fumes and gases, blast overpressure and heat are serious threats for the human body as well. However, HFM-090/TG-25 focuses on the effects of a blast mine detonation under a vehicle, and this report follows that approach.

2.3 OCCUPANT LOADING

The analysis of vehicle mine incidents [Medin, 1998; Radonić, 2004] is necessary in understanding the effects of blast mine detonations under vehicles on the human body. However, information is often classified, not/hardly available, or insufficiently detailed. Therefore, experimental as well as numerical research is performed to achieve this understanding. In full-scale tests, the loads on the occupants are

measured using instrumented anthropomorphic test devices (ATDs) – widely known as crash test dummies- together with other measurement equipment like sand bags, pressure gauges and accelerometers placed inside the vehicle. An ATD is able to withstand crash and vehicle mine detonation tests while simultaneously (and reproducibly) measuring the accelerations, forces and moments in different body parts. The results of these measurements may be used as input for injury assessment and for numerical studies with for example the occupant safety code MADYMO (Mathematical Dynamical Models). In this section, the occupant loading caused by a blast mine detonation under the bottom, the wheel or the track of an (armoured, light-armoured or logistic) military vehicle is described.

It is expected that once the vehicle integrity is secured, effects of fragments, overpressure, gases and heat will have minor physical effects on the occupant inside the vehicle. However, the acceleration effects still occur. The response of the occupant inside the vehicle is influenced by both the local effect (shock and deformation) and the global effect (vehicle motion) of the vehicle mine detonation process (see Section 2.1). The human body or parts of the body can be loaded directly by the shock (primary effect) or by the local deformation (secondary effect) or indirectly by the relative body motion and resulting impacts to the vehicle structure (tertiary effect) [Dosquet, 2004]. The severity of the threat, and therefore, the severity of the loads on the occupant, depend on the distance between the casualty and the detonation point as well as on the vehicle structure, the interior structure, like seat and seat mountings, and the foot plate configurations (e.g. [Radonić, 2004). When a seat or a footrest is mounted on or close to the deforming bottom plate large loads are most likely transferred to respectively the feet, the ankles, the legs and the lumbar spine. Additionally, the chance of injury depends on initial body posture, the presence and use of personal protection equipment and restraint systems. Also age, gender, health, training, etc., may influence the injury probability.

In general, the leg and foot/ankle complex are usually in the position closest to the detonation point and the deforming structure, so they are loaded first. When the feet are placed on the bottom plate or on a floor plate close to the bottom plate, they are loaded severely and accelerated rapidly (see Figure 2.2). The loads can reach levels high enough to crush feet, ankles, legs and knees. Due to the acceleration force, the legs move upwards with the risk of hitting other vehicle parts. The leg motion may also have its influence on the lumbar spine and other body parts.

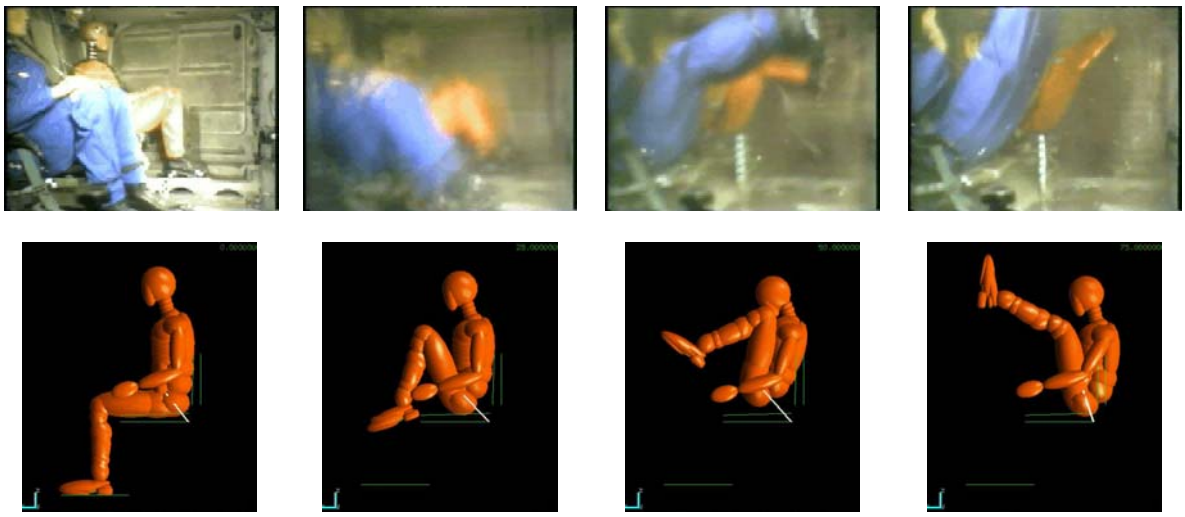

Figure 2.2: Experimental and Numerical Example of Severe Leg Load Situation [Horst, 2002].

The pelvis can be loaded through either the lower extremities or the seat of the vehicle. For seat mountings on the bottom plate, the pelvis will be loaded at about 10 ms after detonation, the severity depends on the

seat suspension system. When a seat is mounted to the side or the roof, the maximum acceleration is reached later (15 to 30 ms) and is usually less severe. The vertical acceleration and motion of the pelvis will cause a compression force in the lumbar spine, which can result in injury. For local effects the maximum spine force is reached at about 20 ms after detonation [see Figure 2.3 and Leerdam, 2002], for global effects the maximum will be at about 40 ms [see Figure 2.4 and Leerdam, 2002].

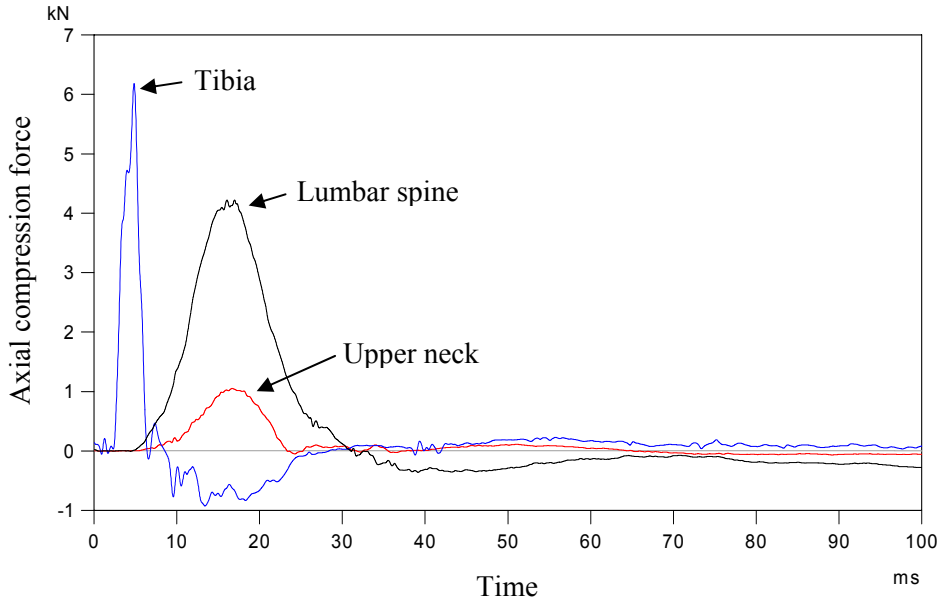

Figure 2.3: Example of Axial Compression Force Signals in Tibia, Lumbar Spine and Neck for the More Local Effects Caused by a Mine Detonation under a Vehicle.

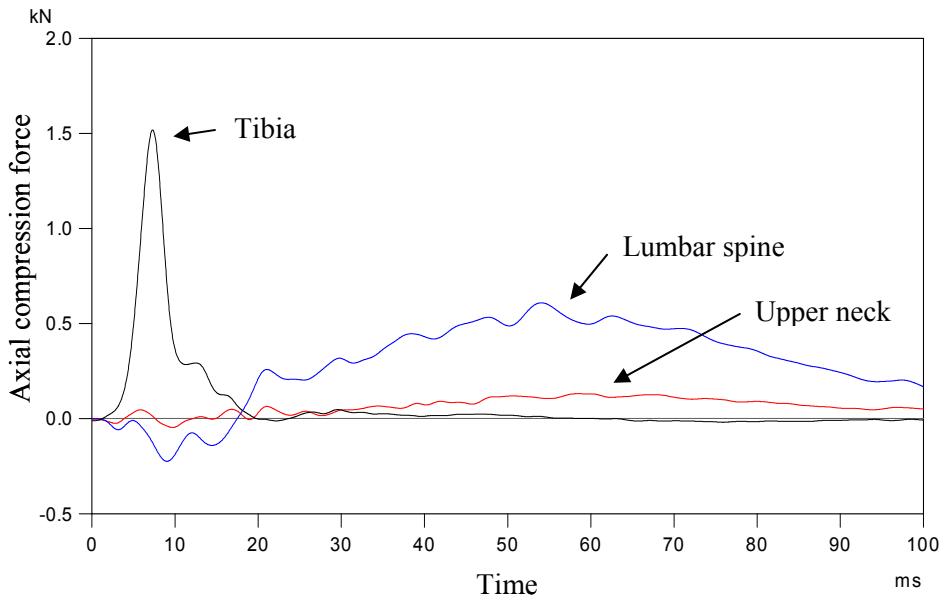

Figure 2.4: Example of Axial Compression Force Signals in Tibia, Lumbar Spine and Neck for the Global Effects Caused by a Mine Detonation under a Vehicle.

The pelvis acceleration and motion will also load the upper body parts, including the neck and the head. The whole body will be launched (mostly) vertically due to the seat impact. When no or inappropriate restraint systems are used, the head can hit the roof of the vehicle. Tests have proven that head contact with a stiff roof structure may cause high acceleration peaks in the head and extremely high loads in the neck. Such high neck loads are life-threatening and must be prevented.

Examples of the force signals measured using ATDs are shown in Figures 2.3 and 2.4, which show that the local effect shows higher peaks than the global effect. The peak values also occur earlier and last shorter. It should be noted that the global and local differences are difficult to distinguish for the feet, ankles and legs. The body parts mentioned in the figures are explained in Chapter 3, but it should already be mentioned that the tibia is part of the lower leg and the lumbar spine is part of the lower back.

Figure 2.5 shows in general terms the time sequence of events on the human body. The loading duration as well as the time at which the peak load occurs are presented for several body parts. This graphic is based on a database of test data for vehicle mine protection studies [Leerdam, 2002]. Over 15 tests were used for this graphic. As in Figure 2.3 and 2.4, it is seen that the duration of the global effects is longer and that the peak values occur later. Because of the difficulties in distinguishing the local and global effects for the feet, ankle and legs, only the local effects are shown.

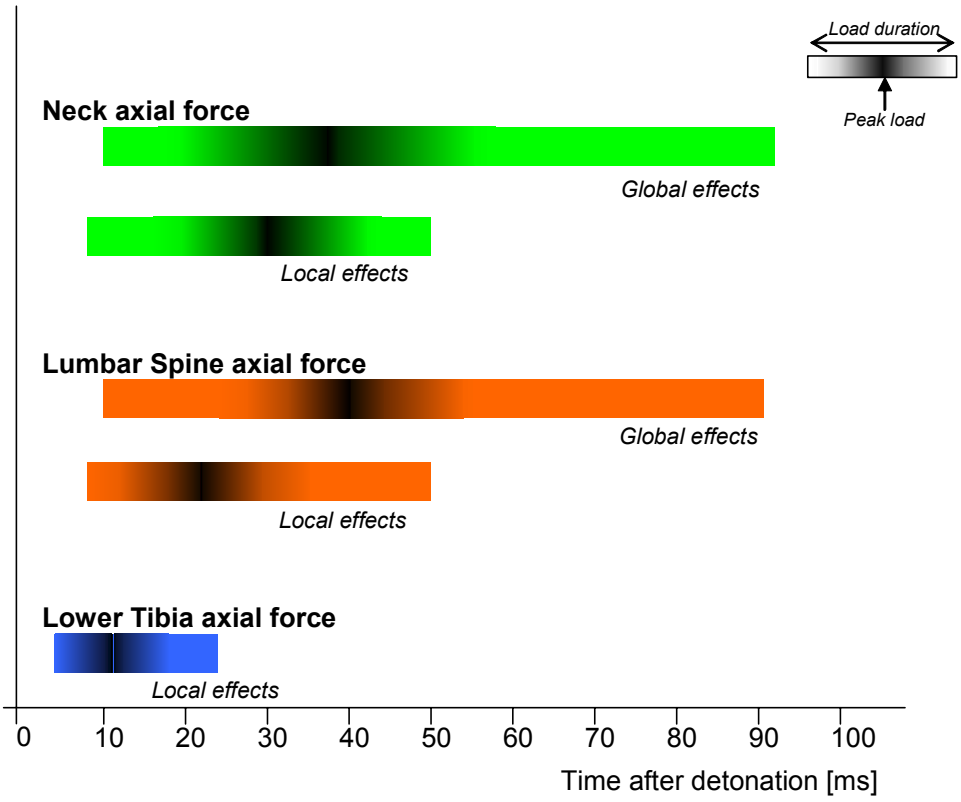

Figure 2.5: Loading Process in Human Body Due to Mine Detonation. Based on test data [Leerdam, 2002].

The initial loading effects to the human body happen within ~50 ms after detonation of the mine under the vehicle. For the global effects it takes about twice as long. Depending on the integrity of seat structure and belt system and on the free space for body motion, contacts between body parts and vehicle objects can occur as long as the entire vehicle is moving. Usually within one second after detonation the vehicle and the occupants come to rest again.

Although not the main focus of this work, the drop down phase should be taken into account also. During this vertical drop of the vehicle, the human body is loaded in the same direction, although the shape of the signal may differ from the loading of the mine detonation. Depending on the severity of this drop down phase as well as on the body posture and the damage to the vehicle just after the mine detonation additional injuries can occur. For example a specific seat system can prevent the body from serious injuries during the first phase, but after this event, the systems can be damaged and may not prevent the body for additional injuries during the drop down phase.

As mentioned at the beginning of this section, the acceleration effects are assumed to have major effects on the human body, because the other effects are considered to have minor effects when the vehicle integrity is secured – but effects resulting from toxic gases and heat may cause serious injuries when occurring [Medin, 1997]. Readers that are interested to these threats for the human body are referred to the literature for more information, e.g. [Ripple, 1990; Stoll, 1968; SFPE, 2000]. Fragments or loose objects that arise in the vehicle cabin can cause serious penetration or blunt injuries (e.g. [Sellier, 1994]). The blast overpressure effects inside the vehicle may cause injuries to auditory and non-auditory organs/systems. Although the overpressure effects are expected to be small when the vehicle integrity is secured, it was decided to include overpressure injury assessment in the proposed method. The fragmentation effects and loose objects can be neglected due to the required integrity of the hull.

In the following chapter, the injury criteria and tolerance levels for the biomechanical as well as the overpressure effects are discussed for each of the identified vulnerable body regions, which are the lower leg (leg/ankle/foot), the spine (thoraco-lumbar and cervical regions), the head and the non-auditory internal organs/systems.

2.4 REFERENCES

Dosquet, F. (2004), Mine protection becoming more and more important, European Safety Symposium (original) : Minenschutz immer bedeutsamer, Europäsischer Sicherheit, September 2004.

Dosquet, F. (2006), Overmatch analysis as enhancement for conventional protection analysis. Third European Survivability Workshop, Toulouse, France, May 2006.

Horst, M.J. van der and Leerdam, P.J. (2002), Experimental and Numerical Analysis of Occupant Safety in Blast Mine Loading Under Vehicles, In Proceedings of International IRCOBI conference on the biomechanics of impact. Munich, Germany, pp. 355-356, ISBN 2-9514210-3-6.

Leerdam, P.J.C. (2002), Research experiences on vehicle mine protection, First European Survivability Workshop (ESW), February, 2002, Germany.

Medin, A. (1997), Blast overpressure, gases and fumes from a HEAT warhead caused temporary incapacitation to the crews of two attacked armoured personnel carriers 302, An experience from the Swedish UN mission in Bosnia, 1994, FOA-R—97-00626-310-SE, ISSN 1104-9154.

Medin, A., Axelsson, H. and Suneson, A. (1998), The reactions of the crew in an armoured personnel carrier to an anti tank mine blast. A Swedish incident in Bosnia 1996, Defence Research Establishment Weapons and Protection Division, SE-147 25 Tumba, Sweden, FOA-R—98-00720-310—SE, ISSN 1104-9154.

Radonić, V., Giunio, L., Biočić, M., Tripković, A., Lukšić, B. and Primorac, D. (2004), Injuries from Antitank Mines in Southern Croatia, *in Military Medicine*, Vol. 169, April, pp. 320-324.

Ripple, G.R. (1990), "Predictive Criteria for Burns from Brief Thermal Exposures"; *Journal of Occupational Medicine*, Vol. 32/3, pp. 215-219.

RTO-TR-HFM-089 (2004), Test Methodologies for Personal Protective Equipment Against Anti-Personnel Mine Blast, Final Report of the NATO Research and Technology Organisation (RTO) Human Factor and Medicine Panel (HFM) Task Group TG-024, Published March.

Sellier, K. and Kneubuehl, B.P. (1994), Wound Ballistics and the Scientific Background, Elsevier, Amsterdam, ISBN 0-444-81511-2.

SFPE (2000), Society of Fire Protection Engineers (Ed.): "Skin Burns from Thermal Radiation – Engineering Guide".

Stoll, A.M. and Chianta, M.A. (1968), Methods and Rating System for Evaluation of Thermal Protection, *Aerospace Medicine*, Vol. 40, pp. 1232-1238.