Health and Safety Executive

Hydraulic injection injury

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Research Report

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Hydraulic injection injury

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Hydraulic injection can be defined as the puncturing of the epidermis by a jet of a fluid under pressure. Hydraulic injection injury is the term used to describe an injury sustained by an individual following an injection of fluid, usually while operating or inspecting pressurised hydraulic equipment. While reported instances of injury through hydraulic injection are comparatively uncommon in the UK, the risk of injury through hydraulic injection is common to all hydraulic equipment irrespective of the system volume and can occur at relatively low pressures.

This report and the experimental work it describes offers an explanation of the injury mechanism and the current understanding of medical prognosis of injured parties upon sustaining an injury of this type.

High speed video footage of simulated hydraulic injection injuries was captured in order to illustrate the nature of injuries of this type. This footage will be made available to the public through various industry bodies in 2013.

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EXECUTIVE SUMMARY

Hydraulic injection can be defined as the puncturing of the epidermis by a jet of a fluid under pressure. Hydraulic injection injury is the term used to describe an injury sustained by an individual following an injection of fluid, usually while operating or inspecting pressurised hydraulic equipment. While reported instances of injury through hydraulic injection are comparatively uncommon in the UK, the risk of injury through hydraulic injection is common to all hydraulic equipment irrespective of the system volume and can occur at relatively low pressures.

Hydraulic injection injuries are almost entirely occupational and sustained by male manual workers, both skilled and unskilled, with injuries mostly sustained to the palm or pads of the digits of the non-dominant hand. Clinical studies identified that a lack of comprehension of the potential severity of injuries of this type on the part of the injured parties and medical professionals is the main obstacle to effective treatment. This appears to be largely due to the apparent benignity of the initial presentation of the wound. If untreated, hydraulic injection injuries can result in amputation or even death.

The aims of this research are to reduce the instances of injuries of this type and improve the prognosis of injured parties through adding to the current knowledge and raising levels of awareness of the potential severity of injuries of this type, irrespective of the type of fluid injected. Clinical studies suggest that injuries treated as surgical emergencies from the outset resulted in the most favourable prognosis.

The results of tests carried out during the course of this research demonstrated that variables such as pressure, proximity and jet size are crucial in achieving hydraulic injection. It is not unreasonable to suggest that if one of these variables is absent or unfavourable then the chances of sustaining injury through hydraulic injection are significantly reduced. This fact may go some way to explaining the comparative rarity of instances of hydraulic injection injury. However, the tests have also shown that when the variables are correct, hydraulic injection can occur in a very short space of time, without any warning and with potentially fatal consequences.

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1. INTRODUCTION

The risks of working with pressure systems of any type are well documented and respected by those involved in work that brings them into contact with pressure systems. Comprehensive risk mitigation and safe working practices are drafted and adhered to by the vast majority of responsible commercial organisations and professional technicians working with pressure systems and equipment as part of their routine work process. A common aspect of risk mitigation when working with pressure systems is, where possible, to use hydraulic power in preference to pneumatic power. In some instances however, such as lifting, cutting and pressing applications, hydraulic power is the preferred and often the only choice. Viewed as the safe option for pressurised equipment, the risk mitigation process can often end with the choice of hydraulic over pneumatic power.

A common risk to all hydraulic systems, irrespective of volume, is hydraulic injection injury. This often overlooked mode of injury can and has resulted in the loss of limb function, amputation and in some cases, death. Although the reported instances of injury through hydraulic injection are comparatively rare in the UK, the potential severity of the consequences to the injured party dictate that understanding, acknowledging and mitigating the risk of injury through hydraulic injection, is essential for any individual or commercial organisation utilizing hydraulic systems or equipment. Although the more serious instances of hydraulic injection injuries occur at higher pressures, anecdotal evidence suggest that injection can occur at pressures as low as seven bar.

Hydraulic injection injury occurs when a jet of fluid under pressure penetrates the skin of an individual, most commonly the hand or the digits of the hand. An individual may come into contact with a pressurised jet of fluid due to the nature of the equipment they are using, such as paint spraying equipment, or when an equipment failure occurs. Types of failure in hydraulic equipment can be broadly categorised as:

- Functional failure, where the piece of equipment stops working completely following catastrophic component failure.

- Material failure, where a small leak has occurred but the equipment remains operational.

Examples of material failure in hydraulic equipment are fatigue cracking in high pressure fuel lines, pin holing in hydraulic hoses, seal failure and bulk material cracking. While both modes of failure can result in injection injury it is perhaps the latter that presents the greater risk to an operator in relation to sustaining a hydraulic injection injury. This is due to the fact that a piece of hydraulic equipment may remain pressurised and in use while ejecting a pressurised jet of fluid. An individual may sustain an injection injury by being in direct contact with a piece of equipment when a failure occurs, by using equipment with an existing failure, or while inspecting a piece of pressurised equipment following a reduction in performance due to a material failure. The tests carried out as part of this research suggested that the smaller the jet, such as those associated with pin holing, the more likely the chance of injection occurring.

2. CASE STUDIES

2.1 CASE STUDY - INJECTION OF OIL BASED SOLVENT

Figure 1 shows the left hand of a 33 year old industrial paint sprayer shortly after sustaining an injection injury of oil based paint to the base of the index finger. Note the seemingly benign nature of the puncture wound where the paint has entered the hand.

Figure 1 *Showing initial puncture wound following injection injury, picture by R Heirner.*

Figure 2 shows one of several incisions made during the debridement process to remove necrotic tissue and paint.

Figure 2 *Showing incision made during debridement procedure, picture by R Heirner.*

2.2 CASE STUDY - INJECTION OF SOLVENT

Figure 3 shows the right hand of 25 year old male 36 hours after sustaining a hydraulic injection of solvent into the pad of the index finger. Due to the initial innocuous presentation of a small puncture wound on the finger, medical advice was not sought upon sustaining the injury. Necrosis of the tissue can already been seen at the tip of the finger.

Figure 3 *Showing hydraulic injection injury to right index finger, picture by ZH Dailiana.*

Figure 4 show the patient after undergoing a wide surgical debridement and pressure relieving of the compartments of the hand. This procedure took place 56 hours after the initial injury.

Figure 4 *Showing the patient after surgical debridment procedure, picture by ZH Dailiana.*

Figure 5 Shows the injured party after amputation of the index finger.

Figure 5 *Showing the patient after amputation of the index finger, picture by ZH Dailiana*

2.3 CASE STUDY - INJECTION OF FUEL OIL

Another common injury site is the palm of the hand, commonly sustained when using a piece of hydraulically powered equipment at the point at which a material or component failure occurs. Figure 6 shows the palm of a 49 year old man after sustaining an injection of fuel oil from a leaking pump. At first inspection the wound may appear entirely superficial to both the injured party and medical professionals.

Figure 6 *showing the point of injection of fuel oil, picture by ZH Dailiana*

Figure 7 shows the same patient undergoing surgical derbridment in order to relieve the pressure from the inner compartments of the hand and remove necrotic tissue.

Figure 7 *Showing surgical debridemt procedure, picture reference Graphic 5, by ZH Dailiana*

3. IMPLICATIONS

3.1 LITERATURE REVIEW

Reviewing the publicly available literature directly relating to the subject matter, a list of which is in the bibliography of this report, it is reasonable to conclude that ignorance of the risk of hydraulic injection injury was a common factor in almost all instances of injuries sustained. This observation applies equally to injured parties, commercial organisations and in many instances, medical professionals. Very few examples of reports of hydraulic injection injury were found that did not include statements from injured parties or witnesses expressing surprise that such an injury could occur or the potential severity of the injury. Several anecdotal examples are publicly available reporting erroneous advice given on initial medical consultation due to a lack of understanding of the potential severity of injuries of this type[1]. While this lack of understanding is almost certainly due in part to the comparative rarity of injuries of this type, another significant factor is the lack of an effective means of dissemination of the useful research that has been carried out in this area to date. Numerous clinical studies have been carried out, the intended audience for which being primarily medical professionals. Similarly, several useful safety bulletins and information sheets have been produced and made publically available by commercial organisations, almost all of which were in response to an instance of hydraulic injury having already occurred resulting in significant injury to a member of staff. These safety bulletins, produced in-house by commercial companies and self-published via the internet, contain accurate and pertinent information on the subject but are not proactively distributed. While the value of this type of information being made publicly available is not in question, the problem of limited dissemination and the challenge of raising levels of awareness to an extent where it forms a part of the standard risk assessment, remains an issue still to be resolved. Reviewing the available clinical studies[1,4] and safety bulletins available it is not unreasonable to conclude that the current level of awareness is low, with the majority of safety bulletins being compiled in response to an incident after a significant injury has occurred. This suggests that existing risk mitigation practices may be improved by the addition of information on hydraulic injection injury at the project planning and risk assessment phase.

3.2 TESTING

The results of the testing showed that the main contributory factors for achieving hydraulic injection are the physical dimensions of the jet, the pressure of the jet itself and ones proximity to it. If any of these three variables were not correct then injection did not occur. This finding may go some way to explaining why reported instances of injury through hydraulic injection are comparatively rare. However, the ease and speed with which hydraulic injection does occur when all of these variables are correct, and the potential severity of the consequences, dictates that acknowledging the risk of hydraulic injection injury and mitigating that risk as far as possible, are essential to good working practice for everyone working with pressurised hydraulic equipment. This is especially important for pieces of hydraulic equipment that are designed to be held while pressurised such as industrial grease guns, hydraulic rescue tools, paint spraying guns and high pressure water jetting equipment.

The smallest jet aperture used in these laboratory tests was 0.3 mm with a lowest jet pressure of 60 bar. While jets of this size and pressure were essential in order to capture useful high-speed video for the purposes of analysis and presentation, this pressure requirement could be substantially reduced for significantly smaller jets such as might be found in fatigue induced cracking. Further work on the minimum jet size and pressure required to achieve hydraulic injection would be a useful area of research to help establish the risk envelope and improve risk mitigation.

An important observation made during the course of the tissue simulant testing was the propagation of the wound in the tissue simulant. Much importance is attached to the toxicity of the fluid injected into the injured party mostly due to its necrotic nature. While this is clearly an important aspect of the injury, it may lead to a complacent attitude when less or nontoxic fluid is injected into the hand. Clinical studies[1,3] identified compartment syndrome as an equally important factor in the need for timely surgical intervention following instance of hydraulic injection injury. Compartment syndrome is caused when fluid under pressure is forced in to the tendon and nerve compartments of the hand creating a significant overpressure resulting in permanent nerve and tissue damage in some instances. Surgical intervention is required to relieve the pressure in each compartment of the hand once they have become filled with fluid. This type of permanent nerve damage can occur irrespective of the toxicity of the fluid injected into the hand of the injured party.

High-speed video of hydraulic injection into blocks of tissue simulant may be the first representative visualisation captured on video of the method through which compartment syndrome may occur following a hydraulic injection injury. Post-test analysis of the high-speed video showed that the wound propagated along several linear incisions made into the tissue simulant of broadly the same physical dimensions of the jet. As the incision made by the jet extended deeper into the tissue simulant, small fluid filled cavities were observed opening up along the length of the incision. Observable expansion and contraction of the cavities in relation to the inrush of fluid was seen. Given the uniform spherical presentation of the cavities and their diminishing size along the length of the incision, it was reasonable to conclude that their formation did not result from the mechanical force of the incision but from the subsequent overpressure created by it. This footage served as an excellent illustration of why such extensive surgical intervention is usually required following an injection injury, with the initial puncture wound appearing superficial, and the subsequent penetration of fluid being substantial and non-linear.

4. METHODOLOGY

Laboratory tests replicating hydraulic injection injury were carried out using a bespoke hydraulic test rig and human skin and tissue simulants. The purpose of these tests was to observe more closely the mechanism of injection and to assess other variables involved in sustaining a hydraulic injection injury, such as jet size, pressure and proximity of the individual to the jet. Skin and tissue stimulant selection was based on the consensus of published research papers establishing the mechanical properties and suitability of human skin and tissue simulants through comparative cadaver testing.

4.1 SKIN AND TISSUE SIMULANT SELECTION

4.1.1 Skin simulant

The mechanical properties of human skin are well documented, having been established through cadaver testing carried out in numerous independent studies. Many of these studies incorporated comparative testing of human skin simulants in order to identify those that demonstrated mechanical properties most consistent with that of human skin. The motivation for many of these studies has been the development of novel investigative and forensic techniques in support of criminal investigations. This has resulted in comprehensive data sets relating to the puncture resistance of human skin simulants by various sharp implements and projectiles. The data generated in these studies was deemed relevant to the selection of a suitable skin simulant for use in hydraulic injection injury testing due to the fact that a jet of fluid has both mass and velocity.

A paper titled Ballistic Skin Simulant[2] reported the results of ballistic penetration tests and subsequent comparison to the accepted mechanical properties of human skin of thirteen potential human skin simulants. Of these thirteen, the authors concluded that cowhide, semi finished chrome tanned upholstery crust, not treated to final softness and having a thickness of 0.9-1.1 mm, gave results most consistent with human skin. While acknowledging that the simulant was a natural product and variations in mechanical properties due to the nature of the material itself and the manufacturing processes should be expected, the authors concluded that the cowhide met the requirements of a skin simulant. Considering the findings of the paper, this type and grade of leather was selected for use in these tests. The above specification was given to leather suppliers Andrew Muirhead and Sons Limited of Glasgow, Scotland, who supplied a completed hide of the same specification with a nominal thickness of 1mm +/- 0.1mm.

A paper titled Puncture Resistance and Tensile Strength of Skin Simulants[3] that focused primarily on the resistance of human skin to stabbing, identified the importance of uniform tension across the test specimen when conducting penetration tests. Considering the findings of this paper, a biaxial adjustable tension test specimen mounting rig, shown in Figure 6 was fabricated.

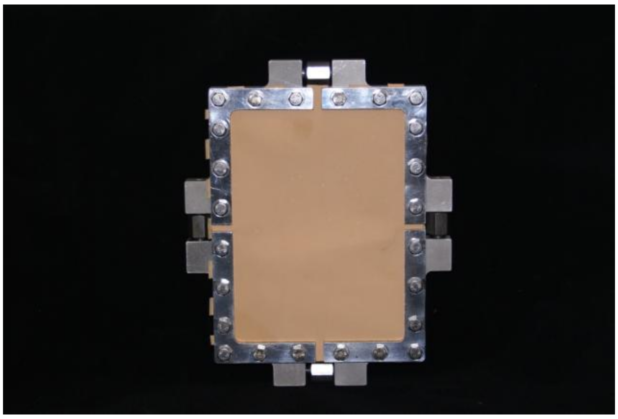

Figure 6 *Showing biaxial adjustable tension test sample mounting rig, picture reference DSCO7306.jpg, by Alan McDonald.*

4.1.2 Tissue simulant

The use of hydrogels, specifically pig skin gelatines, in ballistic impact testing has been generally accepted as the scientific and legal standard for the assessment of wounding characteristics of various ballistic projectiles for a number of years in the US and more recently Europe. A freedom of information request made of Defence Science and Technology Laboratories (DSTL) (UK) confirmed that hydrogels, commonly referred to as ballistics gelatine, is used by the Ministry of Defence for research into ballistics trauma in the UK. Literature reviews revealed that ballistics gelatine is also in use with the Metropolitan Police Force (UK). Based on the available scientific research supporting the mechanical validity of ballistics gelatine and the supporting UK legal precedent for its use as tissue simulant, this type of hydrogel was selected for use in these tests. Gelita Europe of Cheshire, UK, was identified as the sole UK market place supplier for ballistics grade gelatine at the time. A 25kg bag of 100% Pigskin Gelatine for Human consumption SG 721-20/80 was supplied.

The preparation method for ballistics gelatine blocks for use in projectile testing has also been widely published and variously attributed. For the purpose of these tests, the Dr Martin Fackler preparation method was used. This method, which has been adopted by the MOD (UK) and Federal Bureau of Investigation BI (US), indicates that a block of gelatine mixed at a ratio of 10% gelatine by mass with water not exceeding 40 degrees Celsius will give gelatine of a consistency that is acceptable for use as a human or animal tissue substitute. Several iterations of preparation and calibration confirmed that 9 litres of water to 1 kg of gelatine gave the correct consistency. All ballistics gelatine blocks and moulded gelatine body parts used in the test were mixed to the requirement of this method, chilled at 5 degrees Celsius for a minimum of 48 hours before use and used within 30 minutes of being removed from the refrigeration unit.

The accepted calibration test for ballistics gelatine blocks, once set, is to fire a 4.5 mm ball bearing into the block at a speed of 184 +/- 4 meters per second and measure the depth of penetration. The penetration of the ball bearing should be approximately 85mm +/- 15mm. This test was carried out by independent ball bearing gun specialist Mr Christopher Marshall at his premises in Cheshire, UK. Ten 4.5mm ball bearings were fired into a pre-prepared block of ballistics gelatine cooled to approximately 5 degrees Celsius. A maximum velocity of 141 meters per second, measured using a Shooting Chrony Inc Master F1 chronograph, was used and an average penetration depth of approximately 60 mm into the gelatine block was observed. Given the linear relationship between penetration depth and projectile velocity, these results were deemed acceptable. This test was conducted on one gelatine block from a batch of three produced for use in these tests. Figure 7 and Figure 8 below shows a ballistics gelatine block and moulded ballistics gelatine head.

Figure 7 *Showing a ballistics gelatine block prior to testing, picture reference DSCO7288.jpg by Alan McDonald.*

Figure 8 *Showing a moulded ballistics gelatine head, picture reference DSCO7286.jpg by Alan McDonald*

4.1.3 Hydraulic test rig

A bespoke hydraulic test rig was constructed that would allow a jet of variable size and pressure to be fired at skin and tissue simulants. The test rig consisted of a simple loop hydraulic circuit fitted with two integral needle bonnet valves, a pressure gauge and a manually operated ball gate isolator valve. Jet apertures were constructed from lengths of 6mm x 2mm wall seamless 316 stainless pipe drilled with a single hole through one wall thickness only. Nine apertures of this type were constructed in sizes 0.3mm to 0.9mm inclusive. The pressure of the jet was adjusted by restricting the out flow from the hydraulic loop circuit via the integral needle bonnet valves. This was carried out with the jet aperture open and fluid flowing from it in order to achieve an actual jet pressure and not an overall system pressure. The measured flow rate from the 0.3 mm aperture with a jet pressure of 100 bar was approximately 5.7 ml/s. For reference, a tea spoon has a volume of approximately 5 ml. Figure 9 shows an overview of the hydraulic test rig. Figure 10 shows a skin simulant sample present in front of the jet aperture prior to a test.

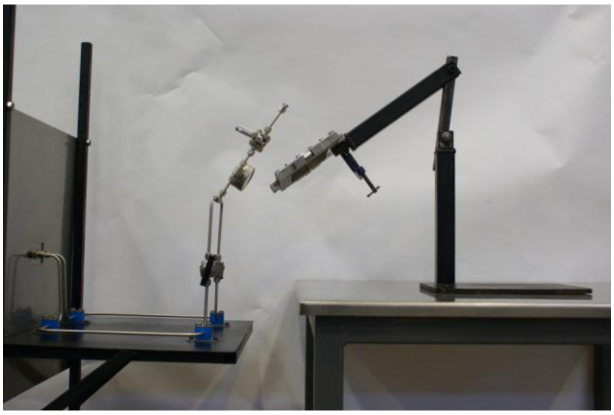

Figure 9 *Showing an overview of the hydraulic test rig and skin simulant sample presentation rig, picture reference DSCO7268.jpg, by Alan McDonald.*

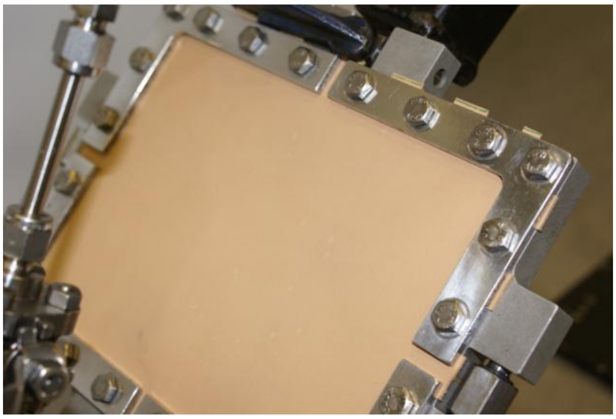

Figure 10 *Showing a skin sample presented in front of the jet aperture prior to testing, picture reference DSCO7272.jpg , by Alan McDonald.*

5. TESTING

5.1 SKIN SIMULANT TESTS

A sample of skin simulant was fitted to the skin sample mounting rig and tensioned equally on both axes. The tension of the sample was adjusted until a deflection of approximately 4mm in response to the application of a force of 2 Newtons applied at the centre of the sample was observed. Force measurements were made using a Mecmesin 0-50 Newton indicating force gauge. Presentation of the skin simulant samples was consistent with these measurements for each iteration of the test.

The mounted and tensioned skin sample was presented to the jet aperture with an approximate distance of 150mm between the aperture and the surface of the sample for the first iteration of the test. This distance was closed to approximately 10mm between the jet aperture and the surface of the sample over several further iterations of the test.

With the sample presented and the hydraulic circuit charged, the ball gate valve was opened allowing a jet of fluid to exit the aperture at pressure and impact the sample. The ball gate valve was opened for a manual count of one second and then closed. This procedure represents a single iteration of a hydraulic injection test carried out on a human skin simulant sample. Variations of pressure, jet aperture size and sample proximity were carried out consistent with this procedure for numerous iterations of the test, several of which were captured on both normal and high-speed video for later study and presentation.

5.2 TISSUE SIMULANT TESTS

Three iterations of hydraulic injection into ballistic gelatine were carried out, all of which were conducted using 0.3 mm jet aperture and with an approximate jet pressure of 60 bar. All three tests were executed with the gelatine at a consistently close proximity of 20mm to 40mm.

With the gelatine presented and the hydraulic circuit charged, the ball gate valve was opened manually for a count of one second allowing a jet of fluid to exit the aperture at pressure and impact the sample. This procedure represents a single iteration of a hydraulic injection test carried out on ballistic gelatine blocks and moulded body parts. All three iterations of hydraulic injection into ballistic gelatine were carried out consistent with this procedure, all of which were captured on high-speed video for subsequent analysis and presentation.

6. RESULTS

6.1 SKIN SIMULANT TEST

Initial iterations of the test using larger jet apertures and a lower jet pressure produced a jet that was not capable of puncturing the skin simulant. A maximum pressure of 100 bar was used in conjunction with the 0.9 mm jet aperture. The jet however, remained mostly diffuse and not capable of puncturing the skin simulant. A likely contributory factor for this is the physical dimensions of the jet in relation to its pressure, with the pressure delivered by the jet at the point of interaction with another object being proportional to its cross sectional area. Attempts to increase the pressure of the jet caused apparent atomisation of the fluid. Possible explanations for this are the wall thickness of the material used to construct the jet and the post-machining finish of the jet aperture itself. No puncture of the skin simulant was observed while using a jet aperture of 0.9 mm at pressures of up to and including 150 bar. High speed video of a diffuse relatively low pressure jet was captured for analysis and presentation.

Similar observations to those made during the 0.9 mm aperture test continued in tests with jet aperture sizes 0.8 mm to 0.4 mm, with the only notable difference occurring when the 0.3 mm jet was fitted to the test rig. At the same pressure of approximately 100 bar, a significant improvement in non-turbulent flow of the fluid was observed from the 0.3 mm jet. A sharp jet could be seen extending up to 40 mm from the jet aperture before any notable increase in the cross-sectional area of the jet occurred. Tests using the 0.3 mm jet resulted in puncture of the skin simulant sample within 10 mm and up to 40 mm proximity of the jet aperture. High-speed video of the 0.3 mm jet test puncturing the skin simulant was captured for subsequent analysis and presentation. Figure 11 and Figure 12 show the damage and puncturing of the skin simulant following these tests. The slot shaped formation of the damage is due to motion imparted into the jet aperture while manually opening the ball gate isolator. The diameter of the actual puncture was approximately 2 mm.

Figure 11 *Showing damage to skin simulant sample, picture reference DSCO1563.jpg, By Alan McDonald.*

Figure 12, *Showing puncture damage to skin simulant sample, picture reference DSCO1564.jpg, by Alan McDonald.*

6.2 TISSUE SIMULANT TESTS

The primary objective of the tissue simulant tests, using ballistics gelatine blocks, was to capture high-speed video of a typical wound path created by injury through hydraulic injection for analysis and presentation. Although achieving penetration of the ballistics gelatine would have been more easily achieved than in the skin simulant tests, the 0.3mm jet at a pressure of 100 bar was used for these tests. Post-test analysis of the high-speed video showed that the fluid easily penetrated the tissue simulant creating a final wound depth of approximately 100 mm in approximately one second. The wound propagated through a series of linear incisions of a broadly similar diameter to the jet. A series of cavities opened up along the length of the incisions that were visually similar to the singular cavitation observed in high velocity projectile impacts, although on a far smaller scale and, most significantly, being opened by the inrush of fluid and not the transfer of kinetic energy. This resulted in the wound having the appearance of a series of interconnecting bubbles of diminishing size within the tissue simulant. As the pressure of the incoming fluid dissipated, the cavities could be seen pulsating and finally becoming static. Sample preparation of the wound path removed from the ballistics gelatine block, shown in Figure 13, clearly shows disruption of the tissue simulant and a significant quantity of fluid retained in the wound. Figure 14 shows the remains of the bubble-like cavities created during the propagation of the wound path.

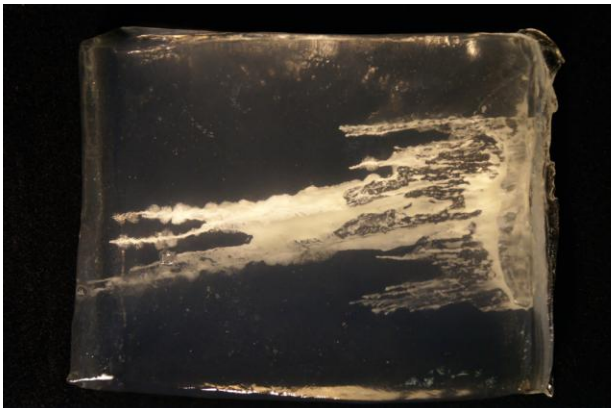

Figure 13 *Prepared cross section of ballistic gelatine wound path, picture reference DSCO1565.jpg , by Alan McDonald.*

Figure 14 *Showing remains of bubble like propagation of the wound path, picture reference DSCO1566.jpg , by Alan McDonald.*

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9. GLOSSARY

Jet	A thin stream of liquid or gas forced out of a small aperture or nozzle
Aperture	A hole, gap, crack or slit.
Necrotic	Of necrosis, the death of one or more cells in the body usually within a localized area.
Debridement	The surgical removal of dead tissue of cellular debris from a wound.

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Hydraulic injection injury

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