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Case report

A biomechanical reconstruction of a wound caused by a glass shard — a case report

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Abstract

During the course of a criminal trial, an investigating pathologist is commonly asked how much force was required to produce an injury. This subjective opinion is based on the pathologist's previous experience of dealing with wounds inflicted with similar weapons. However, in the case of stab wounds inflicted by broken glass, it is unlikely that two glass fragments would be physically similar. In the case studied, two theories were examined: that a wound resulted from a thrown glass fragment or that it had been caused as a stab injury by the glass held in the bare hand. The investigation involved quantifying the energy required for human tissue penetration, comparison of sharpness, a biomechanical analysis of throwing actions and testing of the hypothesis that if the glass shard were used as a stabbing implement it would result in a cut to the hand.

The investigation utilised a scientific methodology that reduced the need for speculative (though informed) opinion from the pathologist by producing quantitative results.

Keywords: Stab wound; Force; Sharpness; Glass; Motion analysis

1. Introduction

Defendant X and deceased Y had an argument within the kitchen of a terraced house Z. A fight broke out during which the main window of the kitchen area was smashed. The fight was stopped and the defendant taken to a neighbour's house to calm down. After a period, X left the neighbour's house. Minutes later, a second scuffle was heard by the neighbour. By the time the neighbour investigated, Y was found dead in the hallway of the terraced house Z with a jagged penetrative wound to the right side of his neck.

A glass fragment soaked in blood was found close to the broken window and next to an arterial blood spurt pattern.

The defendant X later claimed that he had returned to house Z from the neighbour's entering by climbing through the broken kitchen window. The window had broken shards of glass at its periphery and in order to be able to climb through it he had to clear a number of glass fragments, tossing some of them into the kitchen. He then realised that one such fragment had struck Y in the neck.

Some circumstantial evidence suggested X did gain entry to the kitchen and that a fight had occurred

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during which the fatal wound was sustained, raising the possibility that the wound had been caused by the glass shard being used as a stabbing weapon.

These scenarios pose a number of questions as follows.

- Was it possible for the recovered glass shard to penetrate human tissues to the depth reported at post-mortem examination by a throw?
- If it was possible for this shard of glass to penetrate the human body, how much energy would be required for this penetration to occur?
- An expert medical witness later proffered the opinion that if the glass shard was used as a stabbing implement, it would result in an injury to the hand of the assailant. Could this be tested scientifically?

2. The wound

The fatal wound was an incised wound to the right side of the front of the neck measuring 6.6 cm in length, gaping to 1.0 cm in width and is shown in Fig. 1. The wound was orientated at 45° to the vertical and had a jagged contour with a double 'tail' at its upper apex, each tail being separated by approximately 0.6 cm and approximately 1.0 cm in length.

Fig. 1. Photograph of fatal wound.

The lower margin of the wound was undercut and deep dissection showed that it extended downward across the midline of the neck and slightly backwards to a depth estimated conservatively for experimental purposes as 12 cm, such that it caused parallel grooves over the front of the trachea and then severed the left carotid and jugular vessels before entering the apex of the left lung. The chest cavity contained 1.6 l of blood. The parallel 'tails' at the apex of the skin wound together with the grooving over the windpipe were interpreted as being consistent with a causative weapon having an appreciable thickness. The jagged nature to the external wound was felt to be compatible with a shard of glass. No glass flakes or fragments were seen within the wound.

3. The weapon

The glass shard covered with blood found at the scene is shown in Fig. 2. It is a fragment of 4 mm thick plain window glazing glass (neither toughened nor laminated) whose maximum dimensions were 25.6 cm × 9.0 cm. The mass of the glass shard was 85 g.

4. General overview of experimental procedure

The investigation was carried out in following three stages.

- To quantify the energy required to cause a penetrative wound of 12 cm depth due to a glass shard.
- To relate the energy required for penetration to the degree of force required by an individual to produce that energy.
- Using human tissue, to test the supposition that the glass shard would cut the hand if used as a stabbing weapon.

5. Quantification of the energy required for the glass shard to penetrate human tissue

5.1. Scene of crime reconstruction

All reconstruction experiments were based on measurements taken during a scene of crime visit as shown in Figs. 3–5.

The relative positions of the walls door and window were marked out on the floor of a motion analysis

Fig. 2. Recovered glass shard covered in blood.

Fig. 3. Broken kitchen window as viewed from outside.

laboratory. A wooden replica of the window frame was constructed at a height that would have been observed from outside the window and was placed at the appropriate location within the reconstructed scene. Also, at a height equivalent to that of the ceiling, wallpaper covered plaster-board was attached to a scaffold frame to investigate any impacts due to rebounding off the ceiling.

5.2. The motion analysis laboratory

The motion analysis laboratory utilises the MacReflex motion analysis system. The MacReflex system is an optical measurement system that provides a method of carrying out non-contact kinematic motion analysis. The system uses special cameras that emit infrared light towards retro-reflective markers placed at

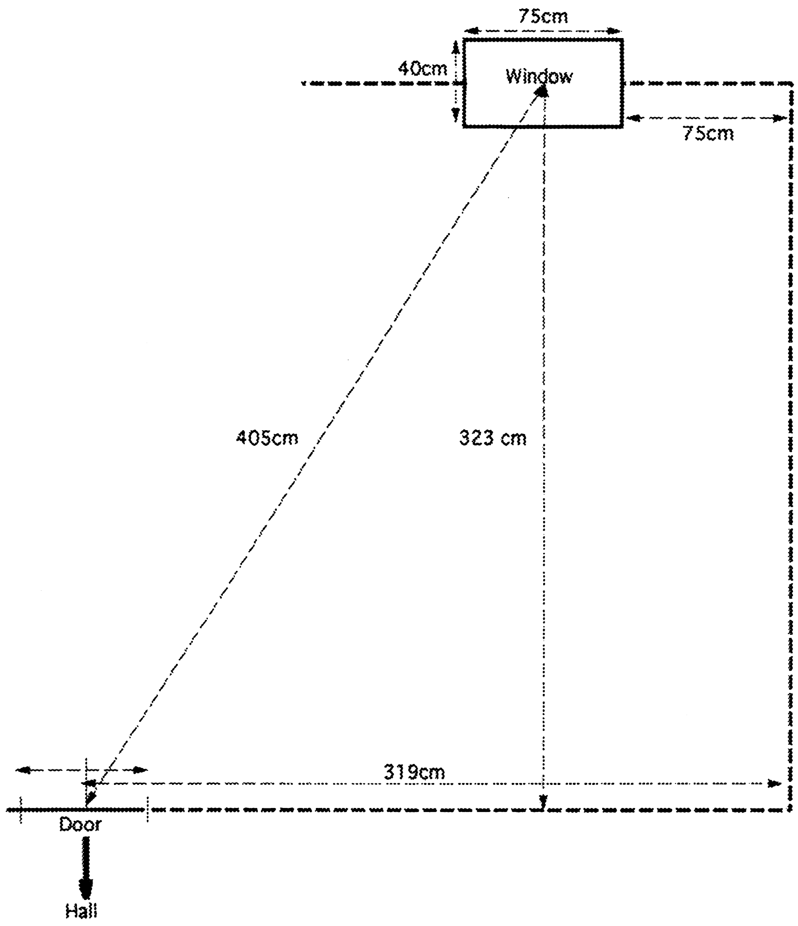

Fig. 4. Diagram of the plan of the kitchen area.

defined points on the body. The light is reflected off the markers and received by the cameras. Provided at least two cameras can see the markers at any one time, their three-dimensional co-ordinates can be calculated. The system operates at a fixed frequency of 60 Hz, so the position relative to time can be calculated.

5.3. Manufacture of glass shard replica for throwing experiments

For the throwing experiments a replica glass shard had to be made in order that no damage occurred to the original. Perspex of 5 mm was chosen as it was more resistant to breakage but of similar density to the glass shard. The perspex was fashioned to the same profile as the original glass shard and two retro-reflective markers were mounted on either side of the replica at the centre of gravity. The centre of gravity was chosen to eliminate any effect of tumbling that may occur during throwing actions. The total mass of the perspex replica, together with the retro-reflective markers was 85 g, the same as that of the original shard.

5.3.1. Experiment 1

5.3.1.1. Preliminary assessment of the range of throwing velocities. Prior to any experimental work involving human tissue, it was necessary to know the range of velocities that could be achieved by an

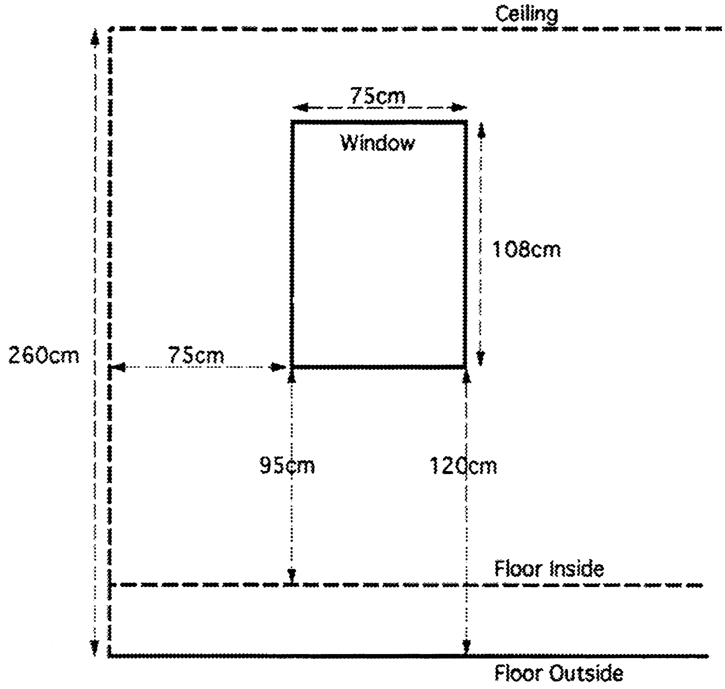

Fig. 5. Diagram of the front view of kitchen area as seen from outside.

average fit adult throwing the glass shard. A preliminary trial was set up within the reconstructed scene to determine this range of velocities.

A volunteer was instructed to toss the perspex replica glass shard through the reconstructed window frame with varying degrees of force. The throwing actions ranged from a very light 'toss', through to a medium strength throw and finally an attempt to throw the shard as hard as possible. This preliminary study allowed the full range of throwing velocities to be determined and it was assumed that the velocity of any throwing event that may have occurred at the scene, would lie in the recorded range.

5.3.2. Experiment 2

5.3.2.1. Replication of glass shard for penetrative testing. To perform experiments into the penetrative potential of the glass shard it was decided to replicate the original so that no accidental damage or blunting would occur. As only the tip of the shard of glass had caused penetration, it was decided that only the first 12 cm of the shard would be reproduced and this was cut from identical 4 mm glazing glass. As the sharpness of the tip of the stabbing implement is of paramount importance to the ease of penetration [1,2], it was vital that the tip of the replica have identical penetrative properties to that of the original. A comparison microscope together with a hand held grinder were used to microscopically replicate the dimensions of the tip of the replica.

5.3.2.2. Comparison of penetration characteristics. For the penetration experiments to be valid, the replica glass shard needed to have identical or slightly better penetration characteristics than that of the original recovered glass shard, i.e. would require identical or less force to obtain the same depth of penetration.

Using a motorised tensile testing machine (Hounsfield No. W5627) a series of comparative experiments were performed to measure the force required to produce a given displacement of the glass shards into a reference material, Roma Plastilina No.1. This is a homogenous clay material that exhibits visco-elastic deformation. This material is used as a flesh simulant for the stab resistant body armour test procedure [3]. Recordings were made and the sharper object was defined as the one which exhibited a greater rate of change of displacement with respect to force. As frictional components had an effect during the test and since friction is related to velocity, the rate at which the replica and the original were compressed into the material, was kept constant.

5.3.2.3. Projection of glass shard. A reproducible method of projecting the replica glass shard was needed to ensure experimental accuracy. A method similar to that used in the PSDB stab resistant body armour test procedure [3] was used to project the shard. The shard was mounted into a holder (sabot) that was machined to fit the barrel of an air cannon from which it was fired. The air cannon works on a principle similar to that of an air rifle. An air reservoir is filled with compressed air to a known pressure The air reservoir is emptied into the barrel thus accelerating the projectile. By varying the pressure of the air in the reservoir, the velocity of the projectile was changed, i.e. the higher the air pressure, the greater the velocity of the projectile. The velocity of the projectile was measured by a velocity sensor at the end of the barrel. The sensor consisted of a pair of infra-red light beams mounted 10 mm apart. The time taken for the two light beams to be broken by the projectile was recorded and the velocity calculated. A schematic diagram of the air cannon is shown in Fig. 6.

The replica shard and the piezoelectric accelerometer were mounted on a nylon sabot which was machined so that the total mass of the assembly was equal to that of the original (85 g). A photograph of the sabot, glass replica and the accelerometer is shown in Fig. 7.

5.3.2.4. Projection of replica shard into human tissue. Fully informed consent was gained from the deceased Y's relatives prior to any experimentation and the site selected for experimentation was the anterior abdominal wall using skin, soft tissues and rectus muscles. Previous dissection of the neck meant that it would be impossible to gain any meaningful results from projecting any glass into the uninjured side of the neck, therefore an area of tissues with similar characteristics was used. Microscopic sections of skin from the neck and the selected site were of similar thickness and the rectus muscle was approximately of the same thickness as the sternomastoid through which the glass had passed. Although, the actual wound was angled, having entered the body at approximately 45° to the skin surface, it was decided to use a perpendicular projection angle in order to give a conservative estimate rather than an over-estimate of the penetrative velocity required. Although, there are clearly differences between the human tissues before and after death and differences in the characteristics of the two sites — neck and abdomen — it was impractical to fire glass into the neck and clearly impossible to perform any useful in-vivo experimentation. In order to reduce the 'stiffening' effect of refrigeration the cadaver was allowed to acclimatise at room temperature of approximately 20°C before any experiments were conducted.

In the preliminary glass throwing experiments the maximum velocity the volunteer could throw the replica glass shard was measured. This value was chosen as the starting point for the human tissue experimentation. A binary search was used to find the velocity that corresponded to the original injury. A binary search is one in which the difference between

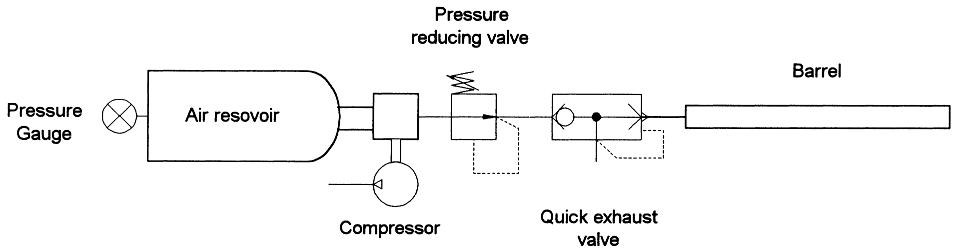

Fig. 6. Schematic diagram of the air cannon.

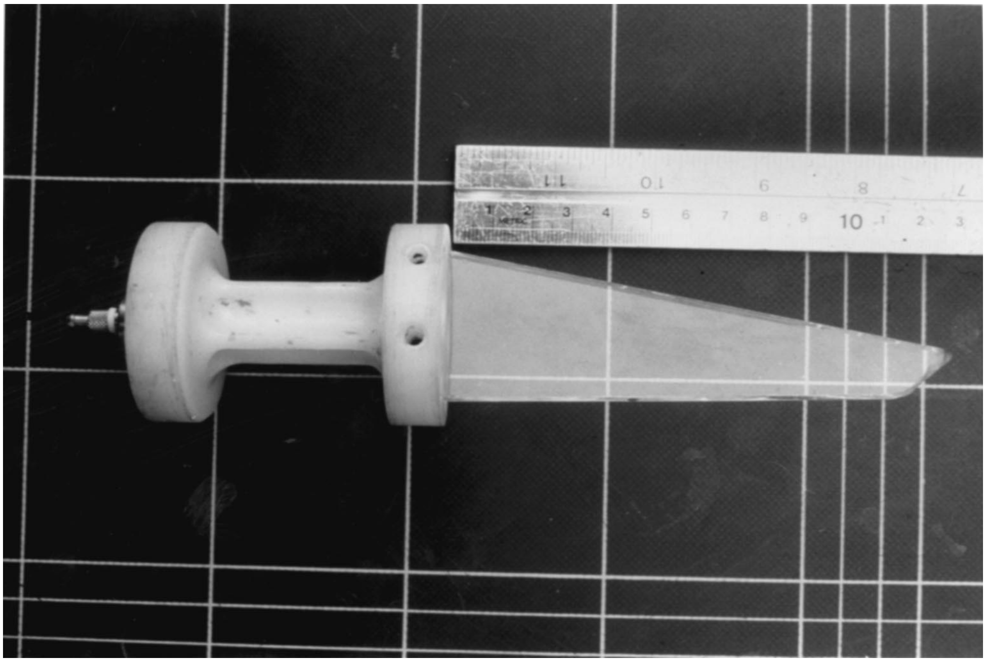

Fig. 7. The nylon sabot together with the attached glass shard and the accelerometer.

successive experiments is halved until the desired value found (i.e. 20 m s^{-1}, penetration; 10 m s^{-1}, no penetration; 15 m s^{-1}, penetration; 12.5 m s^{-1}, no penetration, etc.).

The output from the attached accelerometer was in the form of a charge (coulombs), therefore, a signal conditioner (type Brüel and Kjaer 2626) was used to convert the output into a voltage. The voltage was finally recorded using an Apple Macintosh based data capture system.

A series of penetrations were made and the velocities together with the depth of any penetration were recorded.

5.3.2.5. Results. The velocities and the kinetic energies measured during the preliminary throwing study are shown in Table 1. The results of the human tissue penetration experiments are shown in Table 2.

5.3.2.6. Comments. From Table 2 it can be seen that there was not a true linear relationship between depth of penetration and impact velocity, but there is a general trend with no penetration or only slight penetration occurring below 13.5 m s^{-1} and deep

Table 1
Velocities recorded of the replica glass shard during the preliminary throwing study

Throw number	Velocity (m s^{-1})	Energy (J)[a]
1	6.5	1.8
2	6.0	1.5
3	4.5	0.9
4	4.8	1.0
5	25.0	26.6

[a] Energy (E)=1/2 mv^2 where m is the mass of glass shard and v the peak velocity of glass shard.

Table 2
Velocity, energy and tissue penetration depth of replica glass shard and sabot

Test number	Velocity (m s^{-1})	Energy (J)	Tissue penetration depth (mm)
1	20.0	17.0	100
2	9.8	4.1	None
3	13.5	7.7	None
4	13.5	7.7	None
5	15.2	9.8	8
6	11.8	5.9	Slight

penetration occurring at 15.2 and 20 m s^{-1}. It should be noted that at the lower velocities penetration did not occur to the depth that would have been required in order to have caused the fatal wound.

5.3.3. *Experiment 3*

5.3.3.1. Visual reconstruction of glass throwing actions. Experimental values obtained indicating the range of velocities associated with deep penetration may be of scientific interest but have little use in the explanation of how an incident occurred in the context of a jury trial. In order to give the figures meaning, a video presentation was recorded showing the replica shard being thrown using different throwing actions. A subject stood behind the reconstructed window frame and threw the perspex replica glass shard. The peak velocity of the glass shard was recorded using the MacReflex motion analysis system. A number of different throwing actions were recorded, namely an over-arm throw, an under-arm throw, a forward push and forehand and backhand spinning actions. Target areas were positioned at locations equivalent to the 'back wall of the kitchen' and 'close to the window' (at the same position as the washing machine in the kitchen). The orientation of the wound was 'downward' and it was considered that the trajectory of the projectile would thus have to be either downward or possibly horizontal (allowing for a 'bent forward' position of the deceased). This limit on the trajectory at the target site reduced the maximum velocity of under-arm throws (which had to have an initial 'upward' trajectory to pass through the window. Trajectories that rebounded from the ceiling were also tried using a plaster-board/wallpaper reconstruction at the same height as the ceiling at the scene of the alleged incident.

5.3.3.2. Results. The range of velocities achieved with different throwing actions are shown in Table 3. The results were grouped in increasing order of velocity and then edited onto a video tape to enable the court to see how much effort was required to obtain the velocity of the throw. It could be seen that over-arm throws can achieve a high velocity, certainly of sufficient magnitude to cause deep penetrative wounds. Conversely, gentle under-arm tossing actions, as claimed by the defendant, were insufficient to cause skin penetration. Two further points should also be made. First, throws rebounding off the ceiling failed to achieve significant velocities. Second, the video-tape clearly showed that the perspex replica exhibited a considerable degree of yaw, pitch and tumble during its flight, although, on some occasions it was noted that it embedded itself deeply into a foam 'backstop' used to halt its motion.

Table 3
Velocity and energy of replica glass shard recorded during throwing video presentation

Throw number	Velocity (m s^{-1})	Energy (J)
1	15.8	10.6
2	17.2	12.6
3	20.0	17.0
4	12.9	7.1
5	13.5	7.7
6	4.5	0.9
7	11.0	5.1
8	12.0	6.1
9	5.5	1.3
10	5.4	1.2
11	6.3	1.7
12	12.5	6.6
13	12.5	6.6
14	15.0	9.6
15	9.4	3.8
16	9.0	3.4
17	5.7	1.4
18	8.7	3.2
19	10.1	4.3
20	8.5	3.1
21	8.6	3.1
22	10.5	4.7
23	7.5	2.4
24	7.5	2.4
25	8.5	3.1
26	10.8	5.0
27	8.6	3.1
28	14.0	8.3
29	14.2	8.6
30	9.8	4.1
31	17.9	13.6
32	19.0	15.3
33	18.0	13.8
34	19.0	15.3
35	17.6	13.2
36	5.8	1.4
37	5.6	1.3
38	6.3	1.7
39	7.5	2.4
40	7.9	2.7

5.3.4. Experiment 4

5.3.4.1. To investigate whether it was possible to use the glass shard as a stabbing weapon without causing injury to the hand. Evidence of the circumstances in which the lethal wound was sustained suggested that the assailant had not incurred any wound to his hand from either throwing the shard of glass or using it as a stabbing weapon. There was no evidence that a glove or piece of cloth had been used to protect the hand. The question therefore arose as to whether it would be possible to use this glass shard as a stabbing weapon without causing injury to the person holding it. The method chosen to test the hypothesis was to hold the original glass shard using a cut-resistant glove (Paraderm) covered by a latex surgical glove (Ansell Gammex 7.5). Stabbing attempts were then made into the thigh and abdomen of a human cadaver (appropriate consent having been gained). Stab wounds were also made to an amputated limb specimen (again obtained with fully informed consent) using an instrumented replica shard so that the force required for the stab wound could be measured. The validity of comparing the grip obtained using the gloved hand as opposed to a bare hand was tested using the following method.

The perspex replica of the shard of glass was gripped in the most comfortable position using the gloved hand and then the bare hand, both dry and wet. Stabbing actions were then carried out onto a Bertec force platform and the output recorded using an Apple Macintosh based data capture system. The position of the hand was marked on the perspex profile and any slip following a series of 15 'stabs' by the gloved/bare hand when wet or dry was measured.

5.3.4.2. Results. Stabbing actions using the original glass shard into the cadaver resulted in deep penetration without any damage to the latex glove. The instrumented glass profile required a force of approximately 160 N to penetrate deeply into the amputee limb specimen. The results of the grip experiment showed that there was no significant difference obtained with a bare dry hand compared to that of a hand covered with a cut-resistant glove and a surgical latex glove. It can be seen that the grip obtained with a wet bare hand is much better than that obtained with a wet gloved hand. The results obtained using the glass profile do not suggest that there is any significant difference between the grip characteristics of perspex compared to that of the glass. It was noticed that there was negligible 'slip' under any condition at forces of around 160 N — the force required to obtain deep penetration of the cadaveric tissues.

6. Discussion

In the context of a criminal trial a pathologist is often asked to assist the court by indicating how an injury may have occurred and with what force that injury might be associated. Clearly the experienced pathologist will have a number of cases to draw upon from personal experience where the weapon used is familiar. However, in the case of glass fragments the pathologist is unlikely to have seen a wound caused by a similar fragment. It is unlikely that two glass shards would be similar in physical dimensions and properties. Moreover, there are a number of different types of glass which would also be expected to have differing penetrative characteristics. The circumstance of glass being thrown or used as a stabbing weapon is unusual and if the pathologist is unable to call upon experience it would seem appropriate to use experimental models in order to inform his opinion when it is asked for in court. Due to the very nature of forensic pathology it is impossible to create a perfect experimental model for the following reasons.

Firstly, the weapon itself may have changed its physical characteristics by having been used. A freshly fractured piece of glass may have sharp flakes along its sides and a delicate pointed tip. These are liable to be damaged either when a wound is caused or from handling of the weapon after the wound was inflicted. It is difficult to correct for this fact but since no fragments of glass were found in this wound at post-mortem, it was felt that this was probably not of major importance in this case.

Secondly, it is impossible to experiment using a perfect experimental model which in this case would have been a live human neck of the same dimensions of the deceased. The use of dead human tissue has to be regarded as the next best option and it is felt that as long as a wide margin for experimental error is given, then this is an acceptable substitute. In all cases experiments were designed to err well on the side of caution and the interpretation regarding velocity required for penetration was that a throw of under $10\,\mathrm{m\,s^{-1}}$ would not cause deep penetration. Since deep penetration was only achieved experimentally at a velocity of $20\,\mathrm{m\,s^{-1}}$ (at which velocity the projectile would have four times the energy of the projectile at $10\,\mathrm{m\,s^{-1}}$) this was felt to be a safe inference.

What can be learned from this set of experiments? The main purpose was to obviate the need for a pathologist to give a subjective opinion on the causation of a somewhat idiosyncratic event. Instead a scientific methodology has been used to investigate whether a thrown piece of glass might cause the fatal injury sustained by the deceased and if so, what such a throw might look like allowing a jury to decide whether the defendants account was in keeping with such an appearance. As an exercise in explaining and demonstrating a complex issue of bioengineering to a lay audience we feel that this has been successful and additionally the experiments undertaken have shed light on several issues related to sharp force injury. It is often said that once a pointed object has pierced the skin that it will encounter no further resistance, that is, the knife or the instrument will 'fall' through underlying tissues unless encountering bone or calcified cartilage. This does not appear to be the case for the projected glass shard which penetrated to varying depths depending on velocity. Why is this? We have shown previously that it is a fallacy to suggest that no further force is required to penetrate muscle and other soft tissues following penetration of the skin [4]. This suggestion is the result of sub-optimal experimental techniques in which energy was stored in the apparatus during the subjective experience of stabbing experiments. It appears to the person 'stabbing' that once the resistance of the skin is overcome the knife 'falls' into the soft tissues but this is because only about half the force is required to penetrate muscle compared to skin. The force behind a stab does not finish as the skin is penetrated (the follow through has force behind it and, therefore, will exceed the threshold for penetration of muscle and there will be a perception that no further force was required. Consider, however, a thrown object. It has a finite amount of energy which is used up in overcoming the resistance to penetration of skin and then muscle. As energy is related to the product of force applied over a distance its energy will diminish the deeper it penetrates until it stops. If the object projected has sufficient energy to penetrate say, 8 mm of skin at $10\,\mathrm{m\,s^{-1}}$ then at $20\,\mathrm{m\,s^{-1}}$ it will have four times as much energy, in this case the glass shard with a mass of 85 g would have a kinetic energy of

$$\text{kinetic energy (joules)} = \frac{1}{2}mv^2 \quad = \frac{1}{2} \times 0.085 \times 20^2 = 17\,\mathrm{J}$$

compared to that of 4.25 J at $10\,\mathrm{m\,s^{-1}}$. The average resistive force produced by the skin layer onto the glass shard would be

$$\text{energy} = \text{force} \times \text{distance}$$

$$4.25 = \text{force} \times 0.008$$

$$\text{force} = 530\,\mathrm{N}$$

If we consider the muscle tissue to produce a resistive force to penetration of 50% to that of skin equal to 265 N and the projectile still possessing a resultant kinetic energy of 12.75 J, the projectile would travel a further depth of

$$\text{energy} = \text{force} \times \text{distance}$$

$$12.75 = 265 \times s$$

$$s = 48\,\mathrm{mm}$$

Therefore, when a projectile has an energy 'close' to the penetration threshold the entire difference between a soft throw and a hard throw may lie in the depth of soft tissue penetration. The method shown above is a simple approximation assuming constant resistive forces but does illustrate the point.

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