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ORIGINAL ARTICLE

How sharp is sharp? Towards quantification of the sharpness and penetration ability of kitchen knives used in stabbings

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Abstract Stabbing is the most common method for violent death in the UK. As part of their investigation, forensic pathologists are commonly asked to estimate or quantify the degree of force required to create a wound. The force required to penetrate the skin and body by a knife is a complex function of the sharpness of the knife, the area of the body and alignment with cleavage lines of the skin, the angle of attack and the relative movement of the person stabbing relative to the victim being stabbed. This makes it difficult for the forensic pathologist to give an objective answer to the question; hence, subjective estimations are often used. One area where some degree of quantification is more tractable is in assessing how sharp an implement (particularly a knife) is. This paper presents results of a systematic study of how the different aspects of knife geometry influence sharpness and presents a simple test for assessing knife sharpness using drop testing. The results show that the radius of the blunt edge at the tip is important for controlling the penetration ability of a kitchen knife. Using high-speed video, it also gives insight into the mechanism of knife penetration into the skin. The results of the study will aid pathologists in giving a more informed answer to the question of the degree of force used in stabbing.

Keywords Forensic · Stab · Wound · Knife · Force · Sharpness · Penetration

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Introduction

Stabbing is the most frequent way of committing homicide in the UK [1, 2]. Common stabbing weapons/implements include kitchen (or carving) knives (most common), sheath knives, folding knives, scissors, chisels, samurai swords, bowie knives, bayonnets, kukri, sailmakers awls and glass shards. Kitchen knives are not only used in domestic disputes but also in fights in public places owing to their ease of availability and disposal [1]. Key questions in investigations of stabbing incidents are "how much force was used?" and "how sharp is the knife?"

Pathologists will usually categorise the force required to produce stab wounds into one of three categories: slight pressure, moderate force or severe force [3]. However, the estimation of force is "almost impossible to answer" [4] with any degree of objectivity. There have been several studies focussed on measuring the force required for a knife to penetrate skin [4, 5]. This is further complicated by the fact that skin itself shows preferential cleavage in different areas of the body and therefore behaves differently in different stabbing events [6].

Previous studies have established that the amount of force required to penetrate skin is relatively low, typically in the range 35–55 N [7]. In addition, several attempts to measure the typical impact velocities involved in stabbing have been undertaken, not only related to stabbing in homicides but also related to the designing of stab-resistant body armour [8]. Typical impact velocities were found to be in the range of 8–12 m s^{-1}. There have, however, been fewer attempts to establish how the characteristics of the knife itself affect its ability to penetrate skin. O'Callaghan [9] has made the most comprehensive study of knife sharpness to date and found that examining the tip surface area by scanning electron microscopy is the best method for quantifying sharpness and relating this to penetrability. Unfortunately, from a forensic perspective, this method is destructive. This paper concentrates on a non-destructive method for examining the sharpness of common types of knives used in stabbing [10]. The knives are examined in terms of their geometries, penetration ability and the mechanisms by which they penetrate skin. The results will aid pathologists in giving a more informed answer to the question of the degree of force used in stabbing.

Materials and methods

To understand the factors that control a knife's penetration ability, it is important first to understand the way in which knives are manufactured and the standard industry tests used for measuring sharpness.

Knife-making process

Kitchen knives are usually made from a stainless steel strip. The knives are blanked from the strip and then the cutting edge is ground onto the edge of the strip by passing the knife through a series of rollers [11]. For kitchen knives, there are commonly two types of blade profile: taper ground or hollow ground. Taper-ground knives taper from the back of the blade to the edge. Hollow-ground blades are simply ground close to the tip. Both hollow and edge grinding produce knives that are easily blunted after use. Some modern kitchen knives are forged from steel blanks rather than cut from a strip. These knives are high strength and made of high-strength CrMoV steels. The cutting edge to these blades is formed in a similar way to the knives blanked from steel, but because the material is harder, the blades retain their cutting edge for a longer time than the cheaper stainless steel knives. The edges can be plain, serrated, scalloped or coated with materials such as tungsten carbide. These affect the edge sharpness depending on the cutting action; for example, bread knives are commonly serrated giving multiple sharp cutting points along the blade edge. The tip sharpness is produced from the shape of the knife when it is formed from blank steel and the degree of sharpening close to the tip. The factors that control tip sharpness are discussed in greater detail in the following sections.

Sharpness standards

There are currently no British Standards that focus on the parameters that determine the sharpness of knife in terms of blade geometry and tip sharpness. There is a British Standard Test, BS EN ISO 8442-5:2004 [12], for measuring initial sharpness and durability, which involves pushing the knife through cardboard impregnated with silica. This method is destructive and therefore unsuited to forensic tests as the blade would be altered by the measurements. Additionally, the cutting action in the standard uses the long edge of the blade rather than using the tip of the blade. For stabbing, the sharpness of the tip of the blade is more important than the sharpness of the length as it determines the force required to initially penetrate the skin.

In terms of sharpness of the knife from a forensic pathology perspective, there is no agreed routinely used scientific method for classifying sharpness. Davison [3] recommended testing with the tip of a finger and describing the tip as either blunt, moderately sharp or extremely sharp. This is obviously a subjective test and as such can give varying classifications between pathologists. It is also dangerous in terms of health and safety.

Experimental details and method

We tested a range of kitchen knives to examine their characteristics in terms of edge angle and radius, blade

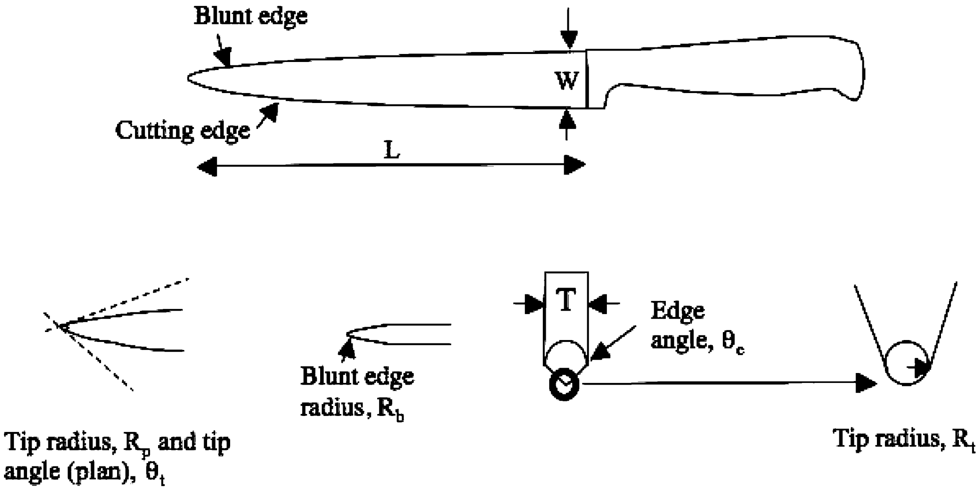

Fig. 1 Schematic diagram showing the different parameters obtained to characterise the features of the different knives

Fig. 2 The five different kitchen knives tested for penetrability (knives *a*–*e*)

thickness and tip radius and angle. The knives tested included new knives and knives that had been in continuous use over a period of time. Figure 1 illustrates how the parameters measured are defined.

To measure the tip and blunt-edge radii, an Olympus stereomicroscope (Olympus SZ-X12, Olympus, Tokyo, Japan) was used to record an image of the knife. Measurements were made in Image Pro Plus v4 (Media Cybernetics, Berkshire, UK), which allowed the angles and radii to be obtained. A stereomicroscope was used as it allowed high-magnification images to be obtained without the need for destructive sectioning of the knife, and it is therefore amenable to identification of important parameters in cases where the knife cannot by altered (for example if a knife has been used in a stabbing incident). To obtain the edge angles, a replica of the knife blade was made in Acrulite casting resin (Rubert, Cheadle, UK). The replicas were sectioned and polished to leave a profile of the blade. These profiles were then examined in an FEI Philips XL30 environmental scanning electron microscope (FEI, Netherlands). The images were evaluated in Image Pro Plus v4 in the same manner as the stereomicroscope images to allow the knife edge radius and edge angle to be determined. This method allowed the edge angles to be obtained with greater resolution than the stereomicroscope.

Fig. 3 Equivalent knives to the Acero carving knife and the Sabatier filleting knife with the tips removed (knives *f* and *g*)

Table 1 Description of the knives tested

Knife	a	b	c	d	e
Manufacturer	Sabatier	Kitchen Devils	Acero	Sabatier	Unknown
Condition	New	New	New	Used	Used
Knife type	Flexible carving/ filleting	Cook's knife	Carving Knife	Carving knife	Cook's knife
Blade type	Single-edged plain ground	Single-edged plain ground	Single-edged plain ground	Single-edged plain ground	Single-edged plain ground at tip, serrated on blade
Sharpness of tip (qualitative)	Extremely sharp	Extremely sharp	Extremely sharp	Extremely sharp	Moderately sharp to blunt
Sharpness of cutting edge (qualitative)	Extremely sharp	Moderately sharp	Extremely sharp	Moderately sharp	Moderately sharp to blunt
Radius of tip on blunt edge of blade (mm)	0.022	Triangular tip geometry	0.0367	0.061	0.261
Tip angle (plan)	51.5	54.3	46.7	58.6	64.2
Tip radius (R_p) (mm) (plan)	Triangular	0.892	0.121	0.383	0.456
Edge angle	48.2	44.9	30.7	20.7	33.4
Edge radius (R_t) (mm)	Triangular	0.023	Triangular	0.025	0.021
Weight of knife (g)	108.1	100	191.2	104	159

Initial tests were made on a selection of five new and used kitchen knives (Fig. 2). These are all described as cook's or carving knives with blade lengths ranging from 15.7 cm for the Kitchen Devils knife (knife c) through to 20 cm for the Acero 'Masterclass' knife (knife b). Knives a and d are the same knife type but knife d had been in regular use for approximately 8 years and had periodically been sharpened using a sharpening steel. Knife e was approximately 10 years old and had been used almost daily. It had been sharpened on a ceramic knife sharpener obtained from IKEA (similar to a whetstone) on a regular basis (approximately monthly). Edge angle and radii, tip radii and angle and blunt-edge radius were determined for the five knives. The data are presented in Table 1 alongside the qualitative assessment of sharpness recommended by Davison [3], which was conducted independently by three people. The tips were removed from two knives to leave flat ends so comparisons could be made between the penetration ability with and without a tip (Fig. 3) Thus, knife f is a direct comparison with knife b, and g compares with knives a and d.

As well as carving/cook's knives, utility knives are often used in stabbings; hence, two utility knives (knives h and i) were also examined (Fig. 4). A bread knife was examined as it is sometimes questioned whether these are sufficiently sharp to be used in stabbings (Fig. 5). This knife has a scalloped and serrated edge with a geometry known as 'sheepsfoot,' which gives good control over the cutting action. Finally, a number of relatively cheap 'own-brand' knives were purchased from Wilkinson (Wilkinson Hardware Stores, Leicester, UK). These knives were deliberately blunted to see the effect of changing the tip geometry on penetration ability. Three distinct types of knife were examined: cook's knives (Fig. 6), carving knives (Fig. 7) and utility knives (Fig. 8).

Penetration testing was performed by drop testing into foam using a drop tower (Fig. 9). The knives were firmly fixed into the holder before testing, and care was taken to

Fig. 4 Utility knives *h* and *i*

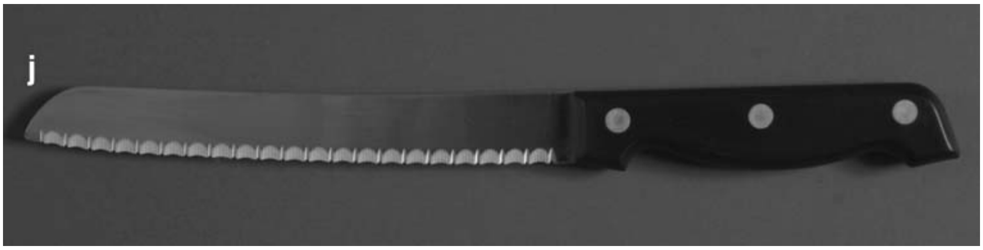

Fig. 5 ‘Sheepsfoot’ geometry scalloped and serrated bread knife

ensure that the blades were mounted perpendicular to the foam. It is difficult to simulate exactly the conditions of a knife attack in the laboratory: the impact velocity, energy and momentum of a knife attack can all be reproduced, but it is impossible to match the combination of all three to the human case [8]. However, drop testing is a good test for comparing knife sharpness under controlled conditions in a reproducible manner.

To get the same kinetic energy for each knife at impact, the height from which each knife was dropped was varied. The height required to obtain a standard kinetic energy (Ke) at impact was calculated using the equation $\mathrm{Ke} = 1/2mv^2 = mgh$ where m is the mass of the knife, v is the velocity, g is the gravitational constant and h is the height above the foam. The mass of the knives was taken and the height then adjusted to give the same equivalent impact energy (i.e. lighter knives were dropped from greater heights). The substrate material in all cases was kept constant by use of a polyether open-cell foam with a density of 23–28 kg m^{-2} and a foam hardness in the range 125–155 N (a medium-hardness foam). Foam has previously been used as a skin analogue by Chadwick et al. [8], although other skin analogues including chamois and gelatin [13], roma plastilina (a modelling clay) [13] and

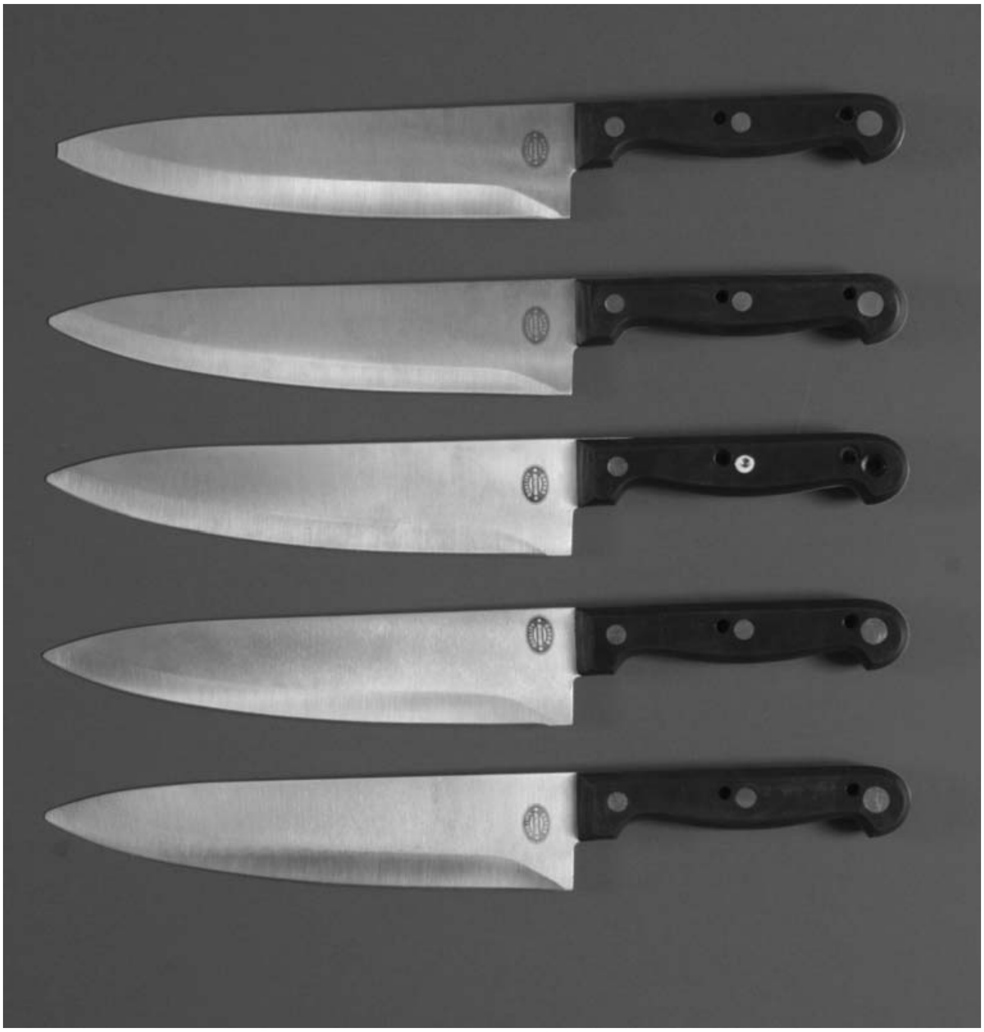

Fig. 6 Wilkinson ‘own-brand’ Cook’s knives

Fig. 7 Wilkinson ‘own-brand’ carving knives

silicone on foam have also been used [14, 15]. In the work presented here, a simple open-cell foam was used as it gave good reproducibility of response for characterizing penetration ability, and we were not trying to extract penetration forces from the experiments. The foam was also found to give a realistic response in terms of elastic deflection of the surface for blunter knives. During these experiments, care was taken to ensure that the knives did not penetrate the full thickness of the foam as their tips could then have become blunted. Three drop tests were made for each knife.

Fig. 8 Wilkinson ‘own-brand’ utility knives

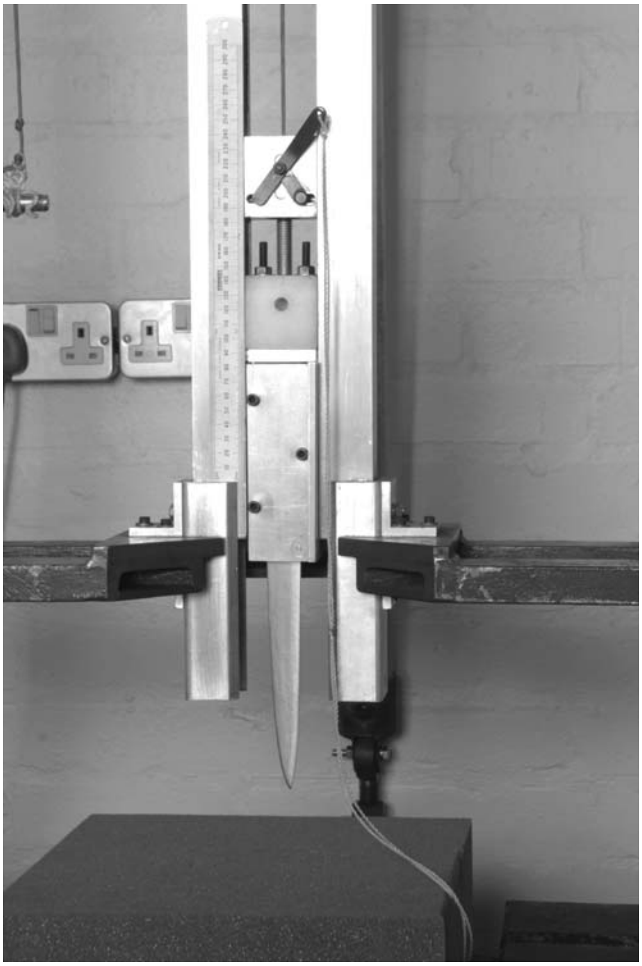

Fig. 9 Experimental setup of drop tower for penetration testing

High-speed video

High-speed video images were taken of three stabbing into a leg of pork (so as to comprise of the skin, fat and underlying muscle tissues) so as to elucidate the stabbing mechanism with different types of knife. The high-speed video images were taken using an Olympus i-Speed Video Camera (Olympus, Tokyo, Japan) with a recording speed of 800 frames per second. Additional lighting was provided by i-Speed 1,000-W photonbeam lamps (Olympus, Tokyo, Japan) to provide good illumination. Knives d, e and j were used in the video experiments to represent a range of knives.

Results

Measurements

The results of the measurements made on each knife are shown in Table 1. There is considerable variation in many of the parameters despite the knives having a qualitatively similar "feel" in their sharpness. Because Knight's observation that it was the "sharpness at the tip" that was important [4], the aim of the characterisation here was to identify parameters that would describe this sharpness without the knife having to be destructively sectioned as in the method used by O'Callaghan [9]. One parameter that does systematically vary is the radius of the blunt edge, which was seen to increase as the knives 'felt blunter.' There are two other tip radii measurements given: the tip or edge radius (Rt) and the radius with the knife in plan view (i.e. with the blade width parallel to the table).

Penetration depth vs blunt edge radius

Figure 10 shows a graph of penetration depth against blunt-edge radius for all the knives where a radius could be defined. For some of the knives tested, there was no measurable radius on the blunt edge at the magnification obtainable by stereomicroscopy; rather, the knives came to a point. The data for these knives are given separately. A power law fit to the data is shown on Fig. 12, which gives a 'master curve' against which the penetration of knives can be assessed.

Triangular tip geometries

For three of the knives tested, the blunt edge formed a point rather than a radius. All these knives had good penetration into the foam. If the blunt edge tip angle was measured, there was no particular link with their penetration ability. The knives in this class were the Kitchen Devils carving knife and the Masterclass and Acero utility knives with blunt edge tip angles of 59.2, 32.5 and 64.9°, respectively.

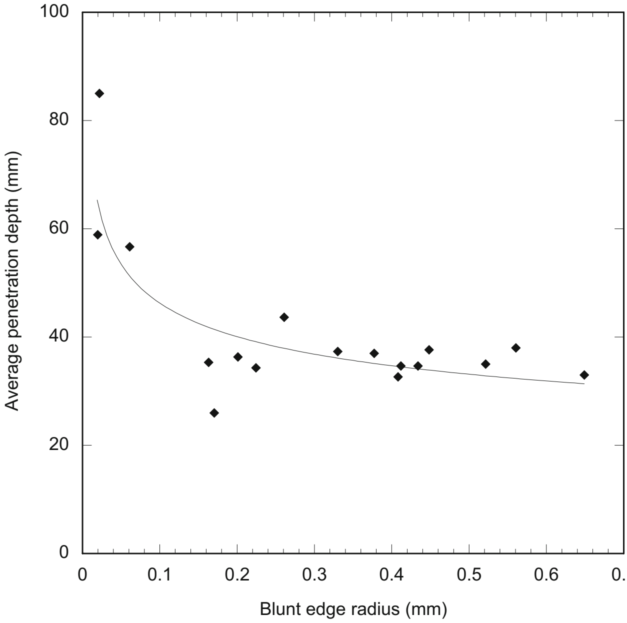

Fig. 10 Penetration depth vs blunt edge radius

The knives penetrated 61.0, 97.7 and 87.0 mm. Thus, there is no clear correlation with the edge angle. The thicknesses of the blade just back from the tip were 0.307, 0.435 and 0.469 mm, respectively, and therefore, the penetration did not simply scale with blade thickness. After initial penetration, the cross-sectional profile of the blade was greater for the Kitchen Devils knife (as can be seen by examining knife c, Fig. 2) in comparison to knives h and i. This accounts for the lower penetration depth achieved with the Kitchen Devils knife.

Effect of tip removal

The tips of two of the sharp knives and one of the blunter knives were removed to leave flat ends. The knives were the Acero and a P. Sabatier Stellar flexible filleting knife, and the blunter knife was one of the large cook's knives. For the sharp knives, the tip removal left a flat edge with lengths of 6.43 and 1.95 mm, respectively, and blade thicknesses at the tip were 0.65 and 0.17 mm, respectively. The penetration depths of these knives into foam were 54.3 and 85.7 mm, respectively. In comparison to the equivalent knives with the tips removed, the equivalent Acero with a tip penetrated 59.0 mm, and the equivalent Sabatier penetrated slightly less (at 85 mm) than the knife with the tip removed. Attempts were made to stab into pigskin with both these knives. The large flat end on the Acero meant that skin penetration did not occur, whilst the P. Sabatier knife penetrated the skin on application of moderate force (on a subjective scale). For the blunter Wilkinson knife, the length of the flat tip was 5.53 mm, and the blade thickness at the tip was 0.54 mm; this knife penetrated 34.7 mm, which is comparable with the other cook's knives, which penetrated to similar depths. This knife did not penetrate pigskin on a simulated stab test, but neither did the comparable knife with a blunted tip. The stabbing tests reinforce Knight's observation that the tip is important in penetrating flesh [4].

Effect of tip radius blunting

For the Wilkinson class of knives that had their tip radii (plan) altered to larger values, there were no clear relationships between the radius of the tip in plan and the penetrability. For the class of cook's knives, there was a link between the tip radius in plan and the penetrability, but this did not hold for all the knives. The most reliable way of assessing the sharpness was still the radius of the blunt edge.

Utility knives

Both the utility knives tested showed considerable penetration into the foam. The Masterclass utility penetrated to 92.7 mm, and the Victorinox utility penetrated to 78.7 mm.

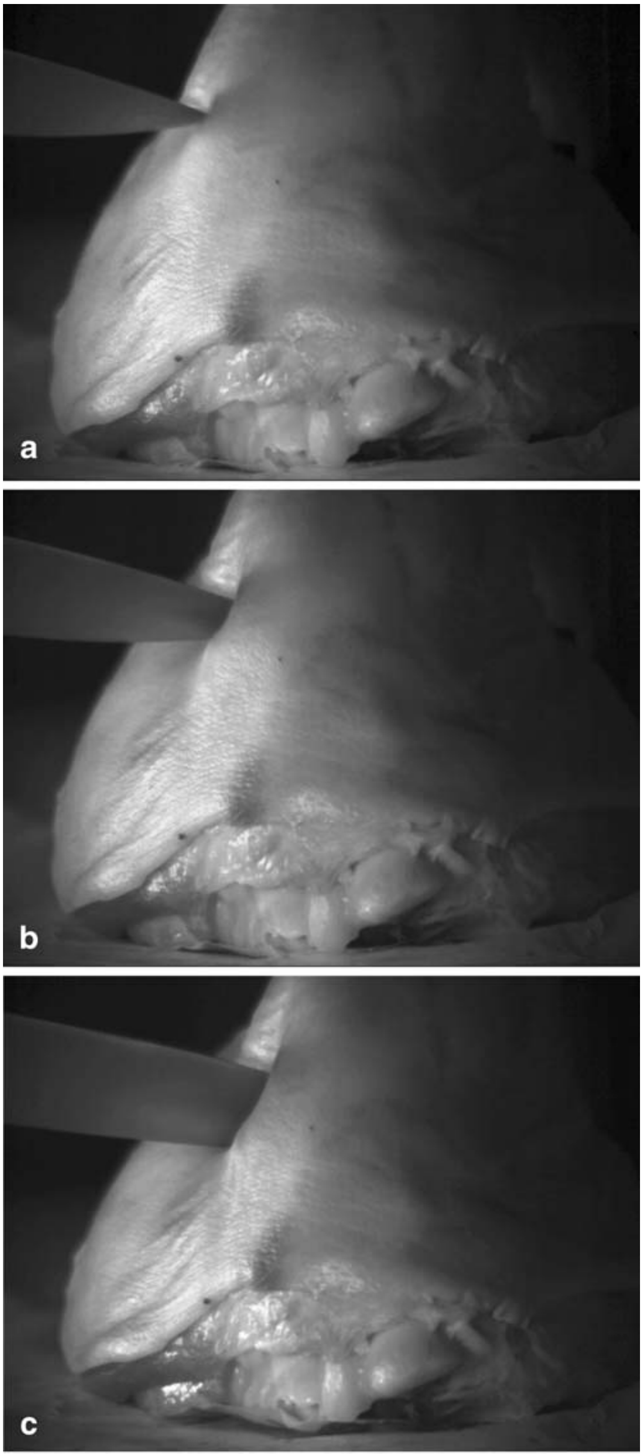

Fig. 11 **a** Initial contact of knife with pork skin. The skin deflects around the knife tip. **b** A later image. At this point, the skin has deflected considerably, and the tip has just penetrated through the skin. The knife now starts to slide into the flesh. **c** Further penetration of the knife into the flesh. At this point, the sharpness of the edge becomes important for further sliding into the pork leg. Note that whilst there is some additional deflection of the skin, the knife now penetrates without further deflection of the skin

These weapons were particularly effective at penetrating into the foam.

Bread knife

The sheepsfoot bread knife did penetrate into the foam but to a shallow depth compared to the other knives with a pointed tip (19.3 mm). This was the least penetration of all the knives tested.

High-speed video

Figure 11 shows a sequence of images taken from the stabbing test with a sharp Sabatier knife. This knife penetrated the foam to 85.0 mm and easily penetrated the pork flesh. Figure 11a shows an initial image where the pork flesh is deflecting as the knife makes contact with the skin. Figure 11b is several images further through the sequence where the tip has just penetrated the skin. There is additional deflection of the skin around the knife tip. Figure 11c is further through the sequence. There is a small additional deflection of the skin, but now the blade is sliding through the flesh. At this point, the sharpness of the edge is important in further penetration.

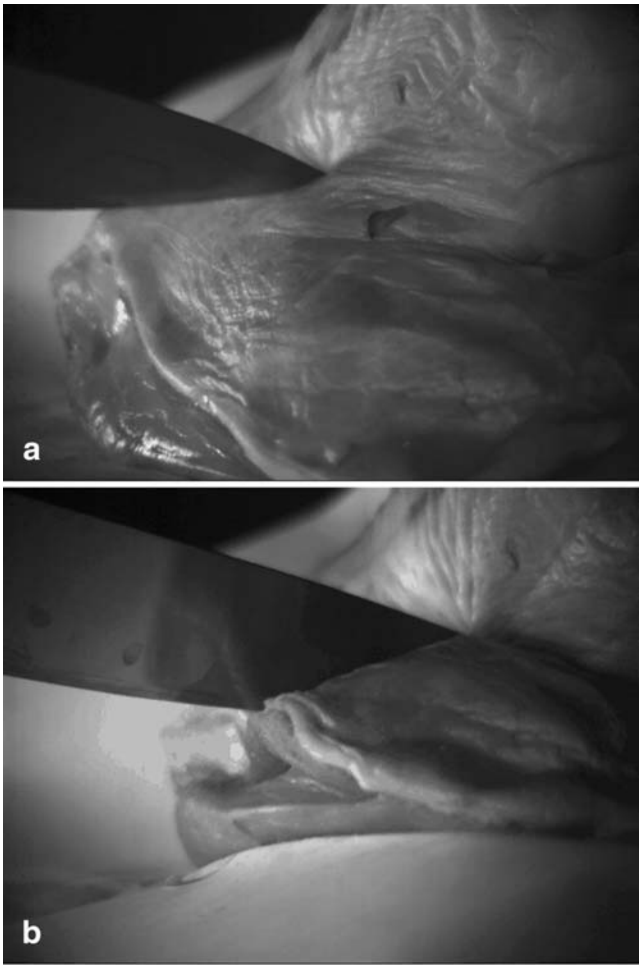

Fig. 12 **a** Initial stages of contact with a 'blunt' knife. At this stage, the mechanism appears similar with deflection of the skin around the knife tip. **b** An image of the 'blunt' knife test. Note the considerable elastic deformation of the skin. No penetration of the knife into the skin occurred in this test

Fig. 13 Gross deflection of the skin without knife penetration at the end of the test with the bread knife

Figure 12 shows a sequence of images taken from the stabbing test with the blunt knife (some marks from previous stabs can be seen on the pork leg). The initial image (Fig. 12a) shows the knife as it just makes contact with the skin. Again, the skin deflects around the knife tip. Figure 12a shows an image later in the sequence. There is considerable deflection of the skin around the knife tip (compare this to Fig. 11c). The initial stab with this knife was made with the same force as previously, but once it was clear that the knife had not penetrated the flesh, additional force was applied. Penetration still did not occur.

The final still image taken from the stab with the bread knife is shown in Fig. 13. It can be seen that there is considerable elastic deformation and flexure of the pork leg, but there was no evidence of knife penetration into the skin when the test was stopped. With this geometry of bread knife, penetration of the skin could not be achieved. Bread knives have, however, been known to cause death by stabbing; the geometry and characteristics of each individual knife must be determined before drawing general conclusions about their ability to penetrate skin.

Discussion

So, what makes a knife sharp? From the results presented within:

- Blunt edge tip radius gives a good indication of penetrability with smaller radii giving increased penetrability.

- Blade thickness—slender ‘filleting’-type knives and slender utility knives penetrate more easily than thicker blades.
- Blade geometry—the shape at the tip is important; a ‘sheepsfoot’ geometry knife does not present a tip to the skin, rather a rounded tip, whereas pointed geometries and particularly points that taper on the blunt and cutting edge are effective. The blade geometry also determines the blade cross-sectional area at any point, and knives with larger cross-sections penetrate to lower depths.
- Edge sharpness—once the tip has penetrated the skin, the edge sharpness is important for continued penetration.

The penetration of knives is a complex problem. There is a complex relationship between knife characteristics (such as tip shape and sharpness and blade geometry) and their penetration ability. It is not possible to extract the exact force required for a stabbing incident from the drop testing and penetrability into foam tests used here, but the tests do give an indication to the pathologist as to where a particular knife falls in terms of its quantifiable characteristics and its ability to cause a stab wound.

High-speed video testing has given an insight into the mechanism of knife penetration into flesh (pigskin). Pigskin is known to be coarser and thicker than human flesh [16], but the microstructure of human skin and pigskin are very similar, and therefore, it is reasonable to assume that the failure mechanism is the same in both. The mechanism of penetration for the sharp knives was found to be:

- Initial elastic deformation of skin and underlying fat and muscle
- At a critical stress depending on the penetration ability of the blade, the knife penetrates the skin
- The knife then slides into skin and sharpness of blade edge becomes important
- Once the skin has been penetrated, the knife penetrates easily into the underlying muscle

For the blunt knife and the bread knife, no skin penetration was observed, but the skin deformed elastically to large deformations. Again, one cannot make generalised sweeping statements in relation to whether a knife could or could not penetrate skin without taking into account the geometry and characteristics the knife.

Conclusions

A series of tests have been made into polyether foam using a drop test tower to characterise the penetrability of kitchen knives that may be used in stabbing incidents. A range of radii, thicknesses and angles have been measured to try and relate quantifiable parameters to the penetration depths that were measured for each knife. Additionally, high-speed video has been used to obtain insights into the way in which kitchen knives penetrate flesh. The findings are summarised below.

- For knives that had a distinct radius on the blunt edge at the tip, there was a good correlation between penetrability and the radius of the blunt edge. The smaller the radius, the greater the ease of penetration.
- For knives with triangular tip geometries, there was no easy correlation between penetration ability and the tip angle on the blunt edge.
- For knives with a flat end (i.e. the tip removed), considerable penetration into foam could still be achieved, but knives with a broad flat tip did not penetrate into pork skin.
- The high-speed video testing showed that knives with a blunt edge radius of 0.26 mm, which felt relatively blunt in a qualitative test of sharpness, were unable to penetrate pork flesh with a short-thrust stabbing motion. Knives with tip radii smaller than this were found to penetrate the pork flesh under these stabbing conditions.
- The high-speed video testing showed that the mechanism of penetration for sharp knives was initial elastic deformation of the skin, followed by penetration. Once the knife had penetrated, the edge sharpness became important for further penetration of the blade into the pork flesh.
- From the high-speed video tests, blunt knives simply caused deflection of the flesh with no penetration under the test conditions used. Similarly, the sheepsfoot geometry bread knife used in the tests did not penetrate the flesh.

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