Objectivity in Forensic Medicine

Modern Methods of Examination and Evaluation of Stab Injuries

Doctoral (PhD)-thesis

Veronika Heckmann M. D.

Supervisor: Tamás F Molnár, M.D., PhD, DSc, FETS

Director of Program: Tamás F. Molnár, M.D., PhD, DSc, FETS (2020-23)

Zalán Szántó, M.D., PhD (2024)

Head of Doctoral School: Lajos Bogár, M.D., PhD, DSc

Clinical Medical Sciences Doctoral School

University of Pécs

OGYDHT Pécs

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I. Introduction, objectives

With the development of science and technology, expert evidence's importance in criminal proceedings is increasing. While medicine has long been characterized by evidence-based medicine, classical forensic medicine still contains many subjective elements. The motivation for my research was the need to move from subjective opinion to objective (evidence-based) forensic medical expertise. My choice of topic fell on stab wounds because, on the one hand, this is one of the most common types of injuries among the ways of committing acts by strangers, and on the other hand, it is necessary to answer several special questions that require the use of new aspects and objective methods.

During my research, I set the following goals:

1) Examination and comparison of international and Hungarian epidemiological characteristics of homicidal stab wounds with Baranya County data.
2) Review the available literature data and develop a new test method to determine the direction of stab wounds as accurately as possible.
3) Examination of the objective modeling possibilities of stab wounds and the development of a method suitable for the comparative examination of stab wounds.
4) Development of a uniform testing method for stabbing tools.
5) Examining the degree of force required to cause the injuries, including
   a) comparison of individual device types;
   b) examining the effect of knife blade characteristics on the minimum force required to cause a stab wound;
   c) examining the effect of clothing on the force of the stab wound.

II. Epidemiological characteristics of stabbing attacks

According to the United Nations Office on the Drugs and Crime (UNODC), there are approximately 440,000-450,000 homicides worldwide each year. In 2021, 458,000 homicides were registered; 19% of the victims were women, and 81% were men. In many countries (e.g. Sweden, Hungary, Poland, the United Kingdom, Canada), most homicides are committed with a sharp instrument. Summarizing the data for each continent, the incidence of sharp force in Europe is 30%; in Asia, the rate is similar (31%), while in America, firearms dominate, with sharp injuries being the cause of death in 14%. The most common instrument of perpetration is a knife (including a kitchen knife), but in a few percent of cases, other sharp instruments (e.g. scissors or screwdrivers) caused the fatal injury.

Hungarian homicide statistics

In Hungary, the number of homicides has been gradually decreasing in recent decades, similar to other countries in the European Union. Before the change of regime, between 1965 and 1990, the annual homicide figures fluctuated around 200. In 1991, the number of registered cases increased to 307, and then from 1999 onwards there was a sharp decrease, a trend that continues to this day. The number of homicides is 100 per year, while the number of serious bodily injuries causing death has been around 20 in recent years in Hungary.

Injuries caused by sharp instruments in the autopsy material of the Institute of Forensic Medicine Pécs

Between 2007 and 2023, 3,790 autopsies were performed at the Department of Forensic Medicine Pécs on official request, of which 88 were in cases initiated by the police for homicide or serious bodily harm causing death, which represents 2.32 percent of all autopsies. The number of cases reflects all such acts committed in Baranya County during the given period, which represents an average of 5.17 acts against life per year. This figure is 1.43 per 100,000 inhabitants, slightly higher than the rate of 1.2/100,000 calculated from national data. In the 2010s, the number of cases was typically around 4-5, but in 2021, for example, no such acts were reported in Baranya County.

Based on the examination of the methods of commission, sharp force injuries stand out: in 31 cases, an injury caused by a sharp instrument played a role in the death. In many acts committed with a sharp instrument (28 cases), a stab wound resulted in a fatal outcome, incising in three cases and cutting in one case. In the case of stab wounds in the institutional material, 57% of the victims in the given period were male (16 cases), while 43% (12 cases) were female. Of the known perpetrators (23), 86% were male (20), while only 13% were female (3). In the case of female victims, in 5 cases, the perpetrator was the victim's current or former male partner, while in three cases, there was another motivation behind the act.

Characteristics of stab wounds in the institute's autopsy material

Of the 27 victims who suffered stab wounds, a total of 167 stab wounds could be identified. Examining the location of the stab wounds described during the autopsies, it can be established that most stab wounds affected the left side of the chest and the abdomen, followed in order by the head, neck and right side of the chest.

III. Examination and assessment of stab wounds

When examining stab wounds, the medical expert must determine the course of the wound track, i.e., the direction of the stabbing, and must also estimate the characteristics of the instrument that caused the injury, i.e., the number and nature of the edges (smooth, serrated), the probable shape, height, length, and thickness of the blade. However, determining the characteristics of the instrument with the available methods is only possible with a high level of uncertainty.

The medical expert must also state the degree and direction of the force that caused the injury. In the case of a stab wound, the degree of force required to cause the injury is influenced by the characteristics of the instrument of perpetration (primarily its sharpness), the anatomical characteristics of the injured body area (skin thickness, skin tension, collagen fiber course); and all those factors that can absorb part of the energy of the stab wound hitting the body surface (e.g. clothing). The degree of force required to cause a given injury cannot be determined objectively; only a probabilistic opinion can be given regarding this issue.

IV. Application of 3D printing to assess the direction of wound track and the weapon's possible characteristics

The most commonly used method for examining the direction of wound track is the insertion of a thin metal probe in the stab wound and then the careful dissection of the tissues layer by layer. The most significant disadvantage of this method is that the instrument can move significantly within the stab wound channel due to its small diameter, so the direction of the wound track can only be determined approximately. If the presumed instrument of perpetration is available, the simplest method for determining the direction of the wound track and identifying the knife would be to insert the knife into the wound. However, it cannot be advised for multiple reasons. The inserted (sharp) weapon can enlarge and deform the wound, and even if the blade does not directly contact the body, the possibility of cross-contamination will always be there.

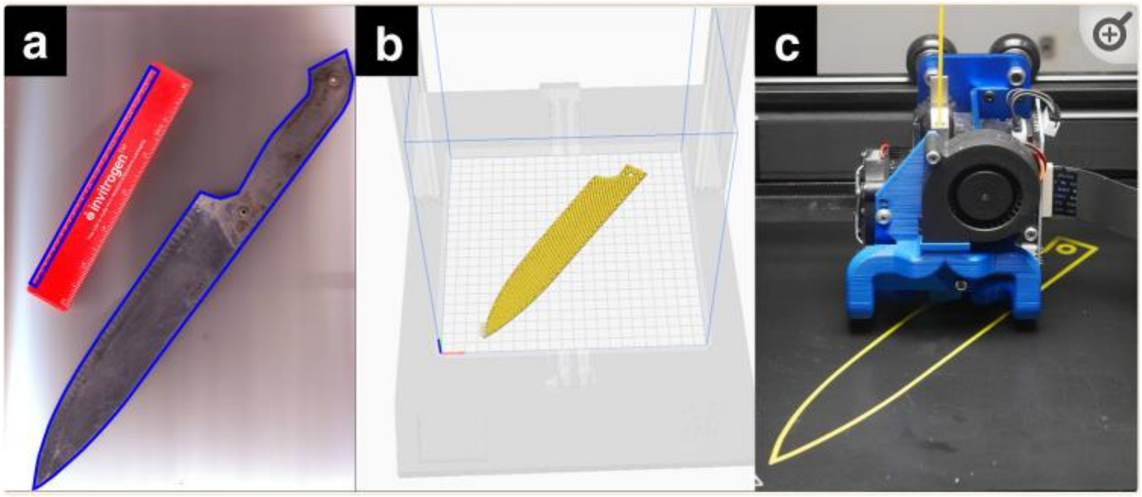
Objectives

During my research, I first examined whether using 3D-printed copies of possible crime tools could be suitable for objectively answering forensic questions. I aimed to investigate the following factors:

- can the tissues be damaged by inserting the copied knives into the injury, and can it change the autopsy findings,
- can the insertion of the copied knives into the injury help in determining the direction of the wound track,
- can the insertion of the copied knives into the injury help assess the instrument used to cause the injury?

Materials and methods

The knives used for the test were digitized with a flatbed scanner along with a ruler, and the blade thickness was measured with a digital micrometer. The digital images were opened in vector graphics image editing software, and the blade contours were traced. The 3D model was created from the exported openSCAD file using Cura software. The edge of the blade was not modeled to avoid tissue damage. The blade was made from PLA filament using an FDM type 3D printer. After printing, the replica blade thickness was compared with the original knives with a digital micrometer, and the other dimensions of the blade were compared with a digital caliper. The maximal deviation was 0.4 mm in the length and width of the blade and 0.05 mm in the blade thickness. For the manual stab tests, a handle was made on the blade by 3D printing.



3D printing of the knives: Scanning(a), digital model creating (b), 3D printing(c)

Free-hand ballistic gel experiment

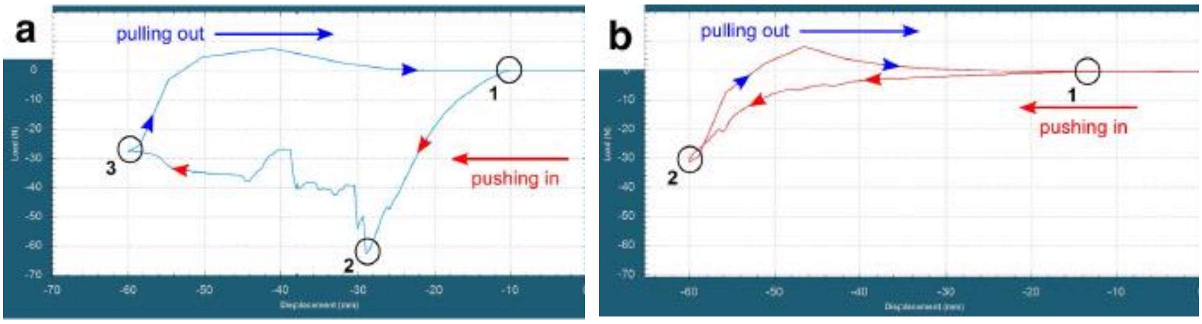
To visually examine the insertion capability, we created stab wounds in ballistic gel with the original knife using a thrust and slash-like stabbing motion. After the stabbing, a mark was placed on the blade at the level of the gel surface (maximal penetration). The 3D-printed replica was inserted into the wound channel, and by applying greater force, we also tried to increase the size of the created wound track. A mark was also placed on the blade replica at the level of the gel surface, corresponding to the maximal penetration depth achieved. The marks placed on the original and replica blades were compared.

Free-hand pork loin stabbing experiments

The original blade was stabbed into a pork loin, and then the entrance wound length was measured by a digital caliper. Replica knives were installed into the same stab wounds, and the maximal possible horizontal force was applied in the direction of its edge (horizontal to the skin surface). Entrance wound length was measured again by a digital caliper.

Dynamic stabbing force measurements

Dynamic stabbing force measurements were performed with a Mecmesin MultiTest-dv motorized test stand (2.5 kN) combined with a Mecmesin force gauge AFG-500 (0–500 N capacity, ± 0.5 N accuracy). The stabbing force was 2.5 kN (250 kg), initial tip–surface distance was 10 mm, and displacement (downwards movement) was 60 and 75 mm, with a constant movement speed of 100 mm/min. The load (force) was measured by AFG-500 and was recorded with Mecmesin VectorPro Software. Wound size was measured with a digital caliper. After creating a stab wound with the original blade on the pork loin, the replica blade was into the stab wound previously created by the original blade. A larger replica blade was also stabbed into the same wound. The tests were performed again so that the replica knives were stabbed 15 mm further than the original knife (75 mm overall displacement).



Creation of the stab wound with original knife (a) and replica knife into the stab wound (b). Red arrows ("pushing in") indicate the downward movement (stabbing), blue arrows ("pulling out") indicate the upward movement of the blade. Number (1) indicates where tip of the blade reaches the surface of the pork loin, number (2) indicates the maximum force, while number (3) indicates the maximum displacement

Model experiment for wound assessment

We made replicas of 6 kitchen knives, numbered 1-6, for the model experiment. Seven stab wounds were made randomly on a pork loin. The stab wounds were marked with letters (a-g) on the sample. Five participants with various forensic pathology experience were asked to compare the wounds with the printed knives and place the knives into the following categories: probable, possible, and excluded. The results were compared using a chi-square test using the online GraphPad QuickCalcs program (https://www.graphpad.com/quick calls).

Results

Free-hand stabbing experiments in ballistic gel

The 3D printed version fit perfectly to the stab wound in the ballistic gel, and it was impossible to stab it deeper or enlarge the wound by applying considerable force. The place of markings on the original blade and on the replica matched.

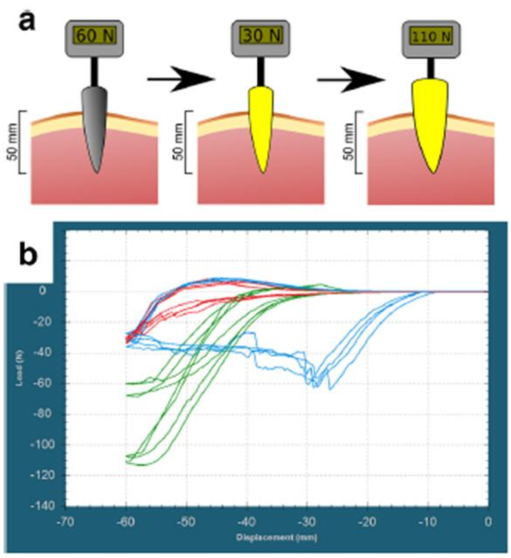
Free-hand pork-loin experiments

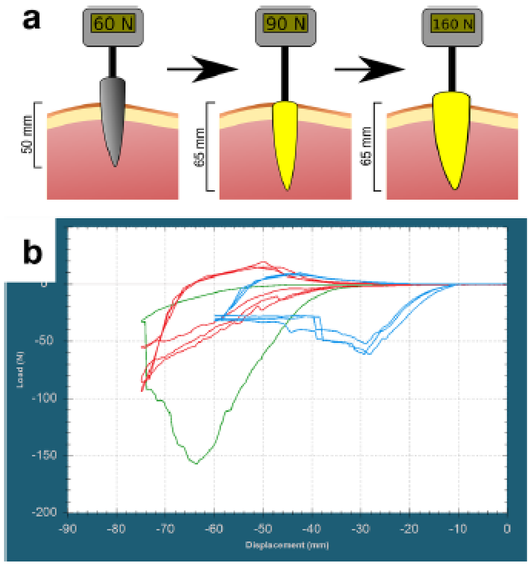
By applying maximal horizontal force towards the pointed end of the entrance wound with the replica knife, the entrance wound was enlarged by an average of 0.48 mm (0–0.61 mm).

Dynamic force measurements

The average maximum load during stabbing with the original blade (label 1) was 63.3 N (62.2–64.3 N), with a constant load between 30 and 40 N after penetration. At the maximum displacement (60 mm), the average load was 32.1 N (27.4-36 N). The depth of the wound channel was between 34-36 mm. When piercing with the replica knife, the load ranged between 1 and 5 N (average 3.8 N at 40 mm displacement). When reaching the end of the entrance wound, the load increased rapidly and reached an average of 32.88 N (31.5-33.9 N) at 60 mm displacement. The average load at 40 mm displacement was 20.2 N (14.7-2.9 N), and the maximum load was 87.75 N (62.5-113.2 N).

In the second series of measurements, the average maximum force with the original blade was 59.3 N (52.9-62.66 N), which occurred at the time of penetration, and then during the further process of stabbing, the load varied between 30-40 N. At the maximum displacement (75 mm), the average load was 38.7 N (33.9-44.2 N). The depth of the wound channel was 33-34 mm. In the case of stabbing with the replica of the knife, the load ranged between 1 and 5 N (average 5.5 N at 40 mm displacement). When reaching the end of the entrance wound, the load increased rapidly, and the blade bent at a displacement of 60 mm. At a displacement of 60 mm, the average load was 37.95 N (N); at a displacement of 75 mm, it was 78.8 N (56.9-94.2 N). When stabbing with a larger knife, marked 2, and reaching the edge of the entrance wound, the knife bent and then started to break at a displacement of 63.3 mm. The complete break occurred at a displacement of 74 mm. The load at a displacement of 60 mm was 140.8 N, and the maximum load (at (63.63mm) was 157.8 N.





Dynamic stabbing force measurements with 60 mm total displacement. Blue: original blade, red: replica of the blade, green: overlarge replica of the blade	Dynamic stabbing force measurements with 75 mm total displacement. Blue: original blade, red: replica of the blade, green: overlarge replica of the blade

Model experiment for wound assessment

The success rate of identifying the knives based on the wound track was analyzed. Summarizing the outcomes, the participants chose 23 times altogether that the used knife was the most probable weapon and 12 times the used knife as a possible candidate. None of the experts incorrectly excluded the knife that was used. The differences between these groups were statistically significant ($p<0,0001$).

Discussion

The method presented above is fast and cost-effective (a 3D printer costs 80-100,000 forints, and the cost per print for a knife-sized object is a maximum of a few hundred forints). Experiments on ballistic gel prove that the replica can be inserted accurately and well into the puncture wound channel and that it cannot be changed with the replica without applying great force. The results of manual stabbing on pork loin also support this: the wound cannot be significantly extended with the replicas, even with the application of great force. During dynamic stabbing tests, changing the dimensions of the stab wound is only possible with the application of very great force, and in the process, the printed knife bends or breaks.

Based on the results of our model experiment, the method can achieve adequate results in identifying the blade causing the stab wound, and false exclusion can be safely avoided. The method cannot distinguish between tools of similar shape and size but is reliable in cases where the blades differ significantly. The method is also limited in the case of superficial stab wounds, as in such cases, the puncture channel does not provide enough information about the tool that caused it. The main limitation of the method is that the identified tool must be available at autopsy: it cannot be applied if a suspected instrument of commission has not been found.

Summary:

- The use of the 3D-printed knives is safe; it does not damage the tissues.
- With the replica knives, DNA contamination can be completely avoided.
- With the replica knives, the direction of the wound track can be well demonstrated.
- The 3D-printed knives are suitable for testing the insertion of the knife.

Application of the method in everyday routine

Based on the results detailed above, the Department of Forensic Medicine Pécs has introduced the use of 3D-printed replicas of crime tools during autopsies into everyday routine practice. In the case of photographs with appropriate size markings, the digital 3D model can also be created based on the photographs, so it is not necessary to provide the tool from the authorities and transport it to the autopsy room. Furthermore, the method is a valuable complement to autopsies not only for knives but also for blunt objects.

V. Examination of stab wounds, mechanics of stabbing

The mechanics of stabbing means the complex stabbing process, which can be characterized by the knife position, the direction of the stabbing, the speed of stabbing, the force, the energy of stabbing, and impulse. There is no uniform procedure for examining the mechanics of stab injuries, and although there are many methods, they differ in terms of the testing instrument and the test target. The two main groups of stabbing simulation methods are constant velocity and dynamic methods. In the case of constant velocity methods, the testing device moves the blade at a constant, defined speed, while in the case of dynamic testing methods, the measuring instrument is in a specially designed knife, or the blade is placed in a drop tower and the attached weight moves (drops) it downwards with acceleration into the sample placed below. During stabbing tests, human skin samples from autopsy, animal (mostly pig) skin samples, and artificial skin-simulating materials (e.g., silicone rubber, polyether foam, gelatin, modeling clay) can be considered as targets.

According to the literature, the average velocity of stabbing is between 5-8 m/s, and there is no significant difference between the authors in this regard, and there is no significant difference in the energy of the stabbing – considering the stabbing technique and the nature of the device. However, there is a significant difference, in many cases, in the degree of stabbing force. The data in the individual publications regarding the stabbing force indicates that the target of the stabbing also plays a decisive role in the degree of the stabbing force. The degree of force required to cause a stab injury is significantly determined by the characteristics of the blade of the device that causes the injury, especially its tip. In addition to the sharpness of the device, the force required for penetration is also influenced by the velocity and energy of the stabbing, the stabbing technique, the anatomical structure of the body area, and the clothing. During expert opinions on stab wounds, the degree of the force is most often determined based on the nature, severity, and depth of the wound caused. There is no way to determine the extent of the force objectively, so subjective categories such as "mild," "moderate," and "large" force are also included in the opinions.

Although stab wounds are most often inflicted with knives, other instruments are also used less frequently. There is limited literature on the mechanics of stabbing with such instruments and the force required for stabbing, even though other types of sharp instruments can also cause serious injury, even penetrating the cranial cavity.

VI. Experimental comparison of the penetration ability of tools with different types of tips and/or edges

Objectives

While studying literature, I concluded that we do not have enough data to determine the penetration ability of individual tools, and the force required to create a stab wound. The different testing methods and test targets greatly influence the results. The description of the physical parameters of individual tools is also not uniform, so we do not have enough data to compare individual tools objectively. For all these reasons, I set the goal of developing an examination method that would provide objective data on the penetration ability of different tools that could be used in everyday forensic practice. The aim of my research was to objectively compare the potential penetration ability of specific household tools compared to each other.

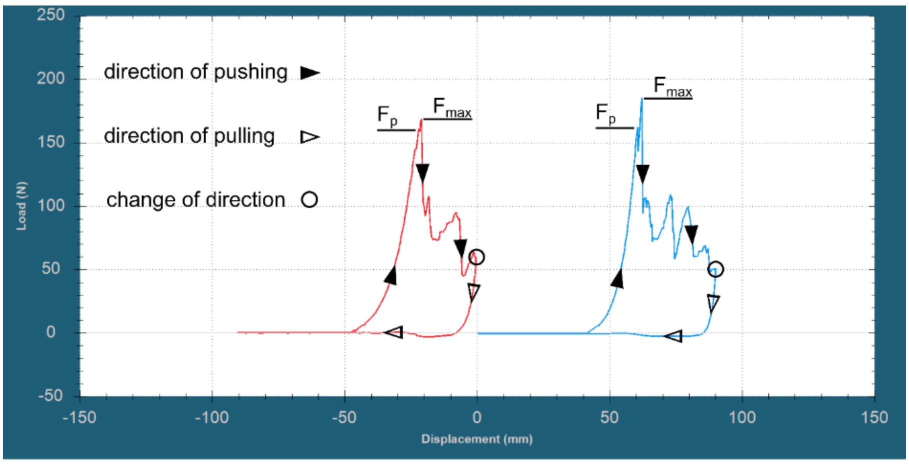
Materials and method

For the study, I performed stabbing tests using 12 household but significantly different tools, for which I used:

-three different types of knives (tools 1-3), a butter knife (tool 4), a scissor (tool 5), a fork (tool 6), three different types of screwdrivers (tools 7-9), a rasp (tool 10), a corkscrew (tool 11) and a utility knife blade (tool 12).

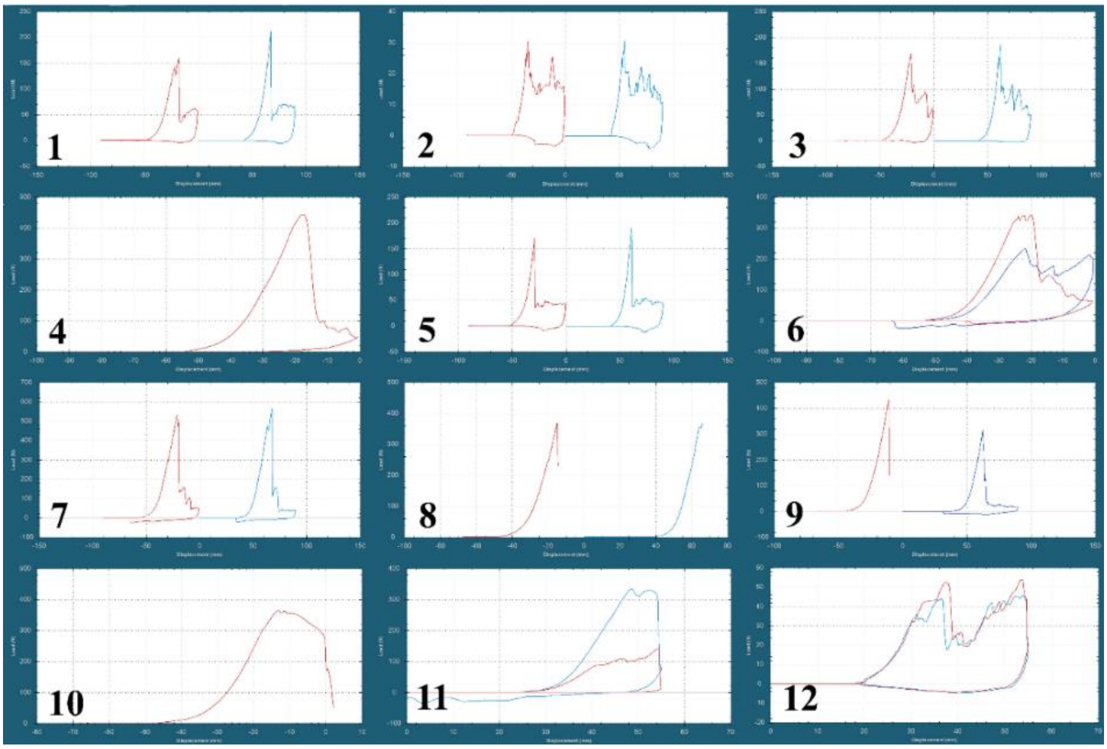
Except for serrated knife number 2, all the knives used had a single-edged blade. To objectively determine the parameters of each tool, I used the characteristics recommended by the literature in the case of knives (i.e., tip angle, tip radius, cutting edge angle), and I used these parameters to describe the other tools as well. I used a digital caliper and a digital protractor to determine the tool parameters. To determine the tip diameter, I digitized the blade using a Cannon MG5750 scanner, and a scaled circle was placed over it using the Gimp image editor. Stabbing tests were performed with a Mecmesin MultiTest-dV automatic material testing device. I used a speed of 1000 mm/min with a vertical displacement of 90 mm. The blades of the tools were fixed to the instrument using a Mecmesin Vice Grip. Stabbing force was registered by a load cell. The force/displacement curve was recorded by the Mecmesin VectorPro MT software. Fresh pork with skin was chosen as the stabbing target, and ballistic gel was used to test the reproducibility of the method. Two test stabs were performed on the pork skin, while 3 test stabs were performed on the ballistic gel with each device.

The penetration of the tools through the skin surface (penetration, Fp) was determined based on the curve, and the maximum force (Fmax) was recorded. The obtained measurement results were also summarized in tables.



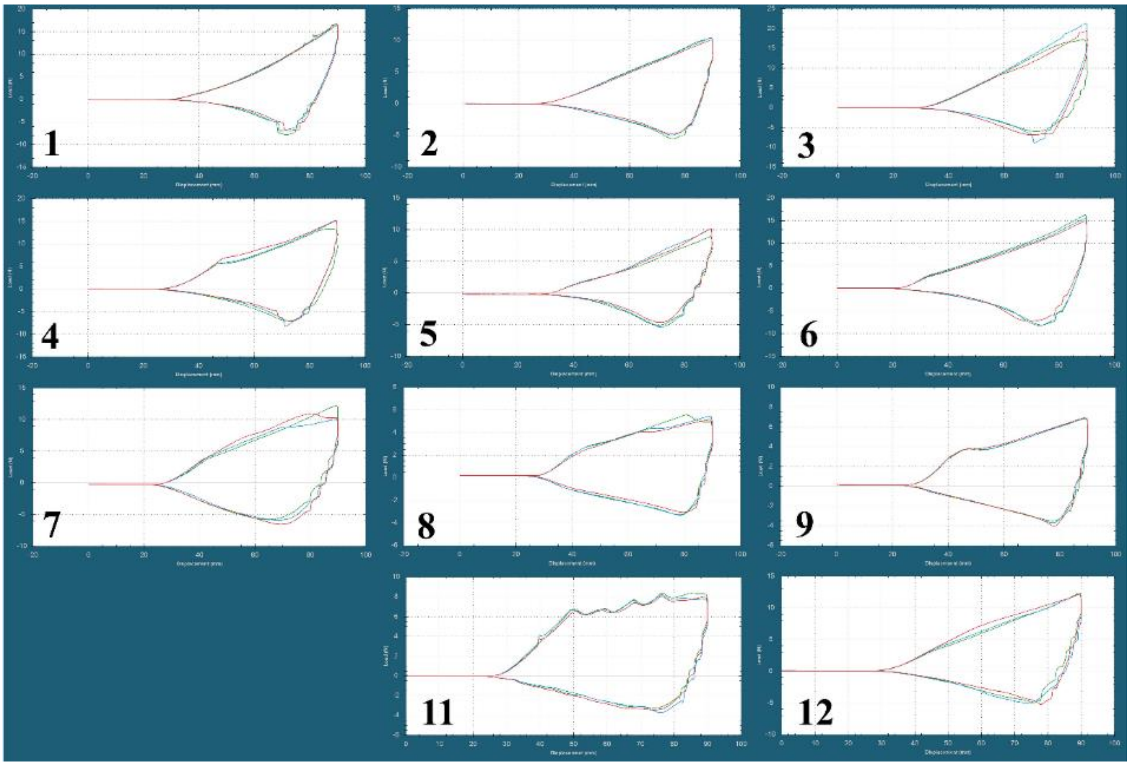
Results

In the measurements of the pork loin, the Fmax for the knives (1-3, 12) was between 30.56 and 212.07 N, for the scissors between 171.39 and 190.43 N, for the screwdrivers between 314.51 and 562.5 N, and for the utility knife blade between 44.14 and 56.62 N. The penetration force for the knives on the pork loin was between 25 and 162 N, for the scissors the same as Fmax, between 171.39 and 190.43 N, for the screwdrivers between 241.34 and 473.2 N, and the utility knife blade between 36.05 and 37.77. The butter knife could not penetrate the pig's skin. The curved fork bent during the first stabbing (when F max reached 342 N), so the stabbings were performed with this tool straightened. With the straightened fork, the values of Fmax and Fp were 233 N. The rasp could not penetrate the pig skin and broke (so no further measurements could be made). In the case of stabbings with knives 2-3, the effect of serration can be identified on the curves: after the fall following the Fmax value, the amount of the stabbing force "oscillated" according to how the teeth of the blade penetrated the tissue. In the case of the utility knife blade, two almost identical peaks are noticeable. The first peak was created when the blade penetrated the tissue, while the second peak was created by a small semicircular impression on the back of the blade as it got stuck in the wound corner opposite the edge.



Curves in pork loin stabbing. Numbers represents the tool number. Fp marks the penetration force (at the first drop on the curve), Fmax represents the maximal achieved force. Load represents force in Newton (N).

The curves in ballistic gel stabbings were identical for the same blades, and the standard deviation of the measured values was low. The measured Fmax values were an order of magnitude lower than for the stabbing of pork loin. In the case of knives, Fmax was between 10.04-21.38 N; in the case of scissors, between 8.95-10.15 N; in the case of screwdrivers, between 5.14 and 12.2 N; and in the case of corkscrews, between 8.03-8.38 N. In the case of stabbing with knives numbered 1-3, scissors, flat-blade screwdrivers, and the utility knife blade, Fp and Fmax were identical. However, in the case of the other tools, based on the break in the curve (Fp), the continuity of the material was interrupted before the tool penetrated the entire sample (Fmax). In the case of the butter knife, the initial break in the curve occurred during gel compression, then during penetration, the force decreased (Fp between 65.6-6-86 N), and then a linear increase was observed due to friction. A similar effect was observed in the case of the posidrive screwdriver. The initial break was visible before penetration in tools 5-8 (scissors, forks, flathead screwdrivers). However, after that, the decrease was not observed, and the force increased linearly until reaching F max (which can be explained by the fact that their ends correspond more to blunt tools). In the case of the corkscrew, two Fp values were isolated. The first break indicated the first Fp value, then the first peak indicated the second Fp value, but after that, with each screw thread penetrating the sample, a force exceeding the previous one could be measured at the peaks of the curve (the Fmax value was determined based on the last, highest peak).



Curves in ballistic gel stabbing. Numbers represent the tool number.

Discussion

1. The applied method is suitable for comparative testing of the penetration potential of individual tools (reproducibility is supported by the similarity of the curves and the results of ballistic gel stabbings).
2. Based on the curves, the highest force is required to penetrate the skin, so we cannot conclude regarding the force of the stabbing based on the depth of the stab wound channel.
3. The characteristics of the tools significantly influence the force required for penetration.
4. Knives generally require less force to cause a stab wound; stabbing with a scissor requires a similar amount of force; screwdrivers require much more force (blunt screwdrivers require force at the limit of human physical strength), and a butter knife is not suitable for causing a stab wound.
5. Pointed instruments require the least force to penetrate the skin, and the blunter the end of the instrument, the greater the force required for penetration.
6. Among the knives, tool 2, which ended in a triangular tip, had the highest penetration potential.
7. In the case of screwdrivers, the flat-head screwdriver with the largest frontal surface (7-inch 10.19 mm2) required much greater force, almost one and a half to two times greater, for penetration on both pork loin and ballistic gel, than the smallest tool (8-inch 3.49 mm2).
8. The slight difference between the stabbings on the pork loin indicates the role of biological variability of the tissues (in the case of ballistic gel, the curves overlap).

The low sample size and the stabbing mechanics limit the direct forensic application of the obtained results. Fresh pork loin with skin was used as the target during the tests. However, the differences in the biomechanical properties do not allow the numerical application of the results to human tissues. The stabbing mechanics used also differ from those of real stabbing, primarily in the stabbing speed: while the velocity of real stabbing is 5-10 m/s, in the experiment, a speed of 1000 mm/min (0.016 m/s) was only feasible due to the limitations of the instrument. However, our results can also be used in practice by comparing the individual tool types and their suitability for creating stab injuries.

VII. The effect of the knife blade characteristic on the force required for stabbing

Objectives

In the following experiment, I investigated which characteristics of the knife influence the force required for penetration and the mechanics of stabbing.

My null hypotheses were the following:

- among the characteristics of the blade, the tip radius and then the tip angle have the greatest influence on the force required to penetration;
- the edge shaping does not significantly affect the force required for penetration, but it does influence the course of the force/displacement curves.

Materials and method

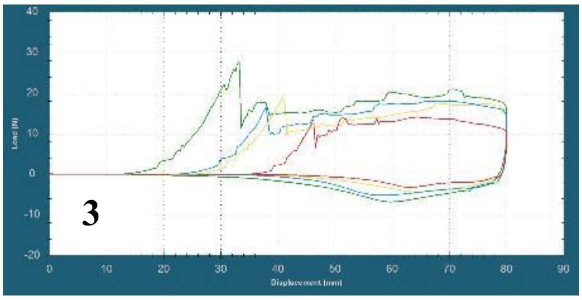
Eighteen household knives were examined, the handles of which were completely removed and the part of the blades close to the handle was removed so that the length of the blades was uniformly 120 mm. I used three blades (numbers 15-16-17) in my previously described experiment. The tool parameters – tip radius, tip angle, blade length, maximum blade height, maximum thickness, and cutting angle – were determined according to the method in the previously described examination. For the test – according to the same method as the previous experiment – I used an automatic material testing device with a speed of 1000 mm/min and a vertical displacement of 80 mm. I used a pork loin with skin as the target for the stabbing, whose thickness was between 50-60 mm. Four stabbing tests were made on the pork loin with each blade.

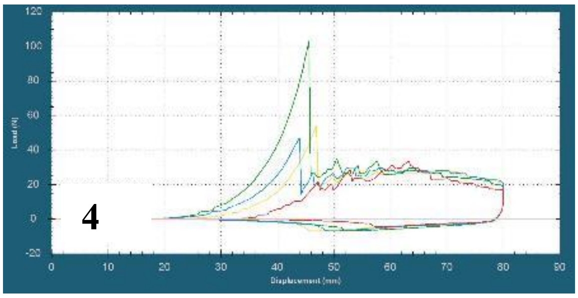
Results

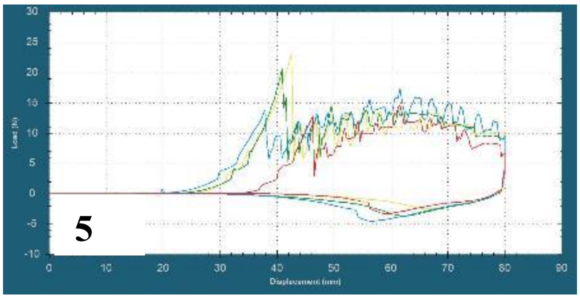
The average maximum stabbing force (Fmax) ranged from 14.07 to 265.22 N (the values for all stabbings ranged from 12.02 to 334.53 N), with the knife with the worst penetration ability (number 10) having 15-20 times greater stabbing force, than the knife with the best penetration force (number 12). The two knives come from the same knife set, but there is a significant difference in the tip radius of their blade characteristics: while knife number 10 has the largest tip radius of all the knives tested (1.04 mm), knife number 12 is triangular. The blade thickness of knife number 10 is also significantly greater (1.78 mm vs. 1.17 mm).

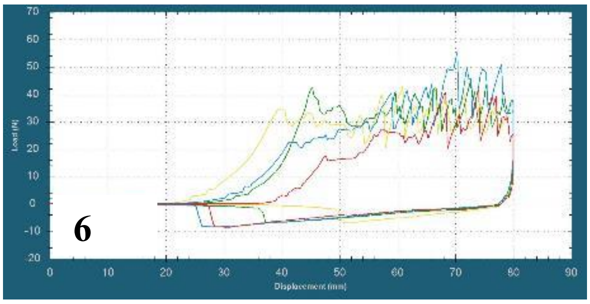
Tool no.	Force (N)	Stab no.				Mean	SD
		1	2	3	4		
1	F_{max}	27,70	31,14	35,03	25,18	29,76	4,27
2	F_{max}	14,91	22,63	22,20	33,27	23,25	7,55
3	F_{max}	14,08	18,04	27,66	19,02	19,7	5,72
4	F_{max}	33,67	47,06	103,28	54,42	59,60	30,35
5	F_{max}	14,65	17,48	20,59	22,98	18,92	3,63
6	F_{max}	41,88	55,35	42,45	42,99	45,66	6,47
7	F_{max}	35,25	44,72	74,88	93,72	62,14	26,99
8	F_{max}	40,20	39,92	66,08	71,44	54,41	16,71
9	F_{max}	97,08	87,84	115,71	105,91	101,6	11,93
10	F_{max}	257,90	233,20	235,28	334,53	265,22	47,53
11	F_{max}	32,00	38,69	41,73	33,01	36,35	4,63
12	F_{max}	14,44	14,27	15,17	12,42	14,07	1,17
13	F_{max}	16,74	15,87	19,83	14,08	16,63	2,40
14	F_{max}	34,92	22,89	55,50	26,81	35,03	14,53
15	F_{max}	170,62	169,55	198,07	158,64	174,22	16,79
16	F_{max}	130,57	111,26	85,83	60,19	96,96	30,60
17	F_{max}	36,11	35,21	41,61	28,84	35,44	5,23
18	F_{max}	24,04	22,49	23,93	16,13	21,64	3,74

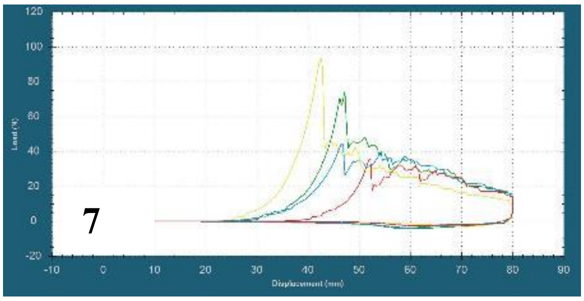
Summary of measurement results

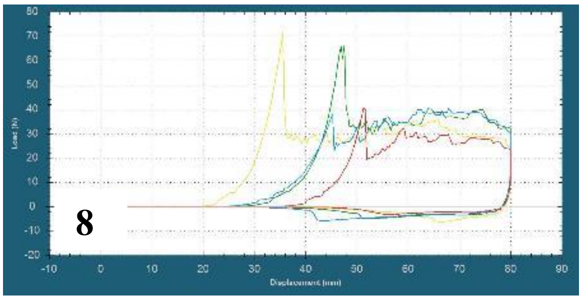


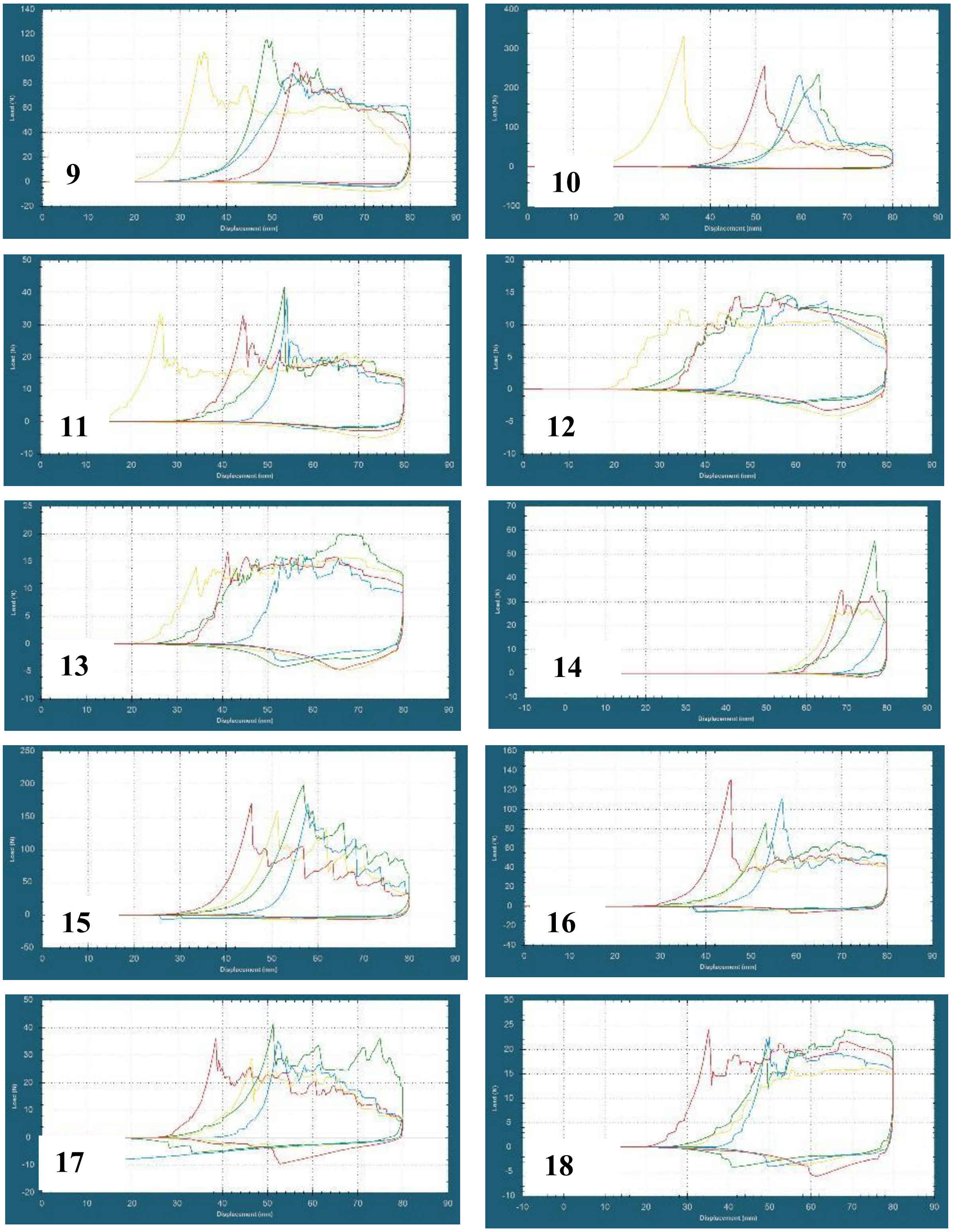












Curves recorded during the test (numbers indicate the serial numbers of the blades): The first measurement series is red; the second series is blue, the third series is green, and the fourth series is yellow.

In the case of serrated knives, oscillation can be clearly identified in the curves after reaching Fmax in the present experiment for knives numbered 1, 5, 6, 15 and 16; however, it is not visible in the case of the least pointed knife, number 10. In the present experiment, not all knives showed a significant decrease in force after reaching penetration (Fmax), and, in the case of knife number 1, it even increased minimally. There were three blades that I examined in both experiments, and the results for two of these devices (blades 15 and 17) are comparable, but for knife number 16, they differ significantly. This knife had a smaller tip angle but a much larger tip radius than the others, which may indicate that the characteristics of the target are much better achieved with a larger tip radius.

Statistical analysis

I examined the correlation between Fmax and individual blade characteristics (tip radius, tip angle, blade height, blade thickness, cutting angle) using a correlation test (IBM SPSS .v.26.0.0). A significant correlation was detected between Fmax and tip radius and blade thickness (significance level $p=0.05$). The correlation with tip radius proved stronger than the correlation with blade thickness. I performed multiple regression and correlation analysis to determine which blade characteristic has a significant effect on the Fmax value. During this test, a significant correlation was shown with the Fmax value for tip radius and blade thickness ($p=0.023$ and $p=0.021$, respectively).

Discussion

Reviewing the curves recorded during the experiment, the skin reacts in the same way when stabbed by the same blades, even in different skin areas (the identical form of the curves shows this). However, the maximum penetration force shows a significant variance even in the case of test stabbings made with the same knife. The explanation for the difference may be that in the present experiment is that the target used (pork loin) was much larger, and the four stabs made with each knife were located far from each other, so this difference between the resistance of individual skin areas was more pronounced. This is also supported by the results of the ballistic gel stabbing tests carried out during the previous experiment, where the variance of the values was minimal in the case of a homogeneous target. All this means that there can be significant differences in skin resistance even within the same body area. The comparison of the results of the previous and the present series of experiments also draws attention to the sharpness of the tool and the prominent role of the tip radius.

VIII. The influence of clothing on stab injuries

Based on theoretical considerations and literature data, the force required to cause injuries can also be influenced by clothing. This can also be objectively examined using stabbing tests.

Objectives

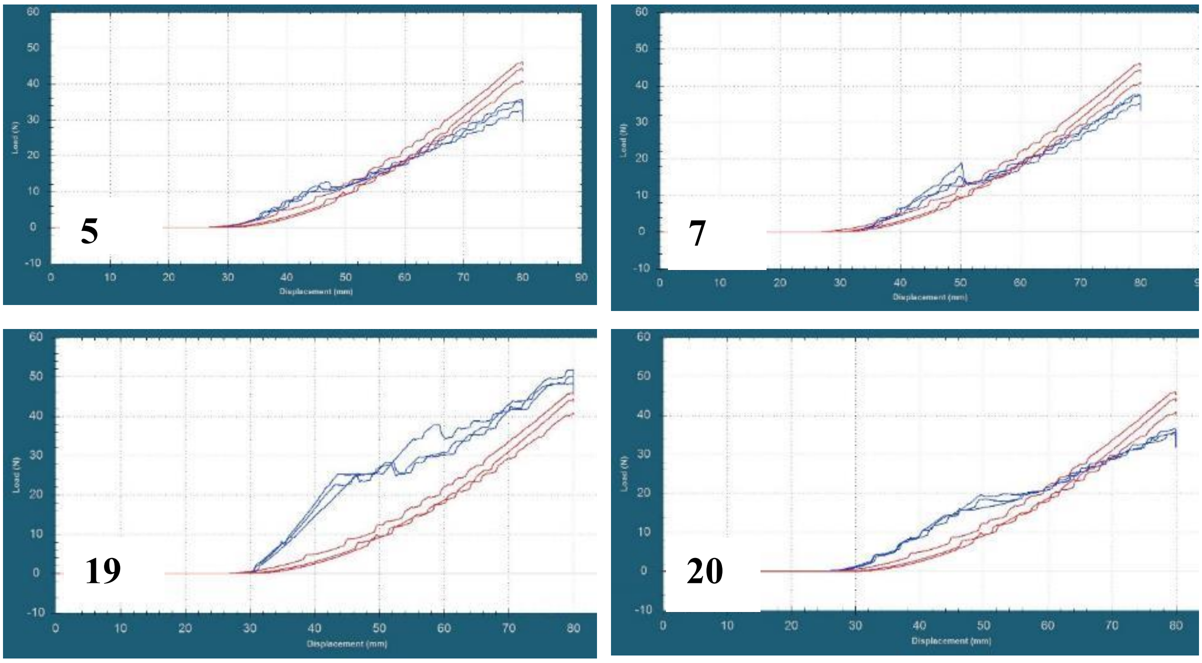
I set a goal to create a testing method that could later be suitable for examining the impact of clothing on stabbings.

Materials and method

For the stabbing test, I used an automatic material testing device at a speed of 1000 mm/min on synthetic ballistic gel and pork loin test targets. I used three of the knives used in the previous experiment as stabbing tools: the blade with the highest (number 12) and the lowest (number 10) penetration ability achieved in the previous experiment, as well as the blade with the number 16. I selected 20 clothing fabrics for the test, of which 14 were clothing samples from everyday wear, and 6 were fabric samples validated by the manufacturer for penetration tests. I determined the composition based on the marking on the given material. I determined the sample thickness with a Mecmesin AFG-25 device connected to a Mecmesin MultitTest-dv motorized test stand. I performed three stabbings on each tissue with the number 12 knife, both on the ballistic gel and on the pork loin target. I performed only one test on the material with the number 10 and 16 knives, provided that the continuity of the tissue was not broken (the tissue was folded into the wound). I performed only ballistic gel stabbing with the number 10 knife - due to the previous experience with the number 16 knife. I read the force occurring at the first penetration (Fp) and the maximum force (Fmax) from the curves made with the VectorPro Software. In the case of ballistic gel stabbings, the force at the end of the stabbing (Fv), and I summarized the exact measurement results in tables.

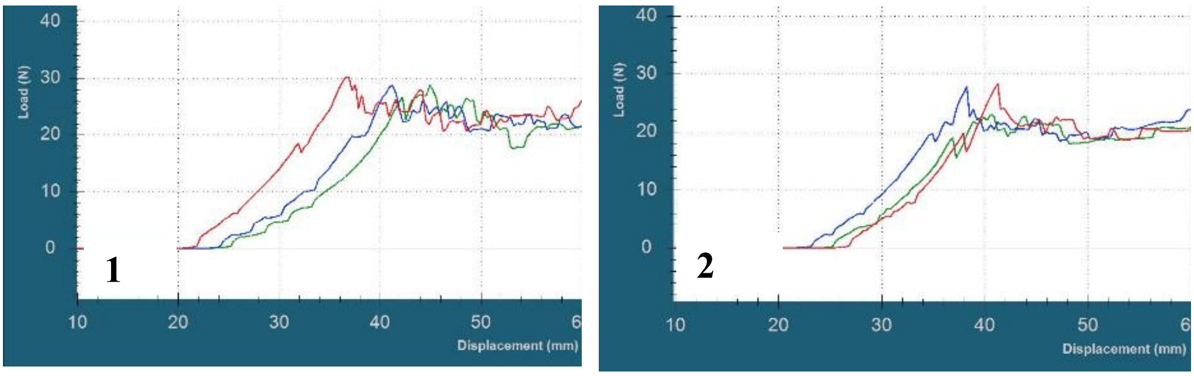
Results

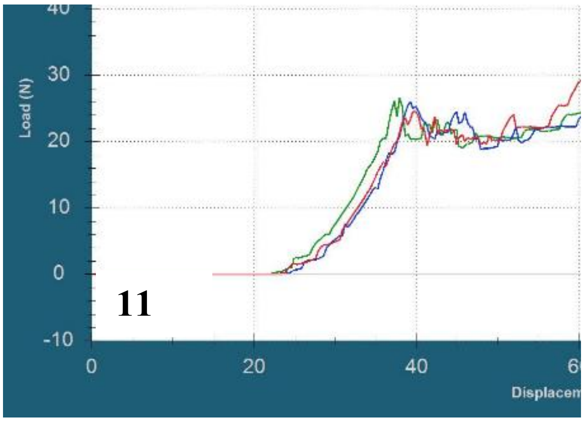
In the case of knife number 12, which has the highest penetration ability, the fabric sample was completely penetrated in both the ballistic gel and the pork loin. During the stabbing of the ballistic gel, the highest force could be registered at the end of the stabbing in all cases (Fmax=Fv). Without the use of fabric, the average Fmax value was 43.70 N (40.77 – 46.08 N-44.26 N), while with fabrics Fmax values between 32.42 N and 57.79 N were recorded. On the stabbing curves, a temporary sharp drop corresponding to the Fp values was identified in the case of fabrics 6,7,12,15,16,17, and 18 (not in all punctures); in the case of some fabrics (5, 7, 11, 20) the curve was less steep than without the use of fabric. Significantly higher force was registered exclusively in the case of thick (5-ounce) leather fabric number 19 over the entire course of the curve.

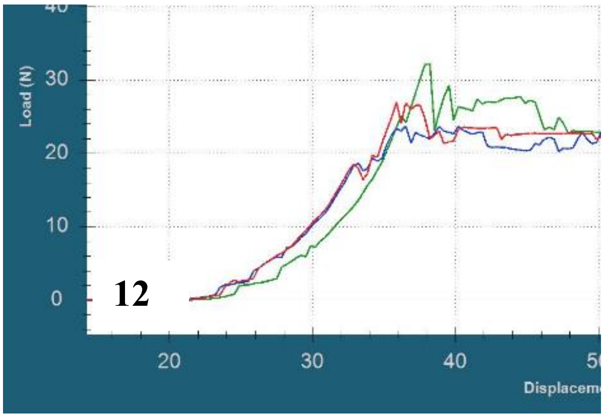


Some curves were recorded during ballistic gel stabbings by knife number 12 (fabrics no. 5, 7, 19, 20). Red indicates stabbing without fabric, and blue indicates curves recorded during stabbings with fabric.

In most of the pork loin stabbing curves with knife number 12, two peaks could be identified: one at a lower force (Fp) and one at the maximum force (Fmax). The Fp value was between 14.27 – 31.07 N; Fmax value was between 18.71 N – 42.86 N. The nature of the stabbing curves was the same during the stabbings, and it also matched the curve recorded in the previous experiment (comparing the penetration potential of knives).

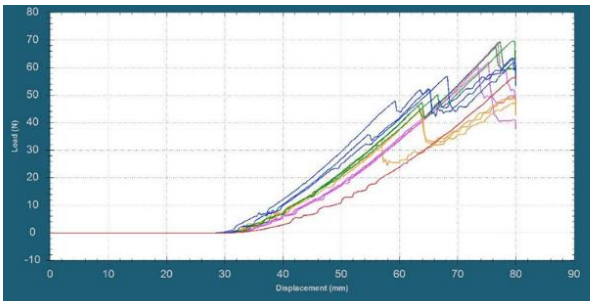


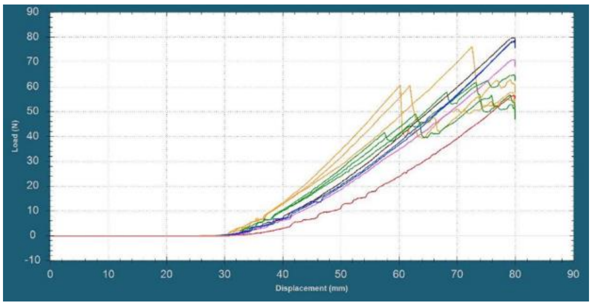




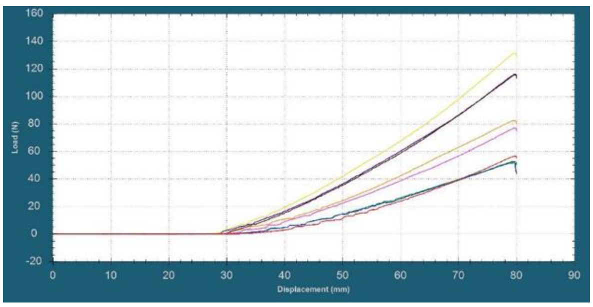
Illustrative curves from those recorded with knife number 12 (tissues 1, 2, 11 and 12). The three colors indicate the three stabbings (in order: red-blue-green).

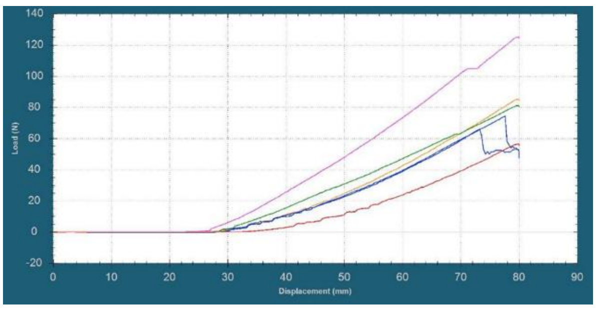
During the ballistic gel stabbing with knife number 16 without the use of fabric, the Fmax value was 56.8 N. In several cases, when fabrics were used, no discontinuity was created in the material. In the stabbings where fabric damage occurred, the Fmax value was between 47.02 N and 69.59 N. The stabbings that reached fabric number 4 and 9, as well as the third stabbing that reached fabric number 8, the Fp value was the same as the Fmax value, while the Fv value was lower. In the case of the first two stabbings that reached fabric number 2, two Fp values could be recorded, of which the first was lower and the second was higher than the Fv value. In the case of the other stabbings, the Fmax value was the same as the Fv value.





A B



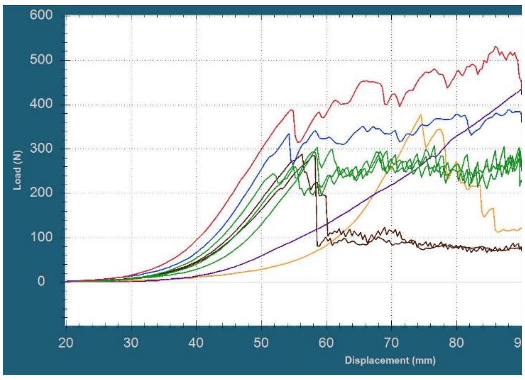


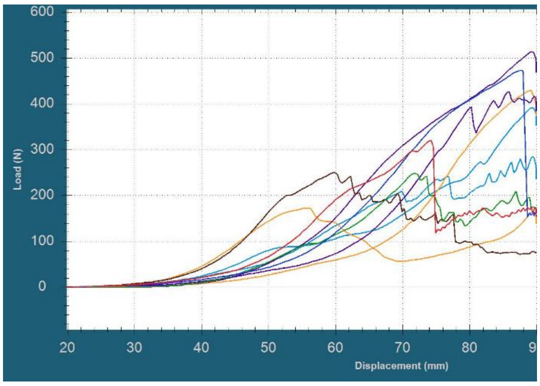
C D

The curves of the stabbings on the ballistic gel with knife number 16:

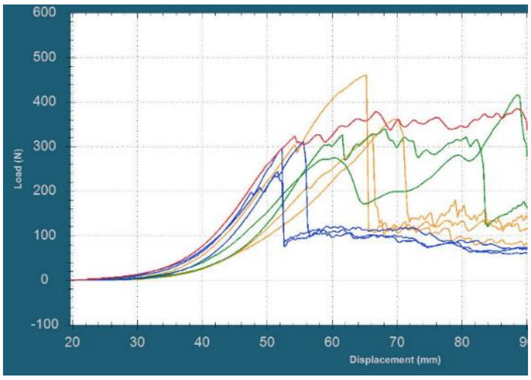
Fabric marking: **A**: red (without fabric), blue (1), green (2), orange (3). purple (4). **B**: red (without fabric), blue (5), purple (6), brown (7), green (8), orange (9). **C**: red (without fabric), blue (10), green (11), purple (12), brown (13), lemon yellow (14), orange (15), purple (16). **D**: red (without fabric), blue (17), green (18), purple (19), orange (20).

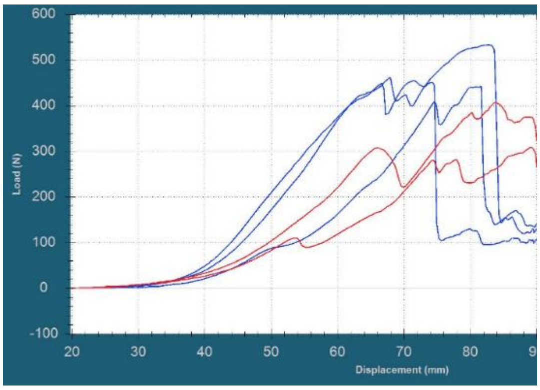
During the pork loin stabbings with knife number 16, in a significant part of the cases, there was no disruption of continuity in the fabric, and the fabric was pulled deep into the wound by the knife, and the knife bent several times. Without the use of fabric, the stabbing force was 185.93 - 189.31 - 205.49 N, while in the case of the use of fabric, the Fp value mostly significantly exceeded this (244.12 N - 458.8 N).





A **B**





C **D**

Curves recorded during pork loin stabbings with knife number 16.
Fabric marking: **A**: red (1), blue (2), green (3), brown (4), purple (6), orange (7). **B**: red (8), blue (9), green (10), brown (11), purple (12), orange (13), light blue (14). **C**: red (15), blue (16), green (17), orange (18). **D**: red (19), blue (20). Image 'E' shows curves recorded without the use of fabric.

In the case of ballistic gel stabbing with knife number 10 without the use of fabric, the Fmax value was 61.2 N. On the fabrics used, discontinuity (penetration) occurred in fabric samples 3 (Fmax: 76.93 - 88.09 N), 4 (Fmax: 86.45 - 94.40 N), 8 (Fmax: 107.15) and 10 (68.38-74.62 N) (in the case of fabric 10, 2 out of 3 stabbings were successful in this regard, and in the case of fabric 8, 1 stabbing was successful). Based on the results of the ballistic gel stabbings (due to the low fabric penetration success rate), we renounced the pork loin stabbing.

Discussion

The results show that clothing influences the minimum force required for penetration. According to stabbings performed on ballistic gel, the resistance to stabbing increases linearly when piercing a homogeneous material. The reason is that the surface area in contact with the gel increases with increasing stabbing depth, thus increasing friction. In the case of ballistic gel stabbings, a flatter curve and a lower maximum force (Fmax) value were recorded for several fabrics than in the case of stabbings without fabric. This can be explained by the fact that the fabric's resistance to stabbing did not reach the resistance of the gel; at the same time, the fabric drifting into the wound reduced friction. However, the experiment showed that homogeneous materials – such as ballistic gel – are not suitable for examining the effect of fabrics on stabbing force.

Based on the results of pork loin stabbings with knife number 12, the highest penetration ability based on previous experiments, the use of fabrics only slightly increased the stabbing resistance in most materials, with a more significant effect only in the case of thick leather material (fabric sample number 19). The comparison of stabbing results with knife numbers 12 and 16 also indicates that, depending on the tip of the tool, the stabbing resistance of individual tissues may be different. In many cases, it was not possible to cause a discontinuity in the fabrics with blades number 16 and 10, because the material could stretch without tearing due to the lower stabbing speed; or the fabrics were not stretched, which caused the knife to pull them into the "stab channel" formed in the test target.

Based on the results, the sharpness of the tip of the instrument used for stabbing has a much greater impact on the force required for penetration than the use of fabrics (such as clothing).

Measuring the resistance of clothing to stabs can be standardized (as is already known in the manufacturing and testing process of stab-resistant vests) and an objective data set can be obtained. However, it should be noted that this data set cannot be used in isolation, as the impact of clothing may also vary with different means of penetration.

IX. Summary

Based on the review of the relevant literature, in the case of forensic sciences, there is a place for the application of modern technologies and experimental investigation in classical medical expert questions, such as examining stab wounds and the expert opinion on injuries. The use of 3D-printed knife replicas highlights that a fast, cheap, and widely available method can be developed. The use of 3D-printed knife replicas can be well integrated into routine autopsy practice and significantly helps in a more accurate (objective) examination of the wound channel, the determination of the instrument of perpetration, the establishment of the mechanism of origin, and has a high demonstrative value.

Screening tests with different tools help to understand the biomechanics of stabbing and the interaction between the tool and tissues. The tests yielded important results that can be used in practical expert opinion so that it is possible to make a more well-founded statement about the force required for penetration with certain tools compared to each other. The test results can also help to assess the question of whether a given tool is suitable for causing more serious injuries (e.g., deep penetrating stab wounds).

Further experiments also show that we should be careful to answers regarding the role of clothing, as knowledge of the type of clothing alone is not sufficient to answer the question of to what extent clothing influences the force required for stabbing. During an opinion, the stabbing speed, the pretension of the clothing, the direction of the weave, and the sharpness and tip of the tool, which are particularly important factors, must be considered. Based on the experiments, the force required for penetration is mostly determined by the type of tool, and the role of clothing is only of lesser importance, which also draws attention to the priority of examining the tool. Based on our current knowledge, there is not yet enough scientific data available to provide an objective and scientifically sound expert answer on the effect of clothing on stabbing force in each case.

Findings, new results

1. Based on the autopsy data of the Department of Forensic Medicine of the University of Pécs Medical School, and in line with international data, the most common method of committing homicide in Baranya County is stabbing, but the proportion of women among the victims is higher.

2/a. Based on a review of the available literature, there is currently not generally "gold-standard" method available that would be suitable for accurately determining the direction of the stab wound channel or for objectively comparing the instrument of perpetration and the injury.

2/b. With our working group, we have developed a new, previously unapplied method for examining stab wounds: the use of 3D-printed copies of the tools provided as evidence during autopsy.

2/c. The experiments prove that the method can be used safely without damaging the autopsy's findings.

2/d. The 3D printed copy of the knives can be easily inserted into the stab wound created by the knives, thereby determining whether the knife seized as evidence could have caused the injury.

2/e. The method is suitable for determining the course of the stab wound channel and, thus, the direction of the stabbing. The demonstrative value of the method is further increased by combining it with photogrammetry, which allows for a numerical, objective determination of the stab direction (expressed in degrees).

2/f. The developed method can be used not only in experiments but also in real, everyday practical expert work. Furthermore, the method is a useful complement to autopsy not only in the case of stab wounds but also in the case of blunt force trauma, helps to determine the mechanism of occurrence and has significant demonstration value.

3/a. By presenting all the methods used for the investigation modeling of stab injuries described in the literature, I concluded that the data obtained with different methods are not comparable. Therefore, it is necessary to develop a uniform, standardized methodology.

3/b. The method used during the experiments is suitable for reproducible modeling of stab wounds and comparative testing of individual devices.

4. The method used to determine the characteristics of the devices involved in the experiments allows the specification of the device properties to be standardized and the parameters to be recorded objectively.

5/a Comparative experiments conducted with various household sharp tools have shown that some household tools – such as scissors – require stabbing force similar to knives. In contrast, other tools (e.g., screwdrivers) need very high force to penetrate the skin, and some tools are incapable of doing so (e.g., butter knives).

5/b. Stabbing tests with different knife blades show that the mechanics of stabbing may differ depending on the blade type. Some blades show a significant decrease in tissue resistance after penetration, while others show a less steep decrease or none.

5/c. Based on the stabbing experiments performed, it can be concluded that the degree of force required to penetrate the skin is primarily influenced by the radius of the tip and the thickness of the blade.

5/d. During stabbing tests, the force can vary significantly in different areas of the same sample, which emphasizes the role of the biological variability of materials, which should be considered when planning further experiments.

6/a. Further tests showed that individual clothing materials influence the force required for penetration, but a more accurate assessment of this and the practical application of the data require further experiments.

6/b. Based on the results of the experiments, the minimum force required for penetration is primarily determined by the sharpness of the tip of the tool, with clothing having a lesser effect in this respect.

Publications

The PhD thesis is based on the following publications:

Simon G, *Heckmann V*. Fatal suicidal injury of a radiocephalic arteriovenous fistula. J Forensic Sci. 2022 Jan;67(1):391-394. doi: 10.1111/1556-4029.14895. IF. 1,6, Q2

Simon G, Tóth D, *Heckmann V*, Poór VS. Application of 3D printing in assessment and demonstration of stab injuries. Int J Legal Med. 2022 Sep;136(5):1431-1442. doi: 10.1007/s00414-022-02846-6. IF: 2,791, Q1

Heckmann V, Engum V, Simon G, Poór VS, Tóth D, Molnar TF. Piercing the surface: A mechanical analysis of stabbing with household tools. J Forensic Sci. 2023 Jul;68(4):1218-1227. doi: 10.1111/1556-4029.15313. IF: 1,6, Q2 (2022)

Summarized impact factor of the pubilations based on the thesis: **5,991**

Other publications:

Nagy VP, Poór VS, Kuzma M, Mayer M, Tóth D, *Heckmann V*, Simon G. Driving under the influence of drugs - The failed quest of finding medical signs indicative to driving impairment. Leg Med (Tokyo). 2025 Feb;72:102567. doi: 10.1016/j.legalmed.2025.102567.

Simon G, Angyal M, Dérczy K, *Heckmann V*. Egy büntetlenül maradt gyermekbántalmazás tanulságai [Lessons of an unpunished child abuse]. *Orvosi Hetilap*. 2024, *165*(14): 553-559. https://doi.org/10.1556/650.2024.33005

Heckmann V, Simon G, Molnár TF. Misconnected chest tube: An extremely unusual fatal complication of secondary pneumothorax. Med Sci Law. 2023 Mar 22:258024231165960. doi: 10.1177/00258024231165960.

Petrus K, Angyal M, Tóth D, Poór VS, *Heckmann V*, Simon G. Forensic assessment of a life-threatening penetrating abdominal air gun injury. Leg Med (Tokyo). 2023 Feb;60:102182. doi: 10.1016/j.legalmed.2022.102182.

Simon G, Tóth D, *Heckmann V*, Mayer M, Kuzma M. Simultaneous fatal poisoning of two victims with 4F-MDMB-BINACA and ethanol. Forensic Toxicol. 2023;41(1):151-157. doi:10.1007/s11419-022-00632-y

Simon G, Tóth D, *Heckmann V*, Kuzma M, Mayer M. Lethal case of myocardial ischemia following overdose of the synthetic cannabinoid ADB-FUBINACA. *Leg Med (Tokyo)*. 2022;54:102004. doi:10.1016/j.legalmed.2021.102004

Simon G, *Heckmann V*. An unusual case of suicide: Near decapitation by a modified table saw. *J Forensic Sci*. 2021;66(5):1986-1991. doi:10.1111/1556-4029.14732

Tóth D, Petrus K, *Heckmann V*, Simon G, Poór VS. Application of photogrammetry in forensic pathology education of medical students in response to COVID-19. *J Forensic Sci*. 2021;66(4):1533-1537. doi:10.1111/1556-4029.14709

Simon G, *Heckmann V*, Tóth D, Pauka D, Petrus K, Molnár TF. The effect of hepatic steatosis and fibrosis on liver weight and dimensions. *Leg Med (Tokyo)*. 2020;47:101781. doi:10.1016/j.legalmed.2020.101781

Simon G, Poór VS, *Heckmann V*, Kozma Z, Molnár TF. The effect of steatosis and fibrosis on blunt force vulnerability of the liver. Int J Legal Med. 2020 May;134(3):1067-1072. doi: 10.1007/s00414-019-02245-4.

Simon G, *Heckmann V*, Tóth D, Kozma Z. Brain death of an infant caused by a penetrating air gun injury. Leg Med (Tokyo). 2019 Jul;39:41-44. doi: 10.1016/j.legalmed.2019.06.004.

Simon G, Rácz E, Mayer M, *Heckmann V*, Tóth D, Kozma Z. Suicide by Intentional Air embolism. J Forensic Sci. 2017 May;62(3):800-803. doi: 10.1111/1556-4029.13320.

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