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GLASS FRAGMENTS AS IMPORTANT CRIMINALISTIC EVIDENCE – CASE STUDIES

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Abstract

Herein the authors present examples of real forensic cases in which glass fragments constituted important evidence. Both large glass objects and glass microtraces were examined. In the case of large glass objects, tool marks examinations (mostly "jigsaw fit" analyses) were performed, while in the case of glass microtraces (and large glass fragments for which tool mark examination was insufficient), elemental composition was determined using a scanning electron microscope coupled with an energy dispersive X-ray spectrometer. In most cases, data obtained from physicochemical analyses (cases II–IV) were additionally interpreted with the use of the likelihood ratio test. Glass evidences were analysed in order to establish: if car lights were switched on during a collision (case I); if a car was involved in a hit-and-run accident (case II); if a pneumatic gun was used for breaking into a car (case III); and whether an event was an accident or not (case IV). Most of the presented cases could only be solved because combined information obtained from tool marks examinations and physicochemical analyses of glass supported by the likelihood ratio approach were used.

Key words

Glass fragments; Tool marks examination; Elemental content of glass samples; SEM-EDX; Likelihood ratio.

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1. Introduction

Glass fragments are often encountered at the scene of various criminal events and accidents such as burglaries, car accidents or street fights (Curran, Hicks, Buckleton, 2000). Their analysis, performed for criminalistic purposes, usually involves establishing which category analysed glass fragments originate from – e.g. whether they belong to the container or windows category (classification problem) – or answering the question as to whether questioned and control glass fragments have the same origin (comparison problem; Aitken, Taroni, 2004; Zadora, Martyna, Ramos, Aitken, 2014). The way in which glass evidences are analysed is determined mainly by their size (Curran, Hicks, Buckleton, 2000). In the case of large glass fragments (e.g. pieces of broken headlamps or windows), tool marks examination, i.e. "jigsaw fit" analysis, is performed first. In "jigsaw fit" analysis, the tool marks expert tries to match recovered glass fragments to control glass fragments in order to determine whether they were part of the same object before it was broken. A positive result of this examination allows for individual identification of the object and enables the forensic expert to draw categorical conclusions. In these types of cases, physicochemical analyses are not performed, because they only allow for group identification – and so conclusions are always formulated in terms of probabilities. Another aspect of tool mark examination is the determination and comparison of morphological features of glass such as colour, thickness or surface characteristics, which usually provide useful information for solving comparison or classification problems; however, such information only allows for group identification (Baldwin et al., 2013).

In most cases, during the breaking of a glass object, a large number of very small glass microtraces with linear dimensions between 0.1 and 0.5 mm are formed (Zadora, Brożek-Mucha, 2002). Such microtraces can be transferred onto clothes, hair and/or shoes of persons present at the scene of an event. Such small glass fragments can be revealed even after many hours; however, the probability of their disclosure sharply decreases with time as a result of using the object or clothes on whose surface the microtraces were deposited. Such glass fragments secured from clothes, objects or the scene of the event are too small to be subjected to tool marks examination. Therefore, it is necessary to perform physicochemical analyses. Such analyses are also performed for large glass fragments for which results of tool marks examination are insufficient (e.g. with a negative result of "jigsaw fit" analysis; Zadora, Brożek-Mucha, 2002).

Among physicochemical methods used in the analysis of glass microtraces for criminalistic purposes are those which determine the elemental composition of glass – e.g. using a Scanning Electron Microscope coupled with an Energy Dispersive X-ray Spectrometer; SEM-EDX (Curran, Hicks, Buckleton, 2000; Zadora, Martyna, Ramos, Aitken, 2014) or by the thermo-immersion method of determination of the glass refractive index, e.g. by the application of Glass Refractive Index Measurement – GRIM (Curran, Hicks, Buckleton, 2000; Zadora, Wilk, 2009; Zadora, Martyna, Ramos, Aitken, 2014). The obtained results can be interpreted using statistical methods, e.g. likelihood ratio (*LR*) tests. *LR* tests allow to express the role of the forensic expert in the evaluation of data – obtained, for example in physicochemical glass analyses – in the context of two contrasting hypothesises: the so-called prosecution and defence hypotheses. Using the *LR* test, the forensic expert may include – in one calculation – all important factors from the forensic point of view, such as between-object variability, within-object variability as well as the rarity of the observed features in the general population. The obtained *LR* values allow the expert to evaluate which of the hypotheses is more strongly supported by the evidence. What is more, *LR* models can be used for solving both classification and comparison problems (Aitken, Taroni, 2004; Zadora, Martyna, Ramos, Aitken, 2014).

Herein the authors present examples of real forensic cases in which large glass objects (tool marks examination) as well as glass microtraces (physicochemical analyses based on establishing the elemental composition of glass by application of the SEM-EDX technique) were subjected to examination. The authors also present cases in which the final conclusions presented in the expert report could be drawn only by taking into account information gained from both types of examinations – namely tool marks and physicochemical analyses.

2. Materials and methods

2.1 Examination of evidences

Large glass fragments were examined in white light. However, for more sophisticated analysis (e.g. in order to established the direction of a force's action on a glass pane), a FSC Nikon SMZ 2T stereo magnifying glass (Japan), or Leica (Germany) comparison microscope coupled with a Leica DFC 490 camera were used.

In cases where glass microtraces had to be revealed, the surface of the evidence (e.g. clothes) was brushed above a sheet of smooth grey paper. Microtraces obtained in this way were then placed in a Petri dish and observed under a Leica MZ 16 stereomicroscope. During this examination, microtraces which looked like glass objects were picked out from the debris using a preparation needle, and transferred directly onto double-sided self-adhesive carbon tape located on an aluminium microscope stub.

The surface of this stub was carbon coated using an SCD-50 sputter coater (Bal-Tech, Switzerland). The sample prepared in this way was then placed in the chamber of a JSM-6610LV Scanning Electron Microscope (Jeol, Japan) equipped with an Inca Energy Dispersive X-ray Spectrometer (Oxford Instruments Ltd., United Kingdom).

2.2 Analysis of the elemental composition of glass by the SEM-EDX technique

The elemental composition of glass microtraces was determined using a SEM-EDX instrument. During analysis, the following analytical conditions were applied: accelerating voltage: 20 kV; count time: 50 s; magnification: from 1000 to 5000 times; calibration element: Co; and a library of element profiles provided by the manufacturer. Each glass fragment was analysed in three different spots. In the first described example (case I), qualitative and quantitative information about all elements present in analysed samples was collected. In the rest of the examples (cases II–IV), where obtained results were interpreted using the likelihood ratio approach, information relating to the elemental content – e.g. O, Na, Mg, Al, Si, K, Ca, and Fe expressed as a weight percentage – was analysed. This information was used for creating seven new variables, defined as the $\log_{10}$ of the content of each of the elements normalized to oxygen content (Zadora, Martyna, Ramos, Aitken, 2014). Moreover, before determining the elemental composition of a particular glass fragment, its linear dimension was established using an SEM image.

2.3 Data interpretation

Data relating to elemental composition of glass fragments obtained with the use of SEM-EDX analysis were interpreted using the likelihood ratio approach (case II–IV; Aitken, Lucy, 2004; Aitken, Lucy, Zadora, Curran, 2006; Aitken, Zadora, Lucy, 2007; Neocleous, Aitken, Zadora 2009; Ramos, Gonzalez-Rodriguez, Zadora, Aitken, 2013; Ramos, Zadora, 2011; Zadora, 2011; Zadora, Martyna, Ramos, Aitken, 2014; Zadora, Ramos, 2010; Zadora, Neocleous, 2009; Zadora, Neocleous, 2010; Zadora, Neocleous, Aitken, 2010). This methodology allowed us to evaluate whether the delivered evidence (E – in this case, the elemental composition determined for the particular glass fragment) more strongly supports the prosecutor's version (H_1; i.e., the prosecutor's hypothesis) or the defence's version (H_2; i.e., the defence's hypothesis). The method relies on establishing the conditional probabilities – $Pr(E|H_1)$ and $Pr(E|H_2)$ and evaluation of the likelihood ratio (LR) value expressed by the equation:

$$LR = \frac{Pr(E|H_1)}{Pr(E|H_2)}. \qquad (1)$$

The likelihood ratio is interpreted in the following way: when the LR value is greater than 1, the evidence (E) supports the prosecutor's hypothesis (H_1), while a value below 1 supports the defence's hypothesis (H_2). In LR interpretation, the following simple principle is also applied: the greater (lower) the LR value is, the stronger (the weaker) the support for hypothesis H_1 (H_2) is. Additionally, in order to reflect the strength of support for the selected hypothesis, when formulating the final report's conclusion, the expert may use a verbal scale which is based on the obtained LR values (Evett, Jackson, Lambert, McCrossan, 2000; ENFSI 2015). For example, when the evidence supports the prosecutor's version (H_1), the verbal scale is presented as follows:

a) $1 < LR \leq 10$ slight/limited support;
b) $10 < LR \leq 100$ moderate support;
c) $100 < LR \leq 1000$ moderately strong support;
d) $1000 < LR \leq 10\,000$ strong support;
e) $LR > 10{,}000$ very strong support.

When obtained LR values are below one, the forensic expert uses the same verbal scale; however, the strength of support relates to the defence's proposition (H_2). For example, an LR equal to 0.001 means that the evidence 1000 times more strongly supports the defence's hypothesis, which on the verbal scale is equivalent to moderately strong support for this hypothesis.

In the presented cases, when solving a classification problem, the following hypotheses were tested:

a) H_1 – the analysed glass fragment originates from the category of car or building windows;
b) H_2 – the analysed glass fragment originates from the category of glass containers, i.e., the other most frequently encountered category in human surroundings, and, by the same token, most frequently disclosed at the scene of an event.

However, when solving a comparison problem, the following hypotheses were tested:

a) H_1 – the compared glass fragments originate from the same source;
b) H_2 – the compared glass fragments originate from different sources.

It should be pointed out that evidence interpretation during the solving of a classification or comparison problem is carried out on the so-called source level. However, fact finders, when asking about, for example, the presence of microtraces on the body, clothes or shoes of a suspected person, usually want to know not only which category they originate from or whether they come from the same object as the comparative sample, but, more importantly, they also want to establish what type of activity caused these particular microtraces to be deposited on the suspect's body, clothes and/or shoes. In such a case, data interpretation is carried out on the so-called activity level (which means that the number of glass fragments as well as primary transfer, secondary transfer and contamination problems are taken into account). For example, in the case of data interpretation carried out on the activity level, the following hypotheses can be tested:

a) H_1 – the suspect took part in the criminal event (e.g. broke a car window);
b) H_2 – the suspect did not take part in the criminal event (e.g. a few glass fragments revealed on his/her clothes resulted from contamination).

Nevertheless, even without LR calculations, it can be *a priori* stated that revealing at least 3 glass microtraces in evidence material (Curran, Hicks, Buckleton, 2000) exhibiting a common origin with the control glass sample is enough evidence that the suspect was involved in the event. However, a small number of glass fragments (less than 3; Curran, Hicks, Buckleton, 2000) does not support either of the hypotheses, because the presence of a small amount of glass may results from contamination (i.e., glass transferred by chance).

More information about the way to prepare data for *LR* calculations as well as information about *LR* models which are applied nowadays can be found in the literature (Aitken, Taroni, 2004; ENFSI, 2015; Jackson, Aitken, Roberts, 2014; Roberts, Jackson, 2012; Puch-Solis, Roberts, Pope, Aitken, 2012; Roberts, Aitken, 2013; Zadora, Martyna, Ramos, Aitken, 2014).

2.4 Software

Likelihood ratio calculations were performed using R software (The R Foundation for Statistical Computing, 2014), using routines written by one of the authors (Zadora, Martyna, Ramos, Aitken, 2014).

3. Case studies

3.1. Case I

In November, two cars collided after dark. The driver of car A, who drove into car B, testified that he hadn't noticed the second car, due to the fact that the lights of car B had not been switched on. However the driver of car B disputed this. In order to check whose testimony was true, the police secured a bulb from the broken headlamp of car B (evidence I.1) and delivered it to the laboratory in order to check if the bulb of this lamp had been switched on during the impact (H_1), or not (H_2).

How a conclusion is reached about whether a bulb was switched on or not during a collision is dependent on whether the glass envelope of the bulb was broken during the collision (Baudoin, Lavabre, 1996). If, during an accident, the envelope of the bulb was not smashed, the tool marks expert analyses any deformations of the filament, makes observations of the filament's ends and/or looks for a specific coating which may be deposited on the inside of the bulb's envelope (Baudoin, Lavabre, 1996). In the case of accidents during which the bulb was broken, the tool marks expert concentrates on searching for a specific type of colored coating fixed onto the filament surface. This type of coating may arise when oxygen present in the air reacts with the still hot filament. If the filament is made from tungsten then the presence of yellow (WO_3), dark-blue ($WO_{2.9}$), reddish-violet ($WO_{2.72}$) or brown coating (WO_2; Goebel, 1975) confirms that the bulb was probably switched on during the impact (H_1). It may also happen that during breaking of the envelope, small fragments of glass which have contact with the still hot filament become melted onto its surface. Revealing of such a fragment of melted glass on the filament surface (Baudoin, Lavabre, 1996) additionally confirms the fact that the bulb filament was still hot and the bulb was probably switched on during the impact (H_1).

The delivered bulb was subjected to examination in white light with the use of a stereo magnifying glass. During this examination, it was established that the glass envelope of the bulb was broken and metal elements of the bulb such as the cap (sleeve), filament and contact wires were bent and damaged. During tool mark examination performed with the use of a comparison microscope, a colored coating associated with the presence of oxides, e.g. tungsten oxides, was not revealed. However, a single object that resembled glass, with linear dimension of around 1 mm, melted onto the filament, was noticed (object labeled no. 1 in Figure 1).

The revealed fragment resembling glass as well as the bulb's filament were subjected to physicochemical analysis. As a result of elemental analysis performed on the clean filament surface, it was determined that this filament was made from tungsten. Additionally, based on filament surface observations performed with the use of SEM (Figure 2), it was noticed that in many places on the filament surface, a foreign solid substance resembling melted glass was present. Elemental analysis performed in two such places as well as examination of one of the small objects attached to the filament (microtrace 1) confirmed that this was glass (Table 1) with special physicochemical properties that are required for glass applied in, for example, bulb production. These special properties are obtained mainly due to the relatively high amount of potassium and barium in this glass (Table 1).

On the basis of the performed examinations, it was concluded that the presence of the single glass microtrace, as well as the melted glass fragments disclosed on the surface of the filament gave much stronger support to the hypothesis that the bulb from the headlamp of car B was switched on during the collision (H_1), than the opposite hypothesis (H_2).

It should also be said that the lack of coating on the filament surface characteristic for tungsten oxides in this particular case was not evidence that the bulb was not switched on during the accident. For such oxides are usually present in very small amounts, which can be lost when a damaged bulb is taken out of a socket or during its packing or transporting.

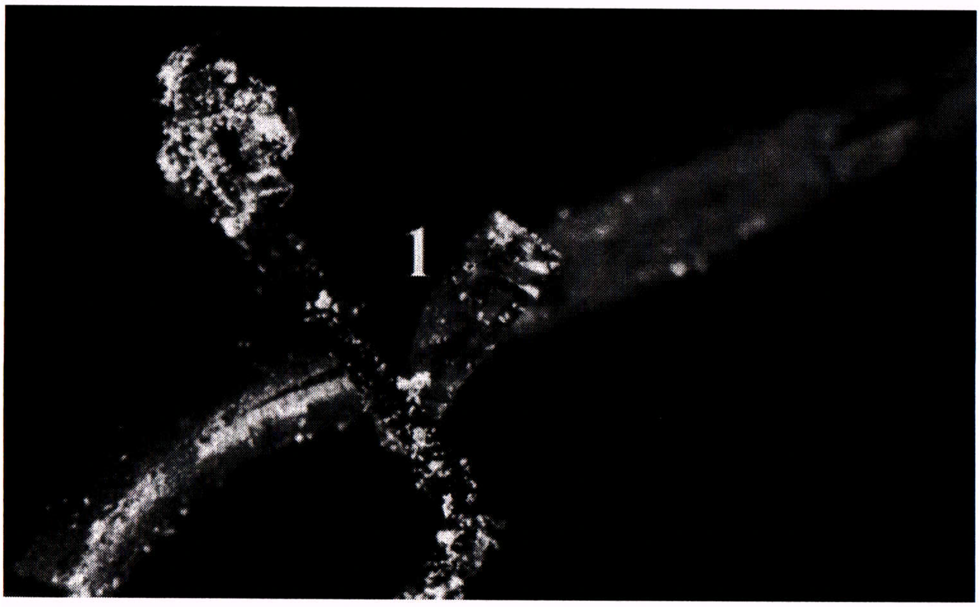


Fig. 1. Photograph of the bulb's filament taken with the use of a Leica FSC comparison microscope (1) denotes a glass fragment, with linear dimension of around 1 mm, melted onto the bulb's contact wire.

Fig. 2. The filament of the bulb with glass melted onto the filament – observed with the use of a scanning electron microscope. (1) and (2) denote sites at which the elemental composition was analysed.

Table 1

Mean elemental composition determined for glass fragments revealed during examination of the broken bulb (evidence I.1)

Analysed material	Content [wt. %]							
	O	Na	Mg	Al	Si	K	Ca	Ba
Microtrace 1 in Fig. 1	48.27[a)]	8.21	2.11	0.68	34.91	1.27	3.65	0.90
	2.06[b)]	0.32	0.11	0.03	1.35	0.12	0.32	0.04
Melted substance observed on the filament's surface (place labelled no 1 in Fig. 2)	49.86	6.63	1.85	1.55	34.84	0.79	3.21	1.19
	0.67	0.42	0.14	0.67	0.86	0.07	0.15	0.25
Melted substance observed on filament's surface (place labelled no 2 in Fig. 2)	48.35	7.13	2.01	0.71	36.02	1.01	3.75	0.89
	4.29	0.62	0.13	0.03	3.73	0.22	0.79	0.31

[a)] Mean, [b)] standard deviation.

3.2 Case II

A dead cyclist was found on a poorly lit local road in July. The police suspected a hit-and-run accident. The police collected twenty six colourless glass fragments (evidence II.1) during the scene of the accident inspection. The victim's clothes, namely trousers (evidence II.2) and a sweatshirt (evidence II.3), were also secured for further analysis. A few days later, the suspected car (marque X) was stopped by the police. Inspection of the car revealed that its front right headlamp was broken. Therefore, three glass fragments (evidence II.4) were taken from it as control material. All evidences were delivered to the laboratory in order to answer the following questions:

1. Did the glass fragments secured from the scene of the accident and the control glass fragments collected from the broken front right headlamp of the suspected car (marque X) originate from the same object (H_1), or did they originate from different objects (H_2)?
2. Were glass microtraces present on the victim's clothes, and if so did they originate from the broken front right headlamp of the marque X car (H_1), or did they originate from different sources (H_2)?

Large glass pieces were subjected to tool mark examination, in which they were observed using a magnifying glass. It was observed that some of the glass pieces (evidence II.1) possess a specific surface pattern characteristic for headlamps, whereas on a few other pieces a headlamp serial code was noticed. In the next step, the tool mark expert performed "jigsaw fit" analysis, trying to match evidence glass fragments (evidence II.1) to control glass fragments (evidence II.2). However, as a result of this examination, only the smallest control glass fragment (evidence II.4) was matched to one evidence glass fragment (labelled evidence II.1.1). It was found that their edges fitted each other tightly, which is illustrated in Figure 3. Additionally, the edges of fragments which matched were also the subject of analysis using a comparison microscope. It was found that the outlines of the edges of fragments of glass which were formed during the breaking of the glass exactly matched (on the fragments which had been fitted each other; Figure 4).

The tool mark expert also managed to fit 3 out of the 26 glass fragments revealed at the accident scene to each other (marked as evidence II.1.2–II.1.4). As a result of this analysis, the specific headlamp serial code was identified, and the expert established that this number was characteristic of a model of headlamp used only by marque X cars. However, an attempt to match the glass fragments bearing specific serial codes (glass pieces revealed at the scene of the accident) with control glass fragments failed. Therefore, physicochemical analysis was performed in order to check whether the fitted glass fragments which were characterised by a specific serial code could have originated from the same object as the control glass samples.

In this analysis, three glass microtraces with linear dimension between 0.1–1.0 mm were sampled from each evidence fragment (i.e., fitted glass fragments collected at the scene of the accident – described here as II.1.2–II.1.4) and from control glass fragments (II.4), and were subjected to quantitative elemental analysis. The obtained results (Table 2) were compared using the likelihood ratio approach (interpretation at the source level) – testing the following hypotheses:

a) H_1 – glass fragments with a specific serial code, which were collected at the accident scene and la-

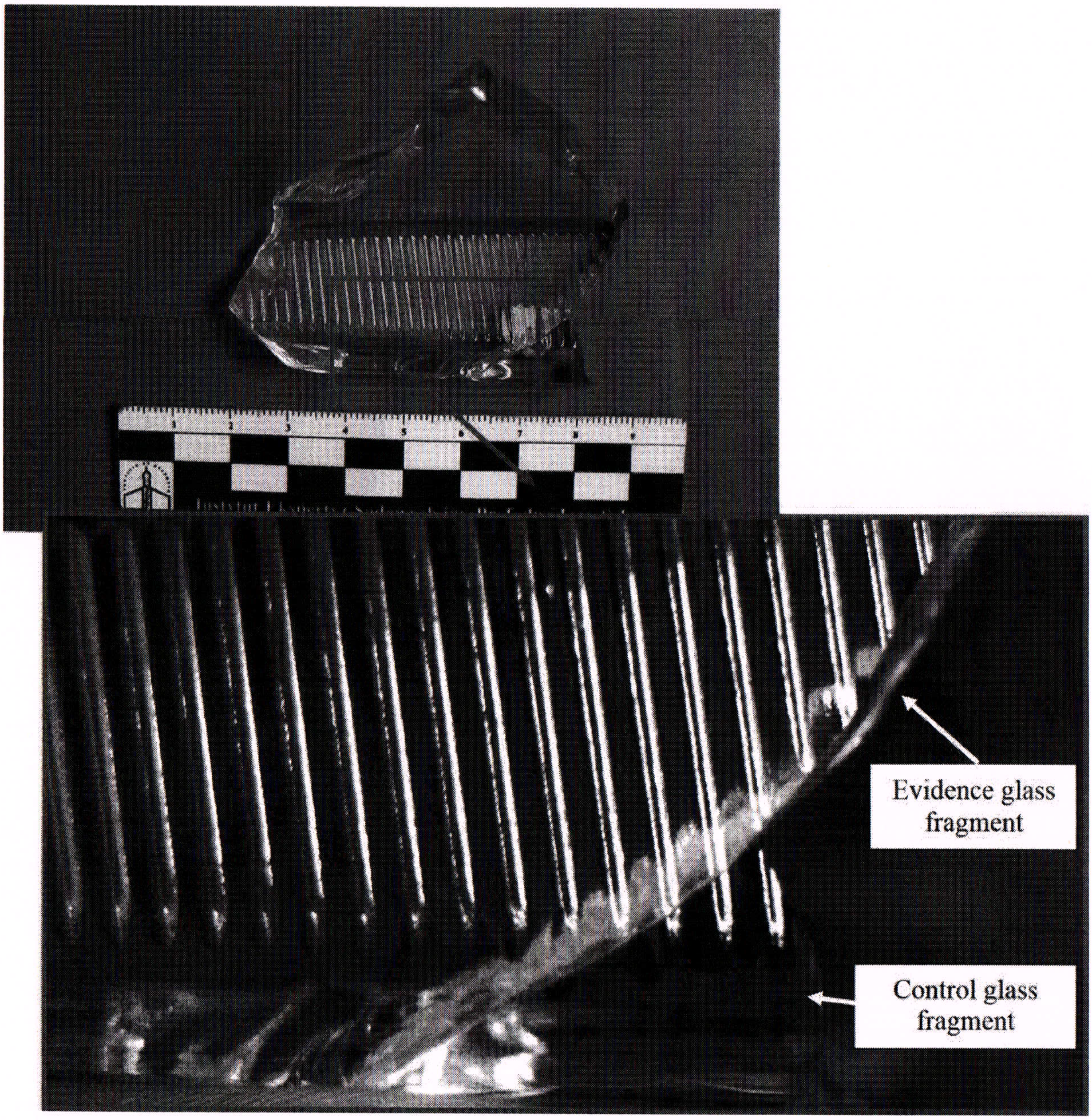


Fig. 3. Evidence glass fragment matched to control glass fragment.

beled as evidence II.1.2–II.1.4, originate from the same object as control glass fragments – evidence II.4.

b) H_2 – glass fragments with a specific serial code, which were collected at the accident scene and labeled as evidence II.1.2–II.1.4, do not originate from the same object as control glass fragments – evidence II.4.

It was ascertained, based on performed likelihood ratio calculations (Table 2), that for glass fragments (that had been matched to each other) on whose surface a specific serial code was revealed (evidence II.1.2–II.1.4), hypothesis (H_1) is more likely – that these fragments originate from the same object as glass fragments that were secured during the examination of car X (evidence II.4), than hypothesis (H_2): that these fragments originate from another glass object. Moreover, it can be ascertained that the strength of support for the hypothesis about their common origin is very strong ($LR >> 10,000$).

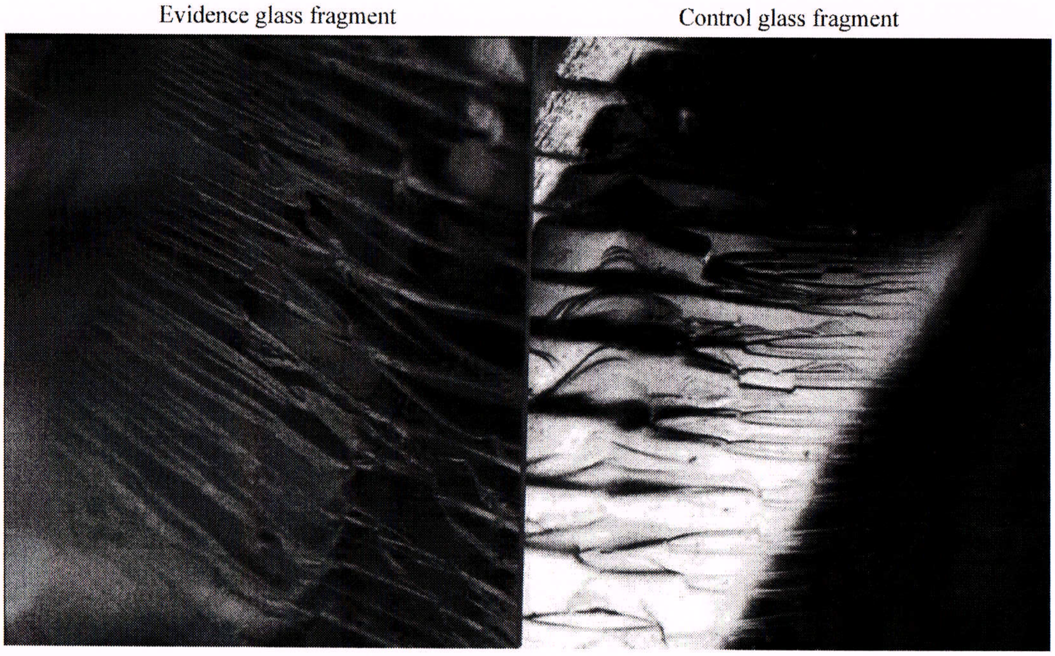


Fig. 4. Comparison of the outlines of edges (cracking) formed during glass fracture. Images of edges of evidence and control glass fragments in their matching place – view obtained with the use of a Leica FSC comparison microscope.

Table 2

Mean elemental composition determined for glass fragments fitted to each other, exhibiting a specific serial code, which were revealed on the road (evidence II.1.2–II.1.4); glass fragments found on victim's clothes (ev. II.2–II.3); as well as results of likelihood ratio calculations (LR)

Evidence	microtrace	Content [% wt.]						*LR* value
		O	Na	Al.	Si	K	Ca	
II.1.2	1	49.08[a]	9.25	1.07	33.11	1.33	6.11	698,500[c]
		1.24[b]	0.28	0.03	0.97	0.09	0.42	
II.1.3	1	49.36	9.36	1.07	32.88	1.30	5.99	429,100
		0.84	0.20	0.03	0.65	0.06	0.27	
II.1.4	1	49.55	9.34	1.07	32.75	1.29	5.96	256,700
		1.50	0.28	0.04	1.22	0.10	0.45	
II.2	1	46.71	8.85	1.12	35.05	1.48	6.77	19,490
		0.42	0.08	0.03	0.34	0.04	0.20	
	2	54.82	2.97	1.34	40.66	0.10	0.00	$LR < 1$[d]
		0.16	0.05	0.07	0.03	0.04	0.00	
	3	45.52	8.45	1.14	35.94	1.55	7.31	1,601
		1.19	0.09	0.05	0.74	0.09	0.39	
	4	47.89	8.99	1.10	34.16	1.39	6.43	55,220
		0.57	0.18	0.03	0.50	0.03	0.14	
II.3	1	48.79	8.98	1.11	33.53	1.33	6.22	26,130
		0.09	0.07	0.03	0.05	0.05	0.09	
	2	48.68	8.92	1.08	33.53	1.36	6.38	19,600
		1.60	0.31	0.01	1.15	0.13	0.62	

[a] mean, [b] standard deviation, [c] value of *LR* > 1, which indicates that the elemental composition of a particular glass microtrace more strongly supports the hypothesis that it originates from the same source as the control material, [d] values of *LR* < 1 indicate that the elemental composition of a particular glass microtrace more strongly supports the hypothesis that it originates from a source other than the control material.

Glass microtraces revealed on the victim's clothes (evidences II.2 and II.3) were also subjected to physicochemical analysis. There were six such microtraces – four secured from debris from the trousers (evidence II.2) and 2 found in debris recovered from the victim's sweatshirt (evidence II.3). Their linear dimension was in the range between 0.1 and 1.2 mm. Results relating to their quantitative elemental composition (Table 2) were interpreted using the likelihood ratio approach. The *LR* values confirmed that for five out of six glass microtraces revealed on the victim's clothes (evidences II.2 and II.3), the hypothesis H_1 about having the same origin as glass fragments collected from the suspected vehicle (marque X) is more likely than the hypothesis concerning their origin from another glass object (H_2). Moreover, the support for this hypothesis (H_1) is very strong.

Results relating to both tool mark examination and physicochemical analysis of glass fragments allowed us to conclude that on the activity level they much more strongly supported the hypothesis that the car from which the broken headlamp glass fragments were collected took part in the hit-and-run accident (H_1) than the hypothesis (H_2) that this car did not take part in this accident.

3.3 Case III

The police noted a series of car break-ins which took place in a small town near Krakow, in a period of time between January and August 2014. After one such event, a suspect was arrested. Police suspected that a pneumatic gun was used to break the car windshield. As a result of looking through the suspect's flat, such a gun was found (evidence III.1). Police also secured the suspect's clothes (evidence III.2) as well as control glass fragments originating from the car's broken windshield, which were delivered for analysis (evidence III.3). All evidences were delivered to the laboratory in order to establish if there were any glass fragments present on the suspect's clothes or inside the gun barrel. If so, then did they originate from the car's broken windshield – fragments of which were delivered to the laboratory – (H_1), or from another glass object (H_2)?

As a result of examination of the inside of the gun's barrel (evidence III.1), which was performed with the use of a stereomicroscope, six objects resembling glass were revealed. However, in the examination of the suspect's clothes, i.e. T-shirt and shorts (evidence III.2), nine such objects were found. The linear dimension of most of these fragments was in the range of 0.1–0.3 mm or sporadically between 0.5–1.0 mm. Additionally, in order to perform a comparison, three glass fragments with a linear dimension of around 0.1–1.0 mm were selected from evidence III.3.

Elemental analysis confirmed that all the microtraces revealed on the suspect's clothes as well as ones found inside the gun barrel were glass fragments. The elemental composition established for these objects is presented in Table 3, while the mean elemental composition (expressed in [wt. %]) calculated for the control glass sample is the following: O: 47.50 ± 1.45, Na: 9.62 ± 0.34, Mg: 2.14 ± 0.06, Al: 0.31 ± 0.03, Si: 33.85 ± 1.33, Ca: 5.87 ± 0.56, Fe: 0.63 ± 0.07.

The likelihood ratio (*LR*) approach was used for interpretation of the obtained results (source level). In the performed calculations, the quantitative elemental composition of glass fragments revealed in evidence III.1 and III.2 (Table 3) was compared with the quantitative elemental composition of control glass fragments (evidence III.3). Based on the performed calculations, it was ascertained that for five out of nine glass fragments revealed on clothes (evidence III.2), the hypothesis (H_1) that they share a common origin with glass fragments collected during the examination of the burgled car (evidence III.3) is more likely than the hypothesis that they originate from another glass object (H_2). Additionally, using a verbal scale which described the strength of the support, it can be stated that for 3 out of the 5 glass microtraces the strength of support was very strong, while for the remaining two glass fragments the strength of support could be described as strong. In the case of glass fragments revealed inside the gun barrel (evidence III.1), it was determined that for two out of the six glass microtraces, the hypothesis (H_1) about them sharing a common origin with control glass fragments (evidence III.3) was also more likely. The obtained *LR* values suggested that the elemental composition of one glass microtrace strongly supports this hypothesis, and that of the second one supports it very strongly.

When interpreting the obtained results on an activity level, the event circumstances as well as the number of glass fragments revealed in this case (see point 2.3) were also taken into account. Revealing as many as 5 glass microtraces on the suspect's clothing – which were established to have probably originated from the car's broken windshield – was sufficient evidence to conclude that the version of the event in which the suspect broke the windshield (H_1) is decidedly more supported than the alternative one (H_2). In the case of the number of glass microtraces revealed inside the gun barrel, a determinative role was played by the circumstances of the event. Taking into account the location where the glass fragments were deposited (inside the

Table 3

Mean elemental composition determined for glass fragments found inside the gun barrel (evidence III.1) and on the suspect's clothes (evidence III.2) as well as the results of likelihood ratio calculations (LR)

Evidence	Microtrace	Content [wt. %]								*LR* value
		O	Na	Mg	Al	Si	K	Ca	Fe	
III.1	1	47.62[a]	9.41	2.00	0.35	33.79	0.00	6.11	0.62	19,110[c]
		0.39[b]	0.13	0.07	0.01	0.36	0.00	0.13	0.02	
	2	48.18	9.34	2.03	0.33	33.39	0.00	5.99	0.63	4,203
		1.51	0.32	0.03	0.03	1.25	0.00	0.53	0.08	
	3	48.19	8.95	2.15	0.58	33.96	0.40	5.44	0.33	*LR* < 1[d]
		0.35	0.02	0.05	0.01	0.33	0.03	0.02	0.05	
	4	52.95	9.33	2.19	0.4	30.00	0.00	4.38	0.80	*LR* < 1
		0.48	0.09	0.01	0.01	0.52	0.00	0.07	0.01	
	5	45.66	8.43	2.09	0.71	36.05	0.44	6.09	0.52	*LR* < 1
		0.73	0.15	0.02	0.01	0.66	0.01	0.22	0.04	
	6	51.28	9.44	2.19	0.48	31.43	0.20	4.72	0.24	*LR* < 1
		0.47	0.10	0.02	0.01	0.49	0.01	0.10	0.02	
III.2	1	49.46	9.61	2.05	0.33	32.31	0.00	5.56	0.57	1,806
		1.39	0.24	0.05	0.01	1.08	0.00	0.50	0.10	
	2	49.09	9.63	2.07	0.30	32.58	0.00	5.65	0.59	6,062
		2.16	0.49	0.03	0.01	1.89	0.00	0.74	0.05	
	3	48.87	8.73	0.28	0.87	33.86	0.38	6.95	0.07	*LR* < 1
		0.43	0.14	0.01	0.02	0.38	0.03	0.17	0.01	
	4	47.95	9.72	2.13	0.34	33.45	0.00	5.72	0.57	36,620
		0.59	0.21	0.07	0.02	0.4	0.00	0.08	0.06	
	5	49.05	9.91	2.09	0.33	32.54	0.00	5.45	0.54	20,540
		0.46	0.04	0.01	0.02	0.37	0.00	0.07	0.03	
	6	55.79	10.67	2.10	0.33	26.85	0.00	3.83	0.36	*LR* < 1
		0.14	0.06	0.00	0.02	0.10	0.00	0.02	0.02	
	7	46.7	9.39	2.04	0.37	34.44	0.00	6.31	0.67	20,380
		1.14	0.32	0.07	0.01	1.00	0.00	0.46	0.04	
	8	52.98	9.4	1.85	0.8	30.11	0.39	4.23	0.26	*LR* < 1
		0.13	0.08	0.02	0.01	0.12	0.01	0.01	0.02	
	9	42.43	8.44	1.99	0.33	39.16	0.00	6.91	0.67	*LR* < 1
		2.85	0.36	0.03	0.02	3.04	0.00	0.14	0.02	

[a] Mean, [b] standard deviation, *c)* values of *LR* > 1 indicate that the elemental composition of a particular glass microtrace more strongly supports the hypothesis that it originates from the same source as the control material, [d] values of *LR* < 1 indicate that the elemental composition of a particular glass microtrace more strongly supports the hypothesis that it originates from a source other than the control material.

gun barrel), the long time which elapsed between the event and the collection of the evidence, as well as the fact that the gun was also used after this event (which was established based on case files), the revealing of just two glass microtraces which could have originated from the car's broken windshield was sufficient evidence to conclude that the hypothesis concerning use of this particular gun for breaking the car windshield (H_1) is decidedly more likely than hypothesis (H_2) that these microtraces were found inside the gun barrel by chance.

However, a relatively large number of glass microtraces (eight) which were different in elemental composition from the control glass samples were found inside the gun barrel as well as on the suspect's clothes. Therefore, additionally, *LR* calculations were carried out for glass fragments for which it was ascertained that they probably originated from other glass objects than control glass fragments (evidence III.3). The calculations were performed in order to determine which category these fragments could have originated from (source level – classification problem). The following hypotheses were considered:

a) H_1 – the i-th glass fragment revealed in evidence III.1 and III.2 originates from the category "car and building windows" (cw);
b) H_2 – the i-th glass fragment revealed in evidence III.1 and III.2 originates from the category "glass containers" (p).

Based on calculated *LR* values (Table 4), it can be concluded that for all evidence glass microtraces which were not congruent with the control glass fragments, the hypothesis that they belong to the category "car and building windows" (cw) was more likely than the hypothesis that they belong to the category "glass containers" (p).

Table 4

Results of classification of glass fragments found in evidences III.1, III.2.1 and III.2.2 whose elemental composition did not match (Table 3) the elemental composition of control glass fragments (evidence III.3)

Evidence	Microtrace	*LR* value	Category
III.1	3	30	cw[a)]
	4	31	cw
	5	5138	cw
	6	5252	cw
III.2	3	491	cw
	6	637	cw
	8	138	cw
	9	1973	cw

[a)] cw – car and building windows.

Taking into account the relatively large number of glass microtraces from this category that were revealed inside the barrel of the gun as well as in debris recovered from the suspect's clothes, it can be concluded (activity level) that these glass fragments originate from, for example, other car windshields which were broken during other break-ins (H_1) rather than that they were the effect of environmental contamination, i.e. glass found by chance (H_2). However, in order to prove such a statement and link the suspect with other break-ins, it would be necessary to perform additional analysis involving control glass fragments originating from such windshields, if they were available for analysis.

3.4 Case IV

The suspect claimed that he found the unconscious victim with injuries to her head, in a pool of blood and among pieces of broken glass from the window of a door which led from a corridor to a stairway. He immediately called the emergency services and tried to give the victim first aid until the time of their arrival. The police also arrived at the scene of the event. During the preliminary interrogation, the suspect testified that the victim (woman) must have stumbled and fallen from the stairs, smashing the door window. The unconscious woman was transported to the nearest hospital and when she awoke, she testified that she had been beaten by the suspect and had been pushed by him in the direction of the door. As a result of her fall onto the door, the door window broke, causing the injuries to her body. Furthermore, the victim also claimed that the location of the event was different. According to her testimony, she had been beaten by the suspect in the corridor, which was separated from the stairway by the closed door. Owing to discrepancies between the testimonies, the police collected glass pieces found at the scene of the event, i.e. ones lying on the floor (evidence IV.1) and ones still attached to the door's window frame (evidence IV.2). The clothes which the suspect was probably wearing during the event (evidence IV.3–6) were also seized by the police.

All the evidences, as well as case files, were delivered to the laboratory in order to establish – on the activity level – whether the event was an accident or not. Generally speaking, the fact finders wanted to know if the victim fell from the stairway on her own, causing the window of the door to smash (H_1) or if somebody else took part in event (e.g. the victim was beaten by the suspect H_2).

Analysis of information included in the case files, which related to the victim's injuries, as well as examination of the bloodstain pattern revealed at the scene of the crime, allowed the conclusion that both versions of the event (H_1 and H_2) are equally credible. Based on information found in the case files, it was ascertained that the suspect's and the victim's testimonies – concerning the fact that the door linking the corridor and the stairway was closed – were congruous with each other.

Therefore, the experts focused on glass evidence examination. Firstly, the glass fragments were subjected to tool marks examination. All the glass pieces were characterised by a specific pattern (relief), which was seen on one side of the glass fragments, whereas the other side was smooth. Based on the case files, it was established that if the suspect's version recounting the victim's independent fall from the stairs was true (H_1), then the door window would have been broken from the pattern side. If the victim's version turned out to be true (H_2), i.e., she had fallen on the door from the corridor side, the force which caused the breaking of the glass panel would have been directed onto the smooth side of the window. As a result of "jigsaw fit" analysis, most evidence glass fragments (Figure 5), i.e. those revealed on the floor (evidence IV.1), were matched to control glass fragments (evidence IV.2), i.e. those still attached to the door frame. After "jigsaw fit analysis" it was ascertained that the window was broken as a result of a single blow in the top right part – when looking at the window from the pattern side (Figure 5 – frame) – as well as a result of a few secondary damages (Figure 5 – arrows). In order to establish which side of the window the force was directed onto, the edges of the glass fragments that constituted the original damage were examined using a stereo magnifying glass (Figure 6). Based on analysis of the primary radial damage, it was ascertained that the force was directed onto the smooth side of the window, which on the closed door was situated on the corridor side.

To sum up, as a result of tool mark examinations, it was ascertained that the window broke as a result of a single blow. The force of this blow was directed onto the smooth side of the window (in the top left part), which was situated on the corridor side when the door was closed. These conclusions more strongly supported the victim's version concerning the location in which the event took place (H_1) than the suspect's version (H_2).

In order to connect the suspect with the event scene, the suspect's clothes, which had been seized one day after the accident, were subjected to physicochemical examination. The aim of the physicochemical examination was to establish if and how many glass microtraces were present on shoes (evidence IV.3), sweatshirt (evidence IV.4), trousers (evidence IV.5) and T-shirt (evidence IV.6) belonging to the suspect. If they were present, then a further aim was to establish if they were similar to control glass fragments (evidence IV.2).

Fifteen objects resembling glass were found (five microtraces collected from each evidence) among debris collected from the suspect's shoes (evidence IV.3), sweatshirt (evidence IV.4), and trousers (evidence IV.5). The linear dimension of most of the revealed microtraces was between 0.3–1.0 mm. Their elemental analysis confirmed that these microtraces were glass (Table 5). In order to perform a comparative analysis, three glass microtraces were collected from one piece of broken window (evidence IV.2). The linear dimension of the microtraces was between 0.1–1.0 mm, and their mean elemental composition was [wt. %] the following: O: 47.55 ± 0.72, Na: 10.30 ± 0.31, Mg: 0.16 ± 0.02, Al: 0.20 ± 0.03, Si: 33.92 ± 0.64, and Ca: 7.83 ± 0.35.

The quantitative elemental composition of glass fragments revealed on the suspect's clothes was compared with the quantitative elemental composition of the control glass originating from the door's broken window, by application of the likelihood ratio test (Table 5). In *LR* calculations, the following hypotheses were tested:

a) H_1 – the i-th glass fragment revealed in evidence IV.3–IV.5 originates from the same glass object as evidence IV.2;

b) H_2 – the i-th glass fragment revealed in evidence IV.3–IV.5 does not originate from the same object as evidence IV.2.

Based on the obtained *LR* results, it was ascertained (source level) that for all fragments revealed on the suspect's clothes and shoes, hypothesis (H_1) – about them sharing a common origin with glass pieces originating from the door's broken window (evidence IV.2) – is more likely than the alternative hypothesis (H_2). What is more, the obtained *LR* values indicated that the strength of the support for this hypothesis is very strong.

Taking into account that a relatively large number of glass fragments exhibiting similarity to control glass samples (from the broken window) were revealed on the suspect's clothes and shoes (see point 2.3), it may be suggested (activity level) that a more credible explanation for the mechanism of glass transfer onto the suspect's clothes and shoes was that he took active part in the breaking of the window or was very close during the breaking of the window (H_2), than that glass transfer occurred by chance, e.g. during the giving of premedical help to the victim (H_1).

Therefore, in this specific case, all collected evidences more strongly support the hypothesis that so-called a third person took part in this event, i.e. the suspect hit the victim (H_2), than the hypothesis that the victim's fall was by chance (accident; H_1).

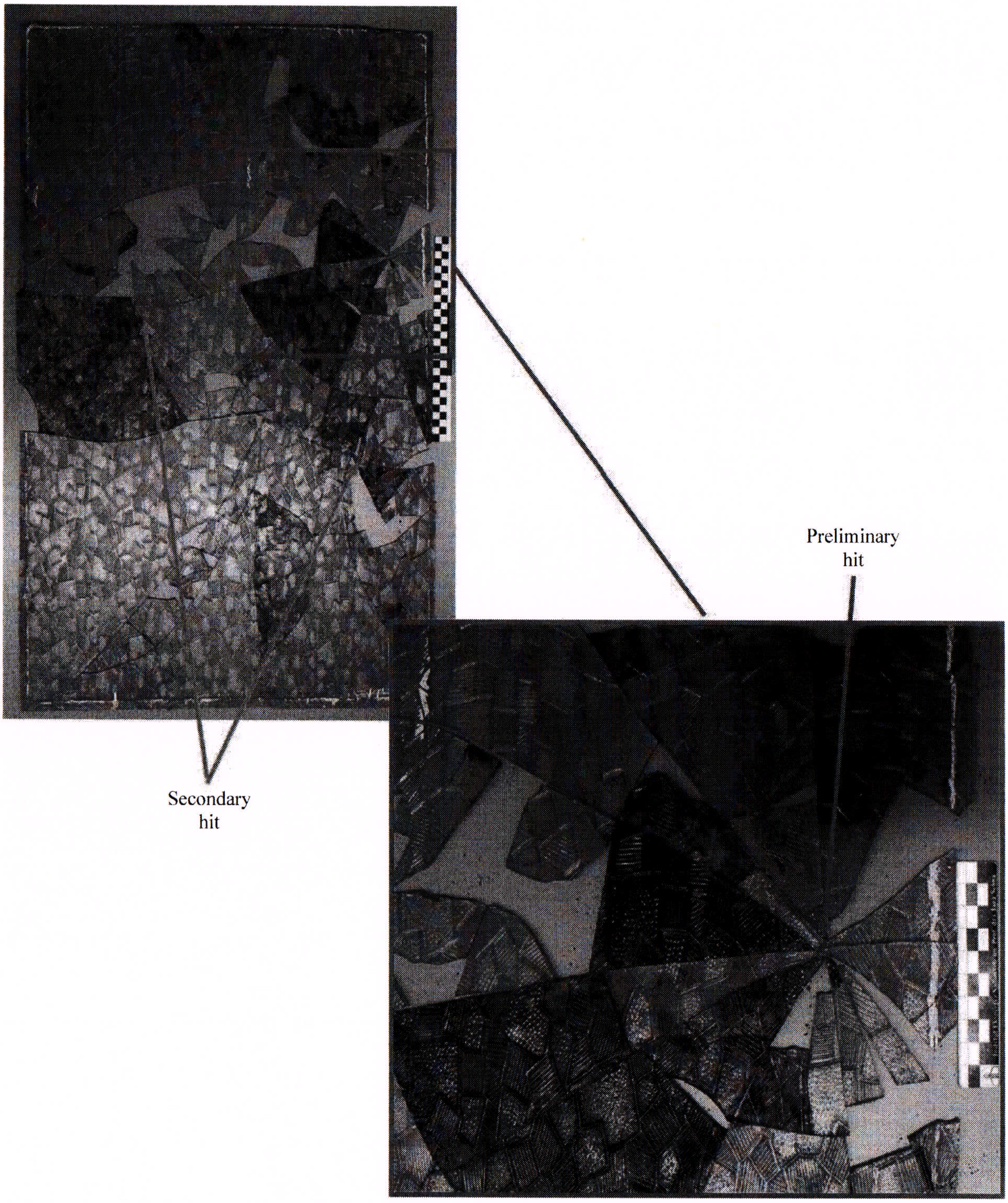
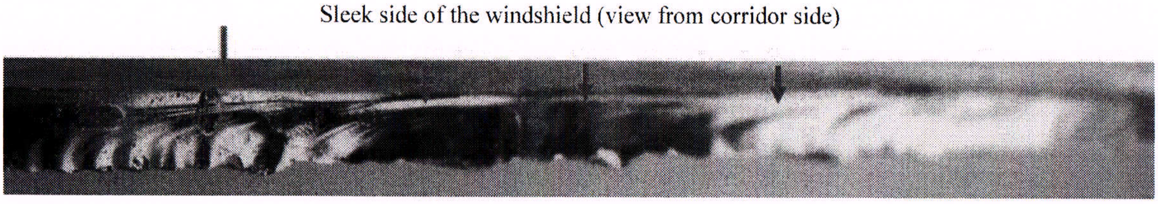


Fig. 5. The door window after reconstruction – using "jigsaw fit" analysis – from glass fragments revealed on the floor and ones visible in the door frame: view from the pattern side of the window. The victim's blood is seen on the surface of selected glass fragments.

Sleek side of the windshield (view from corridor side)



Pattern side of the windshield (view from stairway side)

Fig. 6. An example of an edge of primary radial damage to the window. Arrows show the direction of the force's action.

Table 5

Mean elemental composition determined for glass fragments found in debris from the suspect's clothes and shoes (evidences IV.3–IV.5); and results of likelihood ratio calculations (LR)

Evidence	Microtrace	Content [wt. %]						*LR* value
		O	Na	Mg	Al	Si	Ca	
IV.3	1	47.46[a]	9.98	0.13	0.19	34.19	7.98	30,170[c]
		0.69[b]	0.14	0.04	0.02	0.53	0.24	
	2	44.84	9.37	0.15	0.21	36.22	9.13	1,314
		0.89	0.22	0.02	0.02	0.61	0.45	
	3	46.71	8.85	0.00	1.12	35.05	1.48	19,490
		0.42	0.08	0.00	0.03	0.34	0.04	
	4	45.52	8.45	0.00	1.14	35.94	1.55	1,601
		1.19	0.09	0.00	0.05	0.74	0.09	
	5	47.89	8.99	0.00	1.10	34.16	1.39	55,220
		0.57	0.18	0.00	0.03	0.50	0.03	
IV.4	1	44.97	9.35	0.15	0.20	36.08	9.15	1,109
		0.11	0.14	0.01	0.02	0.17	0.08	
	2	45.78	9.77	0.14	0.19	35.49	8.59	19,200
		0.18	0.04	0.02	0.01	0.08	0.08	
	3	48.79	8.98	0.00	1.11	33.53	1.33	26,130
		0.09	0.07	0.00	0.03	0.05	0.05	
	4	48.68	8.92	0.00	1.08	33.53	1.36	19,600
		1.60	0.31	0.00	0.01	1.15	0.13	
	5	48.30	8.86	0.00	1.08	33.76	1.42	38.890
		1.48	0.37	0.00	0.03	1.16	0.10	
IV.5	1	47.33	10.09	0.16	0.20	34.31	7.87	55,800
		0.21	0.04	0.01	0.01	0.19	0.10	
	2	46.97	10.04	0.16	0.19	34.34	8.15	56,190
		2.32	0.48	0.03	0.03	1.79	0.96	
	3	49.08	9.25	0.00	1.07	33.11	1.33	698,500
		1.24	0.28	0.00	0.03	0.97	0.09	
	4	49.36	9.36	0.00	1.07	32.88	1.30	429,100
		0.84	0.20	0.00	0.03	0.65	0.06	
	5	49.55	9.34	0.00	1.07	32.75	1.29	256,700
		1.50	0.28	0.00	0.04	1.22	0.10	

[a] Mean, [b] standard deviation, [c] value of *LR* > 1, indicating that the elemental composition of the particular glass microtrace more strongly supports the hypothesis that it originates from the same source as the control material.

4. Conclusions

In the presented article, the authors show examples of real forensic cases in which evidence in the form of glass fragments required the performance of two types of analysis – tool mark examination (i.e. "jigsaw fit" analysis) and physicochemical analysis (determination of the elemental composition of glass fragments).

In the authors' opinion, in the presented cases, information obtained from one type of examination would have been insufficient to answer the questions posed by fact finders (whether the bulb was switched on – case I; whether the suspected car was involved in the hit-and-run accident – case II; whether the event was due to beating or an accident – case IV). Only comprehensive analysis of all results concerning both tool marks and physicochemical examination (namely "combined evidence") interpreted with the use of likelihood ratio models allowed the problems to be solved.

In the authors' opinion, glass traces constitute important evidence, and the results of their examination can be used in the clarification of an event's circumstances – despite the fact that in most cases, answers to questions posed by fact finders can only be formulated in terms of probabilities (the expert indicates which of two versions of an event is more strongly supported by the evidence).

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