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Development, design, and realization of a proficiency test for the Forensic Determination of Shooting Distances – FDSD 2015 ☆

Ludwig Niewöhner [a,*], Martin Barth [a], Dieter Neimke [a], Silke Latzel [a], Amalia Stamouli [b], Bart Nys [c], Lawrence Gunaratnam [d], Kira Fries [e], Steffen Uhlig [f], Henning Baldauf [f]

[a] Forensic Science Institute, BKA, D-65173 Wiesbaden, Germany
[b] Netherlands Forensic Institute, NFI, NL-2497 GB Den Haag, The Netherlands
[c] National Institute of Criminalistics and Criminology, NICC, 1120 Bruxelles, Belgium
[d] National Bureau of Investigation, NBI, PL 285, FIN-01301 Vantaa, Finland
[e] Leibnitz-Institut für Neue Materialien, INM, D-66123 Saarbrücken, Germany
[f] QuoData Ges. für Qualitätsmanagement und Statistik mbH, Preller Str. 135, D-01187 Dresden, Germany

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ABSTRACT

Within the framework of the ENFSI Expert Working Group Firearms/GSR a novel proficiency test on the *Forensic Determination of Shooting Distances – FDSD 2015* – was implemented. This proficiency test was developed out of collaborative studies which were previously carried out by a number of pre-selected ENFSI laboratories. The aim of this test was to assess the laboratories' performance in visualizing the lead patterns on a shot object, and compare the questioned patterns with provided test shot patterns. The participating laboratories were requested to estimate the presumed shooting distance following their individual laboratory specific methods (SOPs) for shooting distance/muzzle-to-target determination. The submitted results were compiled by means of z scores according to the IUPAC and EURACHEM guidelines, and an extended statistical evaluation was performed. This is one of the first proficiency tests in the field of qualitative forensic methods where z scores were successfully utilized. This paper summarizes the results of the study and presents the overall performance of the participating laboratories.

The determination of the shooting distance (i.e. muzzle-to-target distance) between a firearm and a target is a question that is answered in many forensic science laboratories. The method that is applied in most cases is based on the chemographic treatment of a secondary trace carrier on which the gunshot residues (GSR) are transferred to in a previous step. This carrier is treated with a coloring agent reacting with metals present in the deposited gunshot residue particles and thereby rendering the microscopic particles visible to the naked eye [1–4].

Within the framework of the ENFSI Working Group "Firearms/GSR" a proficiency testing scheme concerning the determination/estimation of the shooting distance was set up and performed with financial support of the European Union (project 2011/ISEC/AG/2489). The aim of this project was not a competition between laboratories, but the promotion of quality in chemographic GSR investigation.

In recent years, to our knowledge only one other proficiency testing program is offered in the area of shooting distance determination [5]. Although this test is commonly accepted by the forensic community, a significant problem remains in the preparation of suitable GSR test samples meeting the necessary requirements of

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* Corresponding author at: Bundeskriminalamt, KT23 – Gunshot Traces, Appelallee 45, D-65203 Wiesbaden, Germany. Fax: +49 611 554 5087.
E-mail address: Ludwig.Niewoehner@bka.bund.de (L. Niewöhner).

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a proficiency test. This is especially with regard to the requested homogeneity of the sample material [6]. Compared to other proficiency tests, where homogenous source material can be divided into multiple identical samples, it is a major problem to prepare suitable – i.e. identical – test items for a proficiency test on shooting distance determination. In the preparation of test samples with "real" gunshot residues there is always a large statistical variance in the deposited GSR patterns. This is because the exhaust of GSR during a gunshot is not fully reproducible. Furthermore, since chemographic methods are destructive, it is not possible to use a single GSR sample (i.e. a material with a real bullet entrance hole which is initially carefully checked by the organizer of the study) distributed in succession to all participating laboratories for investigation (so-called round-robin study). The idea of using artificial samples is based on an existing proficiency test [7] for the identification of microscopic GSR particles by means of Scanning Electron Microscopy equipped with X-ray micro-analysis (SEM/EDS).

Various chemographic methods are available for the visualization of GSR [4]. The selection of the most appropriate method depends mainly on the chemical composition of the primer/ammunition used in the shooting incident in question. The principle of the chemographic process is that traces of GSR, which may not be distinguishable from other debris particles for the human eye, will form colored chemical compounds after having reacted with a specific reagent. Before the coloration step, however, the particles need to be treated with an acidic solution. The reaction products are then transferred by diffusion to a secondary target medium such as filter paper, desensitized photo paper, or cellulose hydrate films. The most commonly used coloring method for the element lead uses the sodium rhodizonate complex [1–3]. After treatment, lead compounds in GSR particles, if present, will form pink-reddish complexes, while barium and strontium compounds will be visible as orange precipitates. An alternative and non-destructive method for the visualization of GSR patterns in shooting distance determination is an X-ray-fluorescence-system (XRF) equipped with mapping capabilities [8].

1. Materials and methods

1.1. Sample material

The sample sets were designed by the Bundeskriminalamt (BKA), and then printed at the Leibniz Institute for New Materials (INM) in Saarbrücken, Germany, using a screen printing method based on a German patent entitled "*Production of identical particle distribution images comprises visualizing a real lead particle distribution using a known chemographic method, and further processing*" [9]. The test samples consisted of a twill-cotton fabric of at least 20 cm × 20 cm in size which was screen printed with a latent lead-containing paste. The lead containing particles in the paste will display an intensely colored pattern when a test sample is treated with chemographic methods according to the participants' standard operating procedures for shooting distance determination by lead pattern visualization.

The GSR distributions on the test fabrics were obtained from real shots, fired from a Glock 19 semi-automatic pistol and using Geco caliber 9 mm × 19 FMJ ammunition.

For each distance, multiple shots were taken at the same distance to ensure reproducibility, and the most representative shot was chosen for further processing. The GSR patterns were transferred from the fabric to photo paper and visualized by the rhodizonate method as applied by the BKA. The patterns were digitally scanned as color images and thereafter rasterized via Adobe Photoshop in several image processing steps. To improve the visual impression, the samples were screen-printed in a 2-step process using two different lead compounds in order to mimic different levels of saturation. Each print was checked by milli-XRF with elemental mapping capabilities to ensure the quality of the preparation process.

Each participating laboratory received 14 pieces of fabric (12 test shots and 2 case shots) containing lead distributions that mimic the lead distribution pattern of a particular shooting incident. The bullet hole, located in the middle of the sample, was marked by a black circle. Twelve samples were marked as test shot series with the corresponding shooting distance printed in black in the lower left corner. The other two samples were regarded as case shots and only labeled as "A" or "B" (see Fig. 1 for the 25 cm case shot).

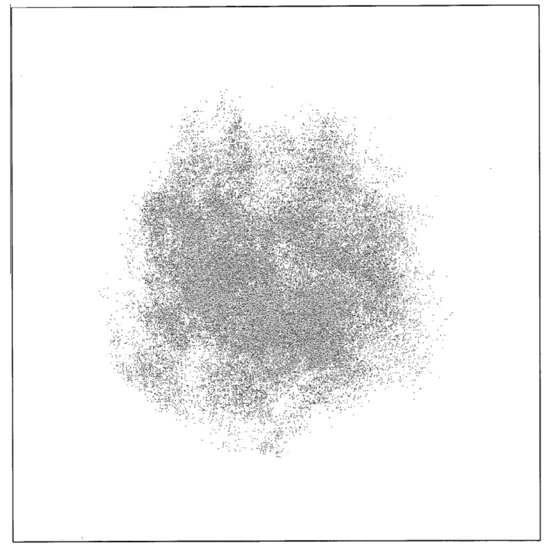

Fig. 1. Binary image of GSR pattern of case shot **A** (25 cm) as used for the screen printing.

1.2. Performance of the proficiency test

In total, 49 laboratories participated in this proficiency test, 45 of which returned results. Among them there were 40 ENFSI laboratories from 22 different countries and 5 laboratories from outside Europe.

The sample sets were shipped to the participating laboratories on 03 February 2015. They were accompanied by a color calibration chart, a test description, and a questionnaire. The completed questionnaire had to be returned by 20 March 2015 at the latest.

Each of the participating laboratories received an identical set of samples. The laboratories were asked to treat the samples analogously to real-life GSR-containing fabric samples and examine them according to the laboratory's standard procedure for chemographic investigations of GSR on fabric [2–4]. The participants were requested to indicate the shooting range for each of the two case shots using the 12 reference test shots. The 12 test shots were fired from distances of:

2, 5, 10, 15, 20, 30, 40, 60, 80, 100, 150, and 200 cm.

The shooting distances of the two case shots were:
25 cm (labeled in this publication as **case shot A**), and
50 cm (labeled in this publication as **case shot B**).

Based on the experience of the first collaborative study with this test sample performed by a small number of participants [10], the participants were asked to categorize their analytical findings in tables provided in the questionnaire (see Table 1). This categorization is required in order to enable a further z score assessment (see for Section 2.3).

Therefore, the participants first were asked to rank each case shot between two neighboring test shots, based on the characteristic changes of GSR patterns with increasing distance. Hereinafter the result of this task is referred to as the *analytical result of the best allocation to a shooting distance class*.

Secondly, for each case shot, the participants had to estimate the shooting range by providing a minimum and maximum shooting distance taking into account the variability of GSR patterns of shots at the same distance. Hereinafter the result of this task is referred to as the analytical result of the *estimated range of the case shot distance*. This would represent the estimated range for the corresponding case shot (A or B) as being stated in the forensic expert's opinion report.

The participating laboratories who submitted their results within the deadline are listed in Table 2. In this study all participants used a chemical method for the visualization of the lead pattern, except one who used milli-XRF with mapping capabilities.

2. Statistical evaluation

The statistical evaluation comprised on one hand the exploratory data analysis and on the other hand a statistically reliable assessment of the laboratory's performance. The evaluation was applied to both case shots and both analytical results, separately.

Table 1
Categorization of the analytical results as reported by the participants: (a) Ranking of the case shot between two neighboring test shots. (b) Estimating the shooting distance (min to max distance) using the provided test shot distances. Table shows a typical assessment as reported by the participants (submitted allocations are marked with X).

Case shot A	2–5 cm	5–10 cm	10–15 cm	15–20 cm	20–30 cm	30–40 cm	40–60 cm	60–80 cm	80–100 cm	100–150 cm	150–200 cm
Rank					**X**						

Case shot A	2 cm	5 cm	10 cm	15 cm	20 cm	30 cm	40 cm	60 cm	80 cm	100 cm	150 cm	>200 cm
Min. distance					**X**							
Max. distance						**X**						

Table 2
List of participating forensic institutes (FDSD 2015).

	Laboratory/Institute	Country
1	National Bureau of Expertises, SNPO	Armenia
2	Australian Federal Police	Australia
3	Forensic Science South Australia	Australia
4	Bundeskriminalamt/Büro f. Kriminaltechnik	Austria
5	National Institute of Criminalistics and Criminology (INCC)	Belgium
6	Research Institute of Forensic Science and Criminology	Bulgaria
7	Forensic Science Centre Zagreb	Croatia
8	Institute of Criminalistics Prague	Czech Republic
9	Estonian Forensic Science Institute/Chemistry Department	Estonia
10	National Bureau of Investigation	Finland
11	LPS Marseille/INPS	France
12	Bayrisches Landeskriminalamt, Kriminaltechnisches Institut, SG 207	Germany
13	Bundeskriminalamt/Lab I	Germany
14	Bundeskriminalamt/Lab II	Germany
15	Hessisches Landeskriminalamt/FB 611	Germany
16	Landeskriminalamt Sachsen-Anhalt/Abteilung 2 – Kriminaltechnik	Germany
17	Landeskriminalamt Schleswig–Holstein/SG 431	Germany
18	LKA Baden-Württemberg	Germany
19	LKA Brandenburg	Germany
20	LKA Mecklenburg-Vorpommern	Germany
21	LKA Nordrhein-Westfalen/TD 51.1 – Schussspuren	Germany
22	LKA Rheinland-Pfalz	Germany
23	LKA Sachsen	Germany
24	Polizei Hamburg/LKA 33	Germany
25	Forensic Science Northern Ireland	Great Britain
26	Key Forensic Services Ltd/University of Warwick Science Park	Great Britain
27	Arma Carabinieri – RIS Parma	Italy
28	Reparto Carabinieri Investigazioni Scientifiche di Cagliari	Italy
29	Forensic Center of Montenegro	Montenegro
30	Netherlands Forensic Institute	Netherlands
31	Central Forensic Laboratory of the Police/Chemistry Department	Poland
32	Forensic Science Center MIA Russia	Russia
33	Russian Federal Center of Forensic Science (RFCFS)	Russia
34	Institute of Forensic Sciences	Slovakia
35	National Forensic Laboratory	Slovenia
36	Comisaria General Policia Cientifica	Spain
37	Dirección General de la Policía y de la Guardia Civil	Spain
38	Instituto Nacional de Toxicología y Ciencias Forenses	Spain
39	Scientific Police Division – Mossos d'Esquadra	Spain
40	Swedish National Forensic Centre (NFC)	Sweden
41	Forensisches Institut Zürich/Kriminaltechnik/Schusswaffen	Switzerland
42	Kantonspolizei St. Gallen	Switzerland
43	Albuquerque Police Department Crime Lab	United States
44	San Diego County Sheriff's Department – Regional Crime Laboratory	United States
45	Washington State Patrol/Crime Lab Division – Seattle	United States

The assessment was not based on the original distances reported by the participating laboratories, but on assigned classes. The analytical results of the participants were assigned to classes from 1 to 12. On the basis of the obtained classes the reproducibility standard deviation – as measure of the variability between single results obtained in different laboratories – was computed using robust statistics. The reproducibility standard deviation provided the basis for calculating z scores in order to assess the laboratory's performance.

The evaluation was performed using the software package PROLab Plus 2015 [11], which is widely employed for the evaluation of methods, interlaboratory tests, and laboratory proficiency tests.

2.1. Data basis

For case shot A all 45 laboratories reported permissible analytical results as required in the test instructions. For case shot B 43 analytical results of the *best allocation to a shooting distance class*, and 44 analytical results of the *estimated range of the case shot distance* were used. One laboratory reported an impermissible range from 30 to 100 cm as result for the best allocation to a shooting distance class and one laboratory could not determine this case shot due to sensitivity problems for test shots greater than 40 cm. As an overview, all reported analytical results for both case shots are displayed in Table 3, including also the corresponding evaluated z scores assessments (see Section 2.3).

2.2. Explorative analysis

According to the instructions, the participating laboratories were asked to indicate the shooting range for each case shot GSR pattern using the 12 test shots and their distance specifications in centimeters. First, the participants had to rank each case shot between two neighboring comparison shots (see Table 1a) and secondly, the participants had to estimate the shooting range for each of the case shots by providing a minimum and maximum shooting distance (see Table 1b). The statistical evaluation was applied to both analytical results.

For the '*best allocation to a shooting distance class*', the case shot A was correctly ranked if the range 20–30 cm was chosen, and the case shot B was correctly ranked if the range 40–60 cm was chosen.

For the '*estimated range of the case shot distance*', the ranges were correctly estimated if:

(1) the minimum shooting distance was less than the actual shooting distance and
(2) the maximum shooting distance was greater than the actual shooting distance.

Accordingly, the submitted results for both the minimum and maximum distances were taken into account for the assessment of the performance of the laboratories.

Table 3
Analytical results reported by each laboratory (cm), assigned class for calculating z score (cl.) and z score assessment (z) for both case shots and both analytical results. A questionable and unsatisfactory z score is marked in yellow and red, respectively.

Lab code	Analytical result of best allocation to a shooting distance class						Analytical result of the estimated range of the case shot distance											
	case shot A (25 cm)			case shot B (50 cm)			case shot A (25 cm)						case shot B (50 cm)					
							lower limit			upper limit			lower limit			upper limit		
	cm	cl.	z	cm	cl.	z	cm	cl.	z	cm	cl.	z	cm	cl.	z	cm	cl.	z
107	15 - 20	4	-1.6	30 - 40	6	-1.5	15	4	-1.3	30	6	0.0	30	6	-1.6	60	8	0.0
114	15 - 20	4	-1.6	30 - 40	6	-1.5	15	4	-1.3	30	6	0.0	30	6	-1.6	60	8	0.0
153	20 - 30	5	0.0	30 - 40	6	-1.5	20	5	0.0	30	6	0.0	30	6	-1.6	40	7	-3.0
189	20 - 30	5	0.0	30 - 40	6	-1.5	20	5	0.0	30	6	0.0	30	6	-1.6	40	7	-3.0
190	20 - 30	5	0.0	30 - 40	6	-1.5	20	5	0.0	30	6	0.0	30	6	-1.6	40	7	-3.0
214*	**20 - 30**	**5**	**0.0**	**40 - 60**	**7**	**0.0**	**20**	**5**	**0.0**	**30**	**6**	**0.0**	**30**	**6**	**-1.6**	**60**	**8**	**0.0**
222	20 - 30	5	0.0	30 - 40	6	-1.5	20	5	0.0	30	6	0.0	30	6	-1.6	40	7	-3.0
228	20 - 30	5	0.0	40 - 60	7	0.0	15	4	-1.3	30	6	0.0	30	6	-1.6	60	8	0.0
246	2 - 5	1	-6.4	60 - 80	8	1.5	2	1	-5.1	5	2	-6.5	60	8	3.0	200	12	5.7
258	20 - 30	5	0.0	40 - 60	7	0.0	15	4	-1.3	40	7	1.6	30	6	-1.6	80	9	1.4
264	20 - 30	5	0.0	40 - 60	7	0.0	15	4	-1.3	40	7	1.6	30	6	-1.6	60	8	0.0
286	15 - 20	4	-1.6	30 - 40	6	-1.5	15	4	-1.3	30	6	0.0	30	6	-1.6	40	7	-3.0
290	20 - 30	5	0.0	30 - 40	6	-1.5	20	5	0.0	30	6	0.0	30	6	-1.6	40	7	-3.0
313	15 - 20	4	-1.6	20 - 30	5	-2.9	15	4	-1.3	20	5	-3.0	20	5	-3.3	40	7	-3.0
323	20 - 30	5	0.0	30 - 40	6	-1.5	15	4	-1.3	30	6	0.0	30	6	-1.6	60	8	0.0
330	20 - 30	5	0.0	40 - 60	7	0.0	20	5	0.0	40	7	1.6	40	7	0.0	60	8	0.0
341	15 - 20	4	-1.6	20 - 30	5	-2.9	15	4	-1.3	20	5	-3.0	20	5	-3.3	40	7	-3.0
355	20 - 30	5	0.0	40 - 60	7	0.0	20	5	0.0	30	6	0.0	30	6	-1.6	60	8	0.0
376	20 - 30	5	0.0	30 - 40	6	-1.5	15	4	-1.3	40	7	1.6	20	5	-3.3	60	8	0.0
399	20 - 30	5	0.0	40 - 60	7	0.0	15	4	-1.3	30	6	0.0	30	6	-1.6	60	8	0.0
422	15 - 20	4	-1.6	40 - 60	7	0.0	15	4	-1.3	30	6	0.0	30	6	-1.6	60	8	0.0
427	15 - 20	4	-1.6	30 - 40	6	-1.5	10	3	-2.6	30	6	0.0	30	6	-1.6	60	8	0.0
456	20 - 30	5	0.0	40 - 60	7	0.0	20	5	0.0	30	6	0.0	40	7	0.0	60	8	0.0
498	15 - 20	4	-1.6	30 - 40	6	-1.5	15	4	-1.3	30	6	0.0	30	6	-1.6	60	8	0.0
513	20 - 30	5	0.0	30 - 40	6	-1.5	10	3	-2.6	30	6	0.0	30	6	-1.6	40	7	-3.0
525	20 - 30	5	0.0	40 - 60	7	0.0	20	5	0.0	40	7	1.6	40	7	0.0	60	8	0.0
545	20 - 30	5	0.0	40 - 60	7	0.0	15	4	-1.3	40	7	1.6	30	6	-1.6	60	8	0.0
577	20 - 30	5	0.0	40 - 60	7	0.0	15	4	-1.3	30	6	0.0	40	7	0.0	80	9	1.4
583	20 - 30	5	0.0	40 - 60	7	0.0	20	5	0.0	30	6	0.0	30	6	-1.6	60	8	0.0
584	20 - 30	5	0.0	40 - 60	7	0.0	20	5	0.0	30	6	0.0	40	7	0.0	60	8	0.0
590	20 - 30	5	0.0	30 - 40	6	-1.5	20	5	0.0	30	6	0.0	30	6	-1.6	40	7	-3.0
601	30 - 40	6	1.6	40 - 60	7	0.0	2	1	-5.1	40	7	1.6	30	6	-1.6	60	8	0.0
623	20 - 30	5	0.0	-	-	-	20	5	0.0	30	6	0.0	30	6	-1.6	100	10	2.8
627	15 - 20	4	-1.6	30 - 40	6	-1.5	15	4	-1.3	30	6	0.0	30	6	-1.6	60	8	0.0
653	15 - 20	4	-1.6	30 - 40	6	-1.5	10	3	-2.6	30	6	0.0	20	5	-3.3	60	8	0.0
664	20 - 30	5	0.0	30 - 40	6	-1.5	15	4	-1.3	30	6	0.0	30	6	-1.6	60	8	0.0
671	30 - 40	6	1.6	40 - 60	7	0.0	20	5	0.0	40	7	1.6	30	6	-1.6	60	8	0.0
702	20 - 30	5	0.0	40 - 60	7	0.0	20	5	0.0	30	6	0.0	30	6	-1.6	60	8	0.0
717	20 - 30	5	0.0	40 - 60	7	0.0	20	5	0.0	30	6	0.0	40	7	0.0	60	8	0.0
734	20 - 30	5	0.0	40 - 60	7	0.0	15	4	-1.3	30	6	0.0	40	7	0.0	80	9	1.4
738	20 - 30	5	0.0	30 - 40	6	-1.5	20	5	0.0	30	6	0.0	30	6	-1.6	40	7	-3.0
798	20 - 30	5	0.0	40 - 60	7	0.0	20	5	0.0	40	7	1.6	30	6	-1.6	60	8	0.0
801	20 - 30	5	0.0	-	-	-	20	5	0.0	30	6	0.0	-	-	-	-	-	-
807	20 - 30	5	0.0	30 - 40	6	-1.5	20	5	0.0	30	6	0.0	30	6	-1.6	60	8	0.0
811	15 - 20	4	-1.6	40 - 60	7	0.0	15	4	-1.3	40	7	1.6	30	6	-1.6	60	8	0.0

*Lab #214 used elemental mapping by milli-XRF instead of a chemographic method.

2.2.1. Analytical results of the 'best allocation to a shooting distance class'

In total, 31 out of 45 participants (≈69%) ranked the shot A correctly between 20 and 30 cm and 21 out of 43 participants (≈49%) ranked the case shot B correctly between 40 and 60 cm. Seventeen out of 43 participants (≈40%) ranked both case shots correctly. Fig. 2 shows a graphical representation of all reported analytical results.

2.2.2. Analytical results of the 'estimated range of the case shot distance'

For case shot A, a total of 42 out of 45 laboratories (≈93%) indicated a shooting range which includes the true distance of 25 cm. Three laboratories indicated a maximum shooting distance less than 25 cm. In total, 17 laboratories (≈40%) indicated the smallest possible range from 20 to 30 cm. Fig. 2 shows a graphical representation of the estimated ranges of case shot A of all participating laboratories.

For case shot B, 32 out of 44 laboratories (≈73%) indicated a shooting range which includes the true distance of 50 cm. Eleven laboratories ranked case shot B less than 50 cm, in fact 2 laboratories indicated a range from 20 to 40 cm and 9 laboratories indicated a range from 30 to 40 cm. In contrast, one laboratory indicated a minimum shooting distance larger than 50 cm with a range from 60 to 200 cm. In total, 5 laboratories indicated the smallest possible range from 40 to 60 cm. The reported estimated ranges of case shot B of all participants are also shown in Fig. 2.

2.3. Assessment of laboratories' performance based on their analytical results

In order to guarantee a statistically reliable evaluation, the analytical results were assigned to the so-called classes. Regarding the analytical results of the best allocation to a shooting distance class, the 12 pairs of neighboring test shots were sorted in

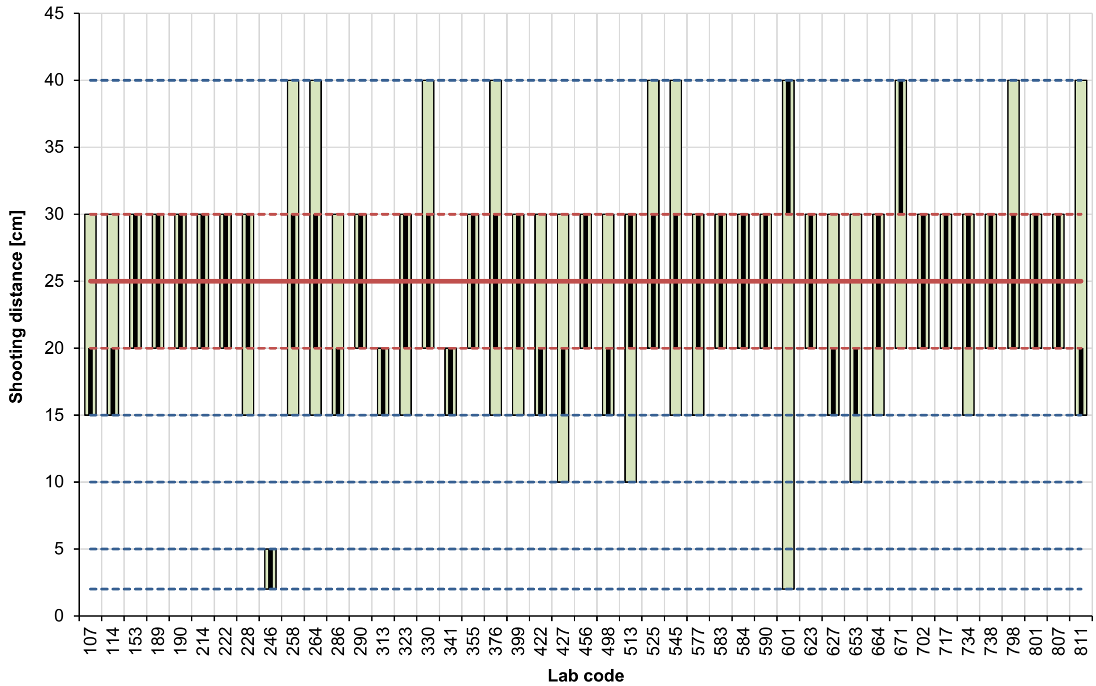

Fig. 2a. Analytical results reported by participants for the case shot A (25 cm). The black bars represent the analytical results for the best allocation to a shooting distance and the green bars represent the analytical results for the estimated range of the case shot distance. (red line: shooting distance of case shot, dashed lines: shooting distances of test shots).

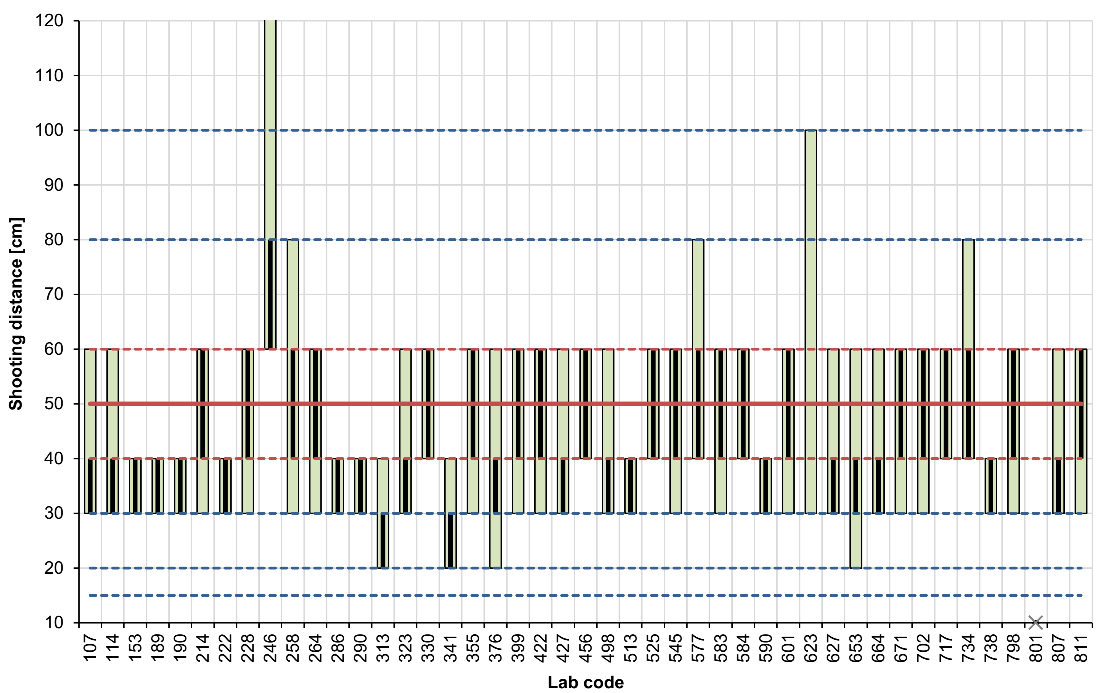

Fig. 2b. Analytical results reported by participants for case shot B (the 50 cm). The black bars represent the analytical results for the best allocation to a shooting distance and the green bars represent the analytical results for the estimated range of the case shot distance (red line: shooting distance of case shot, dashed lines: shooting distances of test shots). #623 did not submit analytical results for the best allocation to a shooting distance class and #801 did not submit both analytical results. The upper limit of #246 is 200 cm.

ascending order and consecutively numbered starting with 1. The resulting classes are summarized in Table 4. The correct assigned class for the case shots A and B are class 5 and class 7, respectively.

The analytical results of the estimated range of the case shot distance were assessed by taking into account the lower limit (minimum shooting distance) on the one hand and the upper limit (maximum shooting distance) on the other hand. Both, the lower limit and the upper limit, were assigned to classes. For this purpose, the shooting distances of the 12 test shots were sorted in ascending order and consecutively numbered starting with 1. The resulting classes are also summarized in Table 4.

Table 4
Classes introduced for the statistical evaluation of the analytical results. Correct assigned classes are highlighted in **gray**.

Assigned class	Analytical result of best allocation to a shooting distance class	Lower and upper limit of analytical result of the estimated range
# 1	2 – 5 cm	2 cm
# 2	5 – 10 cm	5 cm
# 3	10 – 15 cm	10 cm
# 4	15 – 20 cm	15 cm
# 5	**20 – 30 cm**	**20 cm**
# 6	30 – 40 cm	**30 cm**
# 7	**40 – 60 cm**	**40 cm**
# 8	60 – 80 cm	**60 cm**
# 9	80 – 100 cm	80 cm
# 10	100 – 150 cm	100 cm
# 11	150 – 200 cm	150 cm
# 12	more than 200 cm	200 cm

Table 5
Assigned values and standard deviations for proficiency assessment for both case shots and both analytical results.

Case shot	Analytical results	Assigned value (assigned class)	S.d. for proficiency assessment
A (25 cm)	Best allocation to a shooting distance class	# 5	0.63
	Lower limit of the estimated range of case shot distance	# 5	0.78
	Upper limit of the estimated range of case shot distance	# 6	0.61
B (50 cm)	Best allocation to shooting distance class	# 7	0.69
	Lower limit of the estimated range of case shot distance	# 7	0.61
	Upper limit of the estimated range of case shot distance	# 8	0.71

The assessment was not based on the absolute values of the reported shooting ranges but on the assigned classes. The laboratory's performance was assessed using z scores according to ISO 13528 and EURACHEM [6,12–14]. In general, z scores describe the standardized deviation of the laboratory's result from the assigned value. The z scores were calculated for each case shot and each analytical result according to the equation:

$$z = \frac{\text{Participant's result (i.e. the assigned class)} - \text{Assigned value}}{\text{Standard deviation for proficiency assessment}}$$

The assigned values were defined as the class of the correct and smallest possible classification of the case shot, i.e. concerning the analytical results of the *best allocation to a shooting distance class* the assigned value is 5 (20–30 cm) for case shot A and 7 (40–60 cm) for case shot B, and concerning the analytical results of the *estimated range of the case shot distance* the assigned values are 5 (20 cm) and 6 (30 cm) for the lower and upper limit of case shot A, respectively as well as 7 (40 cm) and 8 (60 cm) for the lower and upper limit of case shot B, respectively.

The reproducibility standard deviation was used as standard deviation for proficiency assessment. All analytical results reported by the participating laboratories were assigned to classes and then the reproducibility standard deviation across all classes obtained was calculated. The calculation was carried out by the robust statistical "Q-method" [15] according to DIN 38402 A45 [16]. The robust method was selected in order to take into account the discrete nature of the assigned classes and to minimize the effect of potential outliers. The reproducibility standard deviation characterizes the variability of the data under reproducibility conditions, i.e. test results are obtained with the same method on identical test items in different laboratories with different operators using different equipment or materials.

A summary of the defined assigned values and obtained reproducibility standard deviations is given in Table 5, separately for both case shots and both analytical results.

For the 'analytical results of the best allocation to a shooting distance class' a laboratory's result is

- **satisfactory**, if the absolute value of the z score is smaller than 2;
- **questionable**, if the absolute value of the z score lies between 2 and 3;
- **unsatisfactory**, if the absolute value of the z score is greater than 3.

In principle, the same assessment applies to the analytical result of the estimated range of the case shot distance. However, a laboratory's result is assessed as unsatisfactory if the estimated range does not include the case shot. If the lower limit exceeds the shooting distance of the case shot, then there is an unsatisfactory assessment for the lower limit. If the upper limit falls below the shooting distance of the case shot, then there is an unsatisfactory assessment for the upper limit.

It therefore follows that for the lower limit a laboratory's result is

- **satisfactory**, if the z score lies between −2 and 0;
- **questionable**, if the z score lies between −3 and −2;
- **unsatisfactory**, if the z score is greater than 0 or less than −3,

and for the upper limit a laboratory's result is

- **satisfactory**, if the z score lies between 0 and 2;
- **questionable**, if the z score lies between 2 and 3;
- **unsatisfactory**, if the z score is less than 0 or greater than 3.

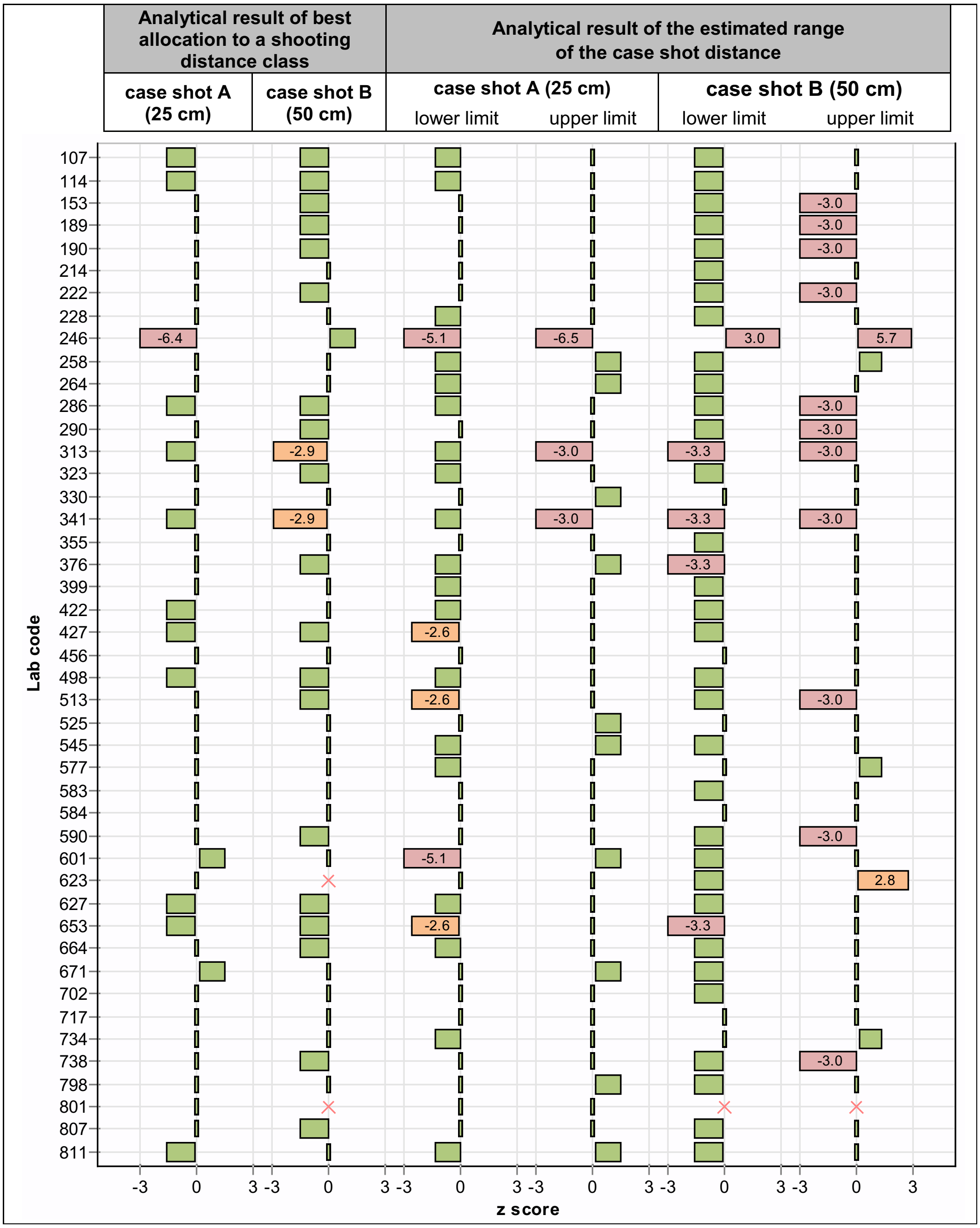

Fig. 3. z scores of all participants for both case shots and both analytical results. Questionable and unsatisfactory results are marked in orange and red, resp., green bars (z = 0) and green boxes represent satisfactory results. A cross represents no reported results.

Table 6
Percentage of participating laboratories who achieved satisfactory, questionable or unsatisfactory results for the best allocation to a shooting distance class for each case shot (in brackets: total number of labs).

Case shot	Satisfactory	Questionable	Unsatisfactory	No results
A (25 cm)	98% (44 labs)	0	2% (1 lab)	–
B (50 cm)	95% (41 labs)	5% (2 labs)	0	(2 labs)

2.4. Assessment of the analytical results of the 'best allocation to a shooting distance class'

According to the calculated reproducibility standard deviations (see Table 5), a laboratory obtained a satisfactory assessment (|z score| < 2) if it ranked the case shot A between 15 and 40 cm and the case shot B between 30 and 80 cm.

The z score assessments of all participating laboratories are displayed in Table 3 and Fig. 3. In total, 40 out of 43 laboratories obtained for both case shots a satisfactory z score. One laboratory

Table 7
Assessment of the analytical results of the best allocation to a shooting distance class. Satisfactory, questionable, and unsatisfactory results are shaded in green, yellow, and red, resp. The number of laboratories, who indicated this distance class, is shown in brackets.

Assigned class	Analytical result of best allocation to a shooting distance class	case shot A (25 cm)	case shot B (50 cm)
# 1	2 - 5 cm	unsatisfactory (1)	unsatisfactory (0)
# 2	5 - 10 cm	unsatisfactory (0)	unsatisfactory (0)
# 3	10 - 15 cm	unsatisfactory (0)	unsatisfactory (0)
# 4	15 - 20 cm	satisfactory (11)	unsatisfactory (0)
# 5	20 - 30 cm	satisfactory (31)	questionable (2)
# 6	30 - 40 cm	satisfactory (2)	satisfactory (19)
# 7	40 - 60 cm	unsatisfactory (0)	satisfactory (21)
# 8	60 - 80 cm	unsatisfactory (0)	satisfactory (1)
# 9	80 - 100 cm	unsatisfactory (0)	questionable (0)
# 10	100 - 150 cm	unsatisfactory (0)	unsatisfactory (0)
# 11	150 - 200 cm	unsatisfactory (0)	unsatisfactory (0)

Table 8
Assessment of the analytical results of the estimated range of the case shot distance. Satisfactory, questionable, and unsatisfactory results are shaded in green, yellow, and red, resp. The number of laboratories, who indicated this assigned class, is shown in brackets.

Assigned class	Test shot distance	case shot A (25 cm)		case shot B(50 cm)	
		Lower limit	Upper limit	Lower limit	Upper limit
# 1	2 cm	unsatisfactory (2)	unsatisfactory (0)	unsatisfactory (0)	unsatisfactory (0)
# 2	5 cm	unsatisfactory (0)	unsatisfactory (1)	unsatisfactory (0)	unsatisfactory (0)
# 3	10 cm	questionable (3)	unsatisfactory (0)	unsatisfactory (0)	unsatisfactory (0)
# 4	15 cm	satisfactory (19)	unsatisfactory (0)	unsatisfactory (0)	unsatisfactory (0)
# 5	20 cm	satisfactory (21)	unsatisfactory (2)	unsatisfactory (4)	unsatisfactory (0)
# 6	30 cm	unsatisfactory (0)	satisfactory (32)	satisfactory (32)	unsatisfactory (0)
# 7	40 cm	unsatisfactory (0)	satisfactory (10)	satisfactory (7)	unsatisfactory (11)
# 8	60 cm	unsatisfactory (0)	unsatisfactory (0)	unsatisfactory (1)	satisfactory (28)
# 9	80 cm	unsatisfactory (0)	unsatisfactory (0)	unsatisfactory (0)	satisfactory (3)
# 10	100 cm	unsatisfactory (0)	unsatisfactory (0)	unsatisfactory (0)	questionable (1)
# 11	150 cm	unsatisfactory (0)	unsatisfactory (0)	unsatisfactory (0)	unsatisfactory (0)
# 12	200 cm	unsatisfactory (0)	unsatisfactory (0)	unsatisfactory (0)	unsatisfactory (1)

Table 9
Percentage of participating laboratories who achieved satisfactory, questionable or unsatisfactory results for each case shot and each limit of the estimated range of the case shot distance (in brackets: total number of labs).

Case shot	Limit	Satisfactory	Questionable	Unsatisfactory	No results
A (25 cm)	Lower limit	89% (40 labs)	7% (3 labs)	4% (2 labs)	–
	Upper limit	93% (42 labs)	0%	7% (3 labs)	–
B (50 cm)	Lower limit	89% (39 labs)	0%	11% (5 labs)	(1 lab)
	Upper limit	70% (31 labs)	2% (1 lab)	27% (12 labs)	(1 lab)

ranked case shot A significantly too low and thus, obtained an unsatisfactory z score. Two laboratories obtained a questionable z score for case shot B. The laboratories which had not submitted any results for case shot B, ranked the case shot A (25 cm) satisfactorily. The total number and the relative value of satisfactory, questionable, and unsatisfactory results across all laboratories are given in Table 6.

For both case shots a satisfactory assessment is ensured if a laboratory ranked the case shot each one class below and one class above the correct class. If a laboratory ranked the case shot B (50 cm) two classes below the correct class (20–30 cm) and two classes above the correct class (80–100 cm) the laboratory obtained a questionable assessment ($2 \leqslant |z \text{ score}| \leqslant 3$). Table 7 summarizes the resulting assessments.

2.5. Assessment of the analytical results of the 'estimated range of the case shot distance'

According to the calculated reproducibility standard deviations, a laboratory obtained a satisfactory assessment ($|z \text{ score}| < 2$) when indicating 15 or 20 cm as lower limit and 30 or 40 cm as upper limit for case shot A. For case shot B, there is a satisfactory assessment, when 30 or 40 cm was indicated as lower limit and 60 or 80 cm as upper limit. The resulting assessments are given for each test shot in Table 8.

The total number and the relative value of satisfactory, questionable and unsatisfactory results across all laboratories are given in Table 9.

Fig. 3 shows the z score – assessments of all participating laboratories, regarding the *analytical results of the estimated range* of the two case shots. In total, 27 out of 44 laboratories (≈61%) obtained satisfactory z scores for both lower limits and both upper limits. One laboratory obtained unsatisfactory z scores for both case shots and both limits. This laboratory ranked the case shot A between 2 and 5 cm and the case shot B between 60 and 200 cm. For case shot A, one laboratory indicated 2 cm as lower limit which is significantly too low. For case shot B (50 cm) four laboratories obtained an unsatisfactory assessment indicating 20 cm as lower limit. The reported value of 20 cm is too low compared to the variability of the data under reproducibility conditions. The unsatisfactory assessments for the upper limit of case shot B are due to the fact that the estimated range reported by the participants does not include the true shooting distance of this case shot.

3. Discussion and conclusions

Based on the analytical results of the *best allocation to a shooting distance class* the case shot A (25 cm) was ranked by 42 out of 45 laboratories (≈93 %) between 15 cm and 30 cm, whereas approximately two out of three laboratories ranked the case shot A (25 cm) correctly between 20 cm and 30 cm and approximately one out of three laboratories between 15 cm and 20 cm. The case shot B (50 cm) was ranked by 40 out of 43 laboratories (≈93%) between 30 cm and 60 cm, whereas approximately 50% of these laboratories ranked the case shot B (50 cm) correctly between 40 cm and 60 cm and the other 50% between 30 cm and 40 cm.

Based on the analytical results of the *estimated range of the case shot distance*, for case shot A (25 cm) the indicated shooting range included the true distance of 25 cm in 42 out of 45 cases (93%), but for case shot B (50 cm), the indicated shooting range included the true distance of 50 cm in only 32 out of 44 cases (≈73%). In total, 11 laboratories ranked the case shot B (50 cm) lower than 50 cm.

Hence, a tendency toward an underassessment of the larger distance case shot (i.e. case shot B) was observed (24% of the participants). This tendency was not observed for the lower distance case shot (i.e. case shot A). Nevertheless, the classification of one class below and one class above the correct value lies within an acceptable tolerance for these two specific case shots, as shown from the reproducibility standard deviation.

Moreover taking into consideration the wording of the conclusions in the reports by the experts, it has to be noted that some laboratories report safer margins in real case work than those submitted in this proficiency test.

Further studies have to verify whether the potential underassessment is due to the visualization process of the chemographical method used in the laboratory or due to the subjective classification by the expert. This will be an issue of further discussions and investigations. In order to enable the discussion all laboratories received the anonymized data, method description and images of the chemographic test results of each participating laboratory.

It should be noted that this proficiency test on shooting distance determination only covers one aspect that forensic laboratories can use when estimating the shooting distance – the chemographic coloring of lead distributions. Other observations like traces of soot or powder particles are usually also taken into account when estimating the shooting distance. To some extent, this fact limits the relevance of this proficiency test regarding the assessment of the results which should be better when considering all available information.

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