First lessons regarding the data analysis of gunshot residue traces at activity level in TTADB

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Abstract

Gunshot residues (GSR) are of interest whenever a crime involves the discharge of a firearm. They do not only inform about their source, but also about the suspect's implication. In order to assess the existing knowledge on GSR in the literature and contribute to the creation of a structured database on transfer traces at the activity level, studies focusing on transfer, persistence, background, population and detection of GSR in various scenarios and on different supports were analyzed, with a critical assessment in a Canadian context. This research establishes a review of the current knowledge identifies gaps in the literature and therefore suggests future research to be undertaken.

RÉSUMÉ

Les résidus de tir sont d'intérêt chaque fois qu'un crime implique la décharge d'une arme à feu. Ils peuvent non seulement informer sur leur source, mais aussi sur l'implication du suspect. Afin d'évaluer l'état des connaissances sur les résidus de tir et de contribuer à la création d'une base de données structurée sur les traces de transfert au niveau de l'activité, des études axées sur le transfert, la persistance, le bruit de fond, la population et la détection des résidus de tirs, dans divers scénarios et avec différents supports, ont été analysées avec une évaluation critique dans un contexte canadien. Cette recherche offre une revue des connaissances actuelles, identifie de potentielles lacunes dans la littérature et suggère de futures recherches à entreprendre.

Keywords: Gunshot residues (GSR); background; transfer; persistence; interpretation

MOTS CLÉS: Résidus de tir; Bruit de fond; Transfert; Persistance; Interprétation

Introduction

Besides identification traces on ammunition components and the firearm itself, forensic firearms analysis also addresses gunshot residues that are available transfer traces resulting from the discharge of a firearm, which can provide information on the suspect's and victim's interaction and implications. The term gunshot residues (GSR) include primer residues, powder residues, smoke, and metal residues from the projectile, casing and firearm. They may be composed of burnt, partially burnt or unburnt particles, or a mixture of all three. During a firearm discharge, GSR are expelled into the environment from the barrel in a conical cloud and from the various opening of the firearm (e.g., chamber, ejection port and slide action). There are two main classes of GSR: inorganic gunshot residues (IGSR) and organic gunshot residues (OGSR). IGSR are essentially made up of heavy metals (e.g., lead, barium and antimony) and come from the primers of the cartridges. OGSR come from the gunpowder and are mainly composed of smokeless powder additives, nitrocellulose and its degradation products which are nitrate compounds (i.e., nitrates and nitrites) [1–3].

Chemical composition and morphology of GSR as well as their spatial distribution can be studied in order, among other things, to estimate the shooting distance and to infer whether a person fired or not [4]. However, the interpretation of GSR faces many challenges since several factors may influence their transfer, distribution, persistence, and recovery. These factors include shooting distance; type, make and model of the firearm; composition, type and amount of powder in the cartridge; barrel length; angle of fire; atmospheric conditions; and target composition and texture. In addition, GSR are highly susceptible to transfer between surfaces or individuals upon contact, which sometimes results in loss, contamination, or cross-transfer [1, 2, 5]. In practice, it is very difficult to assess the influence of each of these factors individually, which may raise many questions in Court about the value of this type of trace evidence [1, 2]. A transparent interpretation of the results is therefore a critical but necessary approach.

Many studies are still being carried out on GSR, particularly on transfer and on new instrumental methods of analysis and detection. Several reviews have focused on the analysis and collection of GSR as well as on various mechanisms important to the activity level during the last decade [6–10]. The purpose of this paper is to establish the current knowledge on the interpretation of GSR at activity level, identify gaps in the literature and suggest future research to be undertaken, particularly in a Canadian context, based on the documents stored in the Transfer Traces at Activity level Database (TTADB) [11].

Materials and methods

The methodology to feed the TTADB is largely influenced by the procedures proposed in Khan et al. [12] and in Petticrew and Roberts [13]. The initial work began with studies cited in previous literature reviews and digests on the topic of interest, such as the INTERPOL International Forensic Science Managers Symposium Review papers (https://www.interpol.int/en/How-we-work/Forensics/Forensic-Symposium). Findings were completed by using ScienceDirect™, ResearchGate™ and Google Scholar™ to identify other relevant studies published in journals dedicated to forensic science, but also in other fields such as chemistry, physics, biology and/or mathematics. Taking advantage of the automated suggestion system of the ScienceDirect™ platform,[1] proposed articles were systematically and iteratively consulted until saturation, that is, until the automated search system no longer suggested new articles. Moreover, since this initial research, which started in 2016, a Google Scholar™ alert routine has been put in place for each type of traces to ensure the continuous supply of the TTADB with newly published studies or with studies that have not been identified by the initial strategies. It allowed to analyze peer-reviewed (e.g., books, articles) and non-peer-reviewed published studies (e.g., theses, research reports), as well as non-published studies (e.g., internal laboratory studies, theses), between 1940 and 2020 that were related to the interpretation of trace evidence at activity level.

The search for studies was primarily conducted in English, but it also covered studies in French to consider Canada's two official languages. Keywords used for the searches can be grouped in three categories: trace evidence terms (such as gunshot residues, GSR, organic, inorganic), type of study terms (such as persistence, transfer, population, pattern, detection, background levels, probabilistic model, methods, etc.) and interpretation terms (such as activity, source, likelihood ratio, Bayesian, evidential value). The inclusion criteria included the presence of one or more keywords previously mentioned in the title and a focus on activity level, identified by an overview of the summary, the introduction and the conclusions expressed in the paper. Non-published studies were also retrieved through privileged contacts with universities offering a program in forensic science and with Canadian laboratories or researchers through contacts made at national and international conferences. As of December 14, 2020, this process led to the identification of 213 relevant papers on GSR interpretation at activity level, these having been added to the more general TTADB, completing it with a total of 2042 studies.[2]

An analysis of each paper to highlight the following characteristics was conducted: year of publication, author(s), country where the study was conducted, type of GSR, experimental conditions and type of study with the aim to assess and review what has been extensively and what remains to be done. This analysis also included a critical assessment of the relevance of the study in the Canadian context, namely the geographical, meteorological, legal, and social context. Once this analysis was completed, the data collected was added to the TTADB, a database open to forensic practitioners, scientists, and lawyers [11]. For this paper, GSR papers have also been classified through the type of firearm used in the study and the type of instrumental analysis method used with the aim to assess and review what has been extensively and what remains to be done. Building the TTADB allowed to identify various voids in the literature of GSR as well as to raise several relevant studies to be undertaken.

Results

A total of 213 studies relevant for GSR interpretation at activity level, ranging from 1940 to 2020, have been listed in the database. The number of scientific publications on GSR in the last decades is increasing (Table 1). It is mainly due to studies on detection and distribution (pattern), but also population and background studies for the last decade, as persistence and transfer of GSR ones seem constant in the literature.

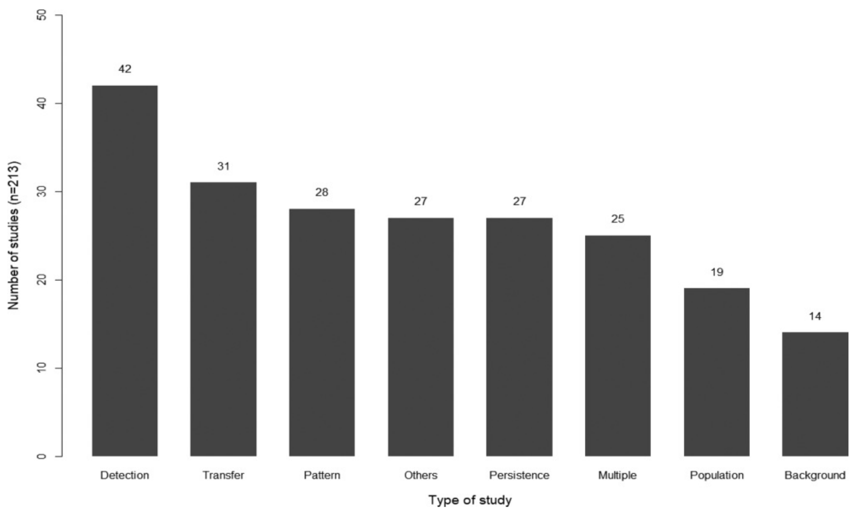
Table 1. The number of GSR studies listed by year of publication.

Year of publication	Number of studies listed
2016–2020	72
2011–2015	42
2006–2010	35
2001–2005	22
1996–2000	9
1991–1995	11
1986–1990	8
1981–1985	4
1976–1980	5
1971–1975	3
1940–1970	2

Year of publication	Number of studies listed
Total	**213**

Figure 1 shows a great variety in the type of studies, categorized for the purpose of the TTADB as transfer, population, distribution patterns, persistence, and detection. The "others" category in Figure 1 includes literature review studies, studies on the interpretation by statistical models and on the degradation/stability of GSR (e.g., on collection devices). In most cases, studies did not focus on a single aspect, but on a combination of several ones. For this reason, papers involving two types of studies (e.g., transfer and persistence) were classified according to their primary interest and papers involving three or more types of studies were classified as "multiple." With this subtlety understood, the number of studies on transfer traces increase from 31 to 45, and on persistence from 27 to 29, confirming their prevalence. Such studies respectively focus on determining the amount of GSR transferred to a person when a gunshot occurs and the period of time during which the particles stay on hands, face and clothing of the shooter [14–18]. They could also document the process of secondary transfer between individuals or between individuals and objects [19–21].

Figure 1. Classification of studies (n = 213) according to the type of study performed.



As shown in Figure 1, detection studies are the most frequent ones. The sampling surfaces typically used for GSR analyses are the hands, face and clothing of the suspected shooter. However, with these surfaces being potentially exposed to risks of secondary transfer and the delay between the discharge of a firearm by a suspect and their apprehension, some recent studies have explored the sample in the nostrils (mucus) [22–26]. The sampling of mucus, rather than on hands, seems less influenced by environmental contamination, and GSR seem to have longer persistence, which overcomes the basic limitations of other detection techniques. Nasal mucus samples have been compared to hand samples and they could eventually replace the current method in the coming years with further validation.

Figure 1 shows that several studies address GSR patterns (n = 28). Even if the interpretation of the results remains complex, it is essential at the activity level [27, 28]. Indeed, GSR pattern is complementary, even primordial to corroborate not only the presence of GSR (e.g., the globular shape of the lead-antimony-barium IGSR complex through scanning electron microscopy and atomic analysis as such as energy dispersive x-ray), but also to differentiate the hand which held the firearm (or the cheek of the rifle/shotgun shooter) from a cross transfer and thus inform on the role of everyone on the scene (e.g., shooter, accomplice, or witness). However, the results of these studies do not seem consistent about the differentiation of a shooter from a non-shooter. For example, a study by Lindsay et al. [27] shows the difficulty in predicting the loss of GSR on a person after shooting and that the distribution and the amount of GSR found on the hands of the shooter compared to those of a bystander vary enormously from one handgun to another (caliber, mechanism, etc.). This can make difficult, if not impossible, to distinguish the shooter from a witness, especially when the number of particles detected is low. As another example, a study by Gerald et al. [28] holds that it is not possible to distinguish a shooter from an individual along the path of the projectile or from a shooting victim simply by counting the number of GSR. On the other hand, a study by Bell and Seitzinger [29] supports that by choosing the appropriate background population, analytical method and data processing, it is possible to differentiate shooters from non-shooters. All these studies were conducted under very different experimental conditions (e.g., sampling method, choice of compound analyzed, analytical method, background, etc.) and the possibility to distinguish (or not) a shooter from a non-shooter therefore depends on all these parameters and additional factors (e.g., firearm and ammunition type, time elapsed after the event, environmental, etc.) that influence the distribution of GSR [8]. The chemical evolution of ammunition (e.g., non-toxic ammunition) and the current analytical choices favouring sensitivity could make it even more difficult to differentiate the shooter from other stakeholders involved in a shooting, especially since the limited amount of background studies on an investigative environment, or even studies on potential contamination if sampling is limited to collection pads.

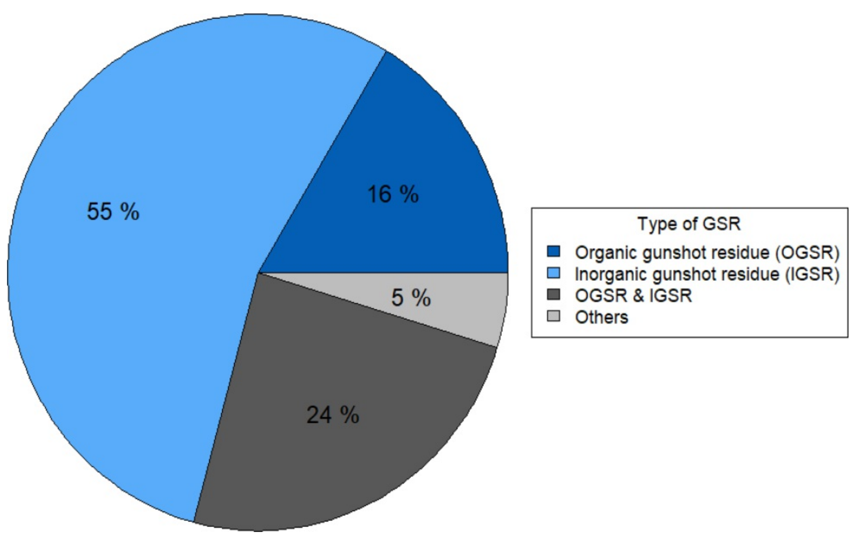
Chromophoric development methods (e.g., the modified Griess test and the sodium rhodizonate test), which are particularly effective in determining the distribution (patterns) of GSR were widely used in early studies [4, 15, 30–33] but neglected in recent ones. However, these methods remain the best way to appreciate GSR patterns. Since then, new techniques have appeared, such as x-ray fluorescence techniques and video spectral comparator, but they remain little exploited in the field [34–37]. To assess GSR evidential value at activity level, it seems highly relevant for forensic scientists to reappropriate basic techniques (e.g., chromophoric revealing or modern technical analogues) to better infer on the distribution of GSR on a person (e.g., hands and face). Rather than focusing only on recovering GSR with analytical instruments having a very high detection threshold, exploiting the geospatial location of these residues, admittedly less sensitive, remains one of the most confident way to differentiate the presence of GSR due to the discharge of a firearm from the presence due to contamination (e.g., transfer).

Figure 1 also shows that several population studies (n = 19) have been conducted. They mainly assess the GSR composition of different ammunition manufacturers [38–40], since the frequency of appearance of particles containing a specific morphological combination of lead, antimony and barium would be a discriminating characteristic for certain types of ammunition. Figure 1 also shows that several background studies (n = 14) have been carried out. Background studies are generally done to better understand the presence of GSR in very specific microenvironments. Background levels of GSR have been investigated in police vehicles [41] and recreational shooter vehicles [42], both being places of high risk of contamination [43–46]. The study of Gassner and Weyermann [41] showed that back seats were slightly more contaminated than the driver's seats and the number of compounds detected simultaneously was up to six out of the seven targeted. The study of Blakey et al. [42] confirmed that vehicles frequently occupied by firearms users are a potential source for transfer of GSR to persons unrelated to firearm activity. Some studies also examined the background on certain target populations, such as police officers [47] and employees at firearms manufacturing facilities [48]. It is only more recently that the researchers have focused on prevalence studies in both an environment exposed and not exposed to GSR [49, 50]. Finally, some papers address chemical compounds similar to GSR by their chemical nature found in vehicles [51], especially on specific components such as air bags [52, 53] and brakes [54]. Although coherent between each other, the singularity and microenvironment specificity of each study makes it hard to compare their results.

Several studies of the "multiple" category in Figure 1 have also focused on the estimation of shooting distance by studying, among other things, the distribution and pattern of GSR on the target, the victim or clothing [36, 55–57], but also by considering the quantity and density of GSR on the latter [58]. Other studies have also evaluated specific cases that may influence the analysis of shooting distance estimation, such as the weathering effect [31] and the cleaning of clothing [59]. Vinokurov et al. [60] investigated accidental transfer, specifically in the effect of the contamination of the victim's clothing with GSR. The study showed that because of the contamination, the firing distance may likely be wrongly assessed especially in case of far distances (>1 m). Further, some studies address the determination of the moment of shooting by collecting residues mainly on the hands and clothes [34, 55, 56, 59, 61].

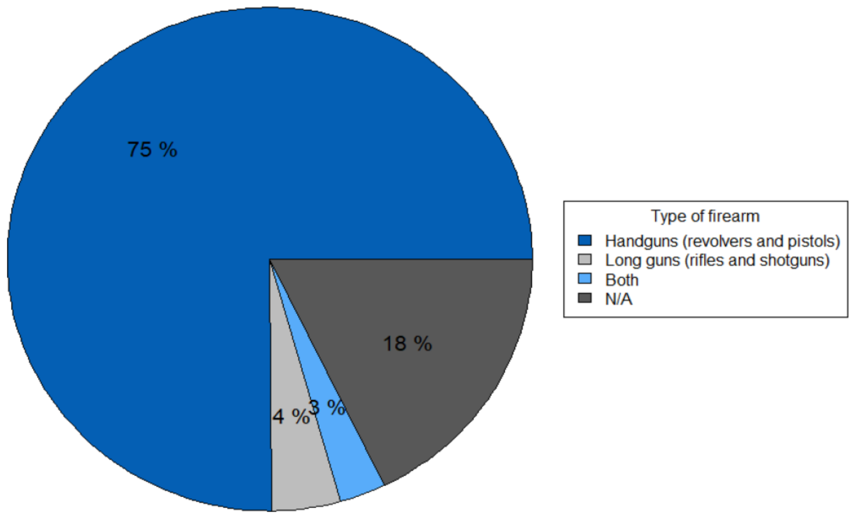
As seen in Figure 2, more than half of the studies were performed on IGSR only. The "others" includes the literature review studies and the studies on the interpretation by statistical models. Although targeting different compounds of the ammunition, OGSR interpretation at activity level does not differ from IGSR. Several studies have also recently been carried out on IGSR and OGSR in a complementary manner to find a viable analysis sequence and/or to compare the results of two methods [45, 61–63]. Nevertheless, the small number of studies carried out on OGSR requests further confirmation, moreover with the advent of so-called non-toxic ammunition (ammunition free of heavy metals in the primer) [18, 64, 65].

Figure 2. Classification of studies (n = 213) according to the type of GSR studied.



As seen in Figure 3, there is little variety in the type of firearms used in GSR studies, in fact most of them focus on handguns (75%) and only 4% of them involve long guns. However, studies have shown that the GSR pattern can vary between handguns and long guns as well as between different types of handguns. A study by Brudenell [66] that looked at velocity, GSR pattern, macroscopic and microscopic results, and ammunition type, shows that the pattern of GSR is not the same for handguns and pistol caliber carbine of the same caliber. Ditrich [67] showed that there is a significant difference in the distribution of GSR between revolvers, pistols, rifles, and shotguns. Indeed, the distribution of GSR depends, among other things, on the specific construction of the firearm. The ejection mechanism (bolt action vs. semi-automatic), ejection port, barrel length and gap in the trigger assembly are all characteristics that can affect the GSR distribution.

Figure 3. Classification of studies (*n* = 213) by type of firearms used (handguns or long guns). N/A: The type of firearm is not mentioned because (1) no test firing was carried out (e.g., literature reviews and probabilistic studies) or (2) the type of firearm is not at the center of the study. This may include background studies of GSR on an individual in a particular geographic region or on specific surfaces (e.g., vehicles) and studies of contaminants that may resemble GSR (e.g., airbag, fireworks).



Discussion

As supported throughout the article, the assessment of the significance of GSR should be made at activity level, given competing hypotheses on the implication of an individual in the discharge of a firearm (shooter vs. any alternative hypothesis proposed by the defense [68, 69]). Hence, studies providing statistical data on the probability of observing transfer and/or persistence mechanisms of GSR under various conditions [19–21, 48, 70, 71], or on the influence of a range of parameters on the transfer, persistence and/or recovery of GSR [4, 15, 30–34, 55, 56, 59, 60] seem particularly useful for practitioners to interpret the evidential value of those traces at activity level. Nevertheless, there is currently a gap in the TTADB regarding case-specific characteristics, since no studies or empirical data seem to address some specific criteria that may have an important role in interpretation, such as the influence of the shooter's height, the hand used to fire, the shooter's position and the victim's position. Such information could also be inferred from these transfer traces.

The interpretation of the weight of GSR evidence at activity level should also be addressed in regard to the relevant populations, environments and activities under investigation. Types of firearms and ammunitions mainly used in Canada in recent years—whether for legitimate or criminal activities—and contemporary trends in legitimate and criminal gun use among Canadians should be considered. The suitability of the current research on GSR for the Canadian environment could be assessed consulting available Canadian data (e.g., Statistics Canada). Indeed, with the large number of people owning guns in Canada, in relation to its population [72], it would be interesting to propose studies on the background level of GSR present in the Canadian population and in public places, at least regarding specific populations (e.g., hunters), or in cities where crimes committed with a firearm tend to be concentrated [73]. Moreover, firearms ownership and firearm crime trends show wide variations between countries therefore limiting their transferability to the Canadian context [74, 75]. Considering that there are almost four times as many long guns than handguns registered in the province of Quebec [72, 76, 77] and that 65% of firearm homicides in Canada in 2018 were committed with handguns and 35% with long guns according to official statistics [78], it is reasonable to say that more studies on pattern, transfer, and persistence of GSR carried out with a larger variety of firearms, such as rifles and shotguns, are needed.

Transfer and persistence mechanisms of GSR in Canadian particular climatic conditions and appropriate clothing retention capacity (e.g., winter clothing) should also be considered when assessing the value of this type of trace evidence at activity level. Yet, most of the studies reviewed were conducted in different countries in Europe (103 studies) and the United States (59 studies), while there are only 12 studies from Canada that were listed in the database. Among these, few relate to the persistence (*n* = 2), transfer (*n* = 2) and detection (*n* = 2) of GSR on a target population or objects and some relate to GSR background in a vehicle (*n* = 3) and their pattern (*n* = 3). A study by Fojtasek et al. [79] showed that the location of GSR in the surroundings of a shooting pistol is greatly influenced by environmental factors, and a study by Schumacher [80] established a link between the number of GSR present with the climatic conditions. The presence of different seasons and climatic conditions—which in turn affect the type of clothing (fibre composition) individuals wear—could therefore influence the transfer, persistence, patterns, and detection of GSR [7]. In fact, no study seems to assess and evaluate the impacts of temperature variations (between + 40 °C to − 40 °C, for example, over a year as observed in Quebec) as the main factor on the underlying mechanisms (transfer, persistence, detection) of GSR or a prolonged exposure of GSR to cold temperatures on the mechanisms related to the activity level interpretation. Should this topic be studied to offer Canadian practitioners' data to interpret their observations from an activity level point of view? Furthermore, there are no studies on the transfer, persistence, or detection of GSR on pieces of winter clothing (e.g., gloves, mittens, winter coat, winter pants, boots). As there is a wide variety of winter clothing and the climatic conditions can vary considerably between the Canadian provinces (e.g., British Columbia and Quebec), several studies could be undertaken in the future to better understand these mechanisms.

A more extensive knowledge on the average amount of GSR on individuals arrested and charged for their involvement in some types of criminal activities (e.g., organized crime) would also be useful to the interpretation of GSR as those individuals may have been in contact with firearms to a very different extent than law-abiding citizens. Distribution patterns and probabilities of transfer and persistence of GSR in different scenarios reproducing criminal particular modus operandi (e.g., use of a silencer, multiple discharges of a firearm, means of "*counter-traceability*" [81] like wearing gloves or balaclava) could also be relevant for forensic scientists in an effort to qualitatively and even quantitatively assess the significance of observing GSR given the effects of conditions alike those of the investigated cases. But, as the elaboration and the use of probabilistic models appear today essential to ensure reliable, transparent, and efficient assessment of the probative value of trace [6, 82], the English R. v T. hearing, while addressing a shoemark identification, is relevant for any forensic interpretation [83] and states "*an approach based on mathematical calculations is only as good as the reliability of the data used.*"

Conclusion

The use of firearms for criminal purposes still represents today a persistent issue for public safety and law enforcement agencies. Forensic scientists are called upon in various cases to provide information on the criminal activity alleged and to assess, among other things, whether a suspect fired or not and if so, what was the shooting distance. GSR may be especially useful to answer to those types of questions asked by investigators and the court. However, the interpretation of the GSR analysis results faces several challenges since there are many factors that influence their transfer, distribution pattern, persistence, and recovery. Several studies and recent American and Canadian reports urge the development of a structured database for the interpretation of transfer traces in forensic science, as pointed by Cadola et al. [11]. The first work on the constitution of the TTADB is preliminary and does not claim to be exhaustive, as a proactive surveillance is still in progress to update the database. On the other hand, this initial work on GSR now makes it possible to provide an overview of the current knowledge on GSR and, mostly, identify gaps in the existing literature for a Canadian application, such as the little variety in the type of firearm used in studies and the lack of studies addressing case-specific characteristics that have an important role in interpretation.

It appears that most of the up-to-date studies reviewed were conducted in different countries in Europe and the United States, while there are only few studies from Canada. Given the particular Canadian context about climate and weather, crime patterns and firearm ownership trends, the results of many studies may not be fully relevant and exactly transposable. Therefore, more studies covering these factors, in addition to others like the impact of individuals' cleaning/hygiene routines, are needed to assist forensic scientists in their transparent and reliable interpretation of GSR results.

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[1]The ScienceDirect™ platform offers, following consultation of an article, a series of similar or cited articles that could be of interest to the reader.

[2]All data analyzed in this article can be found in the .csv spreadsheet (under .xlsx format) joined as supplemental material in the study by Cadola et al. [11]. Only the online TTADB will be continuously updated in the future, accessible at the following address: http://www.uqtr.ca/LRC/BDATT-TTADB.

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