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CASE REPORT

Assessment of bullet holes through the analysis of mushroom-shaped morphology in synthetic fibres: analysis of six cases

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Abstract
Textiles damage analysis is a very valuable tool in forensic investigations. However, to date, very little research has been carried out to understand the impact of bullet causing damages to clothing. According to the review of the most recent scientific papers, the frictional heating and crushing action of a bullet passing through synthetic fibres cause a unique transformation in their ends called mushroom-shaped morphology. In this study, the textile remains of six individuals executed during the first decade of the Chilean military dictatorship period (1973–1990) were analysed. The purpose was to examine their clothing in order to describe the fibre defects in the bullet holes. The fibres were directly observed using two different models of stereomicroscopy (MZ16A and EZ4D, Leica Microsystem Ltd., Wetzlar, Germany) and through a combination of transmitted, oblique and co-axial illumination (with Leica DFC500 Digital Camera), at × 230 and at a resolution of up to 840 Lp/mm. The mushroom-shaped morphology, along with rupturing of yarns, fibrillation or splitting of fibres, was observed in the bullet holes. Although the mushroom-shaped is a useful pattern for bullet hole identification in synthetic fibres, further research needs to be performed for developing a sounder interpretational framework of this type of forensic evidence.

Keywords Forensic sciences · Ballistic damages · Synthetic fibres · Mushroom-shaped morphology · Chile

Introduction

In Chile, the development of Forensic Sciences is closely linked to the military coup that took place in September 1973, during the mandate of Salvador Allende. It caused the detention, murder and disappearance of many civilians (almost 13,000), and over 1100 detention camps were constructed in that time across the Chilean landscape [1]. According to the "Valech Report" [1], over 3215 people disappeared, most of them between 1973 and 1978. The "Rettig Commission" documented also the violence executed by the military under the auspices of General Pinochet and the *Dirección de Inteligencia Nacional/Central Nacional de Informaciones* (DINA/CNI) that resulted in death and unearthed sites of numerous mass graves throughout Chile [2].

According to the guidelines of the Human Rights Program of the Chilean Legal Medical Service (SML hereafter) (Exempt resolution No. 004742 2011, 1), the *Unidad de Derechos Humanos* (UDDHH hereafter) "must assist the jurisdictional and investigative authorities in human identification and determination of cause of death in complex cases, in order to perform expert analyses, actions and procedures in line with quality standards, coordinating and collaborating with organizations and institutions, both public and private, related to the field of forensic identification". Among their technical tasks, the UDDHH must perform, in a comprehensive and multidisciplinary forensic approach, the analysis of partially skeletonized remains (complete, incomplete, single and commingled remains). In line with the Exempt Resolution No. 004742 2011, 2, this team must also develop its forensic work in those cases of the human rights violations for the

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period September 1973 to March 1990, in order to establish identity, cause and manner of death [2].

Since 2007, archaeology has been played a permanent active role in the majority of cases studied by the UDDHH [1, 2]. The application of the traditional archaeological methods to the investigation of forensic cases has enriched the analysis of skeletal remains and associated cultural elements, contextualizing the findings and improving the laboratory work [2]. Nowadays, in the UDDHH, the cultural evidences are always analysed through a quantitative and qualitative process that includes the following steps: description of the type of fibres that compose the evidence; specification of their models, state of conservation and degree of degradation, fabrication patterns and colours; and evaluation of those damages that could be of interest in forensic investigation.

When the textile is recent, the damages caused by a firearm may be obvious [3, 4]. However, where there is a loss of strength through material degradation or because of the passing of time or environmental changes, these damages may be more difficult to characterize as they may appear as tears or rips in line with similar degradation or loss on the textile garment [4].

To date, there are limited studies discussing damage caused to apparel fabrics by firearms. Some of them have examined the morphology of fibres recovered from the margin of a bullet hole [4–6]. According to the literature [7, 8], the ends of natural fibres showed indistinguishable morphology regardless of whether the damage was caused by stabbing or by a firearm ammunition. On the other side, the frictional heating and crushing action of a bullet passing through synthetic fibres cause a unique transformation in their ends called mushroom-shaped morphology [7–9]. When the bullet wipe has been accidentally removed or it has not been deposited on the garments, it may not be possible to identify a bullet hole from the physical attributes alone, except in two cases: with polyamide (nylon hereafter) and polyester (PET hereafter) fibres. The severed ends of nylon or polyester melt and take on a swollen, club-like appearance that can be observed with a polarizing or light microscope [7–10]. Already in 1958, Susich et al. [11] observed fibrillation of nylon fibres and mushroom-like shape. Likewise, Carr et al. [4] found that the morphology of fibre ends at the bullet hole edge varies in appearance even within a single specimen and that thermoplastic fibres may appear bulbous or like a mushroom cap. Palenik et al. [12] reported a mushroom morphology in polyester fibres but not in cotton fibres. Prosser et al. [13] indicated that heat, generated between the surface of the bullet and the yarns, between yarns and between filaments within a yarn, induced mushroom-shaped ends and filament bridges in a bullet impact. Roberts et al. [14] highlighted that only microfibres, nylon and polyester fibres assumed a mushroom-shaped morphology when damaged by a bullet.

The aim of this work is twofold: first, to describe the fibre defects observed in the bullet holes of clothing belonging to six individuals executed during the first decade of the Chilean military dictatorship period (1973–1990) and, second, to assess if the mushroom-shaped morphology is useful to assess a bullet hole in synthetic fabrics.

Material and methods

Sample

This research examined 110 bullet holes from nine different pieces of clothing and accessories belonging to six individuals that were executed during the first decade of the Chilean military dictatorship (1973–1990). After being died, they were buried in different mass graves from cemeteries located throughout the Chilean territory. Once the court's order has been issued, the UDDHH exhumed each individual in the period between 2015 and 2019, and their remains as well as their cultural belongings, such as clothing and accessories, were stored with their respective chains of custody at the SML headquarter (Santiago, Chile).

The evidences analysed consisted of eight pieces of clothing and one accessory: precisely, four shirts, two jackets, one vest, one sweater and one sleeping bag.

All the individuals are males, and each of them is associated with a documentation folder including data about sex, age at death, dates of birth and death and cursory information about the cause and manner of death, determined and registered by a forensic doctor in a brief autopsy report from that period.

The age-at-death range was between 25 and 52 years, the years of birth were between 1923 and 1951, and the years of death were 1973 and 1981 (see Online Resources 1, Table 1). The textile fabrics examined were in a good state of preservation, and, except in one case (case no. 6), no ballistic evidences associated with clothing, such as metallic fragments of ammunition, were observed.

Regarding the skeletal remains, bone preservation varied. None of the cases had reached an overall chalky and friable appearance. In general, the remains were fragmented, and, only in three cases, they were well preserved (> 90%) and included hand and foot bones, vertebrae and rib fragments as well (see Online Resources 1, Table 2).

In addition, the elements showed some taphonomic changes associated with decomposition and diagenetic processes (e.g. adhering soil sediment or coffin's fragments, acidic soil corrosion, exfoliation of cortical bone). Evidences of previous autopsy with mechanical saw cut, such as uneven sectioning of the calotte and cutting of the rib plate, were observed. The presence of fly pupae indicated that the corpses had been buried or the graves backfilled 5 to 10 days *postmortem*.

The forensic anthropologists observed *perimortem* traumas in the skeletal remains, ranging from smaller penetrating injuries to gross anatomical disruption of the hard tissues due to blast-related trauma.

Analysis

A three-level approach to the examination of damages to clothing was used in this case: fabric, yarn and fibres [3]. In a first step, each piece of clothing was identified, and, after that, they were macroscopically screened through an unaided visual examination.

All the items were described in terms of the type of garment and its association with the body, colour(s) and composition of yarn(s) in the fabric. In addition, any label or distinguishing feature, which may include the size, make and fabric composition, were meticulously described. In order to identify the fibre types that composed each fabric, only the microscopic observation was performed [15]. In fact, because of the need to preserve the physical integrity of the fibres, for further court examination, both the burning and the dissolving tests [4], as well as all the other destructive techniques that require a considerable amount of material [3, 4], were not allowed in these cases. A simple burn test was only performed to determine if the fabric had natural fibres, synthetic fibres or a blend of natural and synthetic fibres [3]. In this case, the unique limitation is that many fibres have similar burning reactions that might cause doubt and occasional confusion [3].

Concerning the microscopic observation, a microscope Projectina Type 4002 (Projectina, Heerbrugg, Switzerland) was used for longitudinal and cross-sectional analysis of the fibres [16].

In order to improve the standardization and reliability of textile damage examinations, the forensic archaeological team of UDDHH developed specific file cards with proformas for items of clothing that include basic diagrams such as T-shirt, shirt, underwear, long sleeves-jacket, sockets and trousers. In it, garment measurements and all those defects that can be correlated with information about injuries in autopsy and medical reports were also scored.

Once the damages were detected, location, orientation, shape and type of damage were registered macroscopically. A digital camera (NIKON D300S, Nikon Corporation, Tokyo, Japan) was used to take high-resolution photographs of clothing and damages. The photos were saved in JPEG format, and the camera had the following setting: F-number (5.6 or 5), shutter speed value (6.9), photo resolution (X: 3456, Y: 2304 pixels) and exposure time (1/125 or 1/100). As regards the microscopic analysis, the fibres were not removed from the damaged fabrics, and each damage was directly observed in the clothing using two different models of stereomicroscopy (MZ16A and EZ4D, Leica Microsystem, Wetzlar, Germany). The fibres were analysed through a combination of transmitted, oblique and co-axial illumination (with Leica DFC500 Digital Camera), at × 230 and at a resolution of up to 840 Lp/mm, to determine the morphological and optical properties associated with the damaged fibre ends. The obtained photos were saved in JPEG format.

Results

Taphonomic damages

Light degradation, discolouration and embrittlement of the fabrics were observed. In addition, fungal growth occurred and several rust stains, due to the massive oxidation of the metallic parts of the coffin (shell and handless), were detected.

Fibres composition

According to the results of microscopic analysis, all the pieces of clothing are made of synthetic fibres, especially polyester and nylon. In only one case (case no. 6), a label was observed describing the textile composition of the sleeveless vest: 30% acrylic and 70% polyamide. All these fibres were common in Chile from the sixties onwards [17].

Ballistic damages

The number of bullet holes according to the textile composition was indicated in Table 3 (see Online Resources 1-Table 3).

From a macroscopic point of view, the majority of bullet holes in the fabrics was relatively circular in shape and without tears. In addition, fibres at the edge of the holes had been pushed through the thickness of the fabric.

The predominant defects that were observed in the bullet holes, mainly close to the path of the bullet, were namely rupturing of yarns, fibrillation or splitting of fibres, friction and bowing. The ends of the broken yarns appeared messy and disorderly (see Online Resources 2, Fig. 8).

Fibrillation is the breakdown of single filaments into numerous extremely fine fibre units; it is normally achieved by splitting of a fibre along its length. On the other side, friction and bowing refer to the breakage of the fibres near the impact region and to the displacement of strained yarns from the bullet impact point, respectively.

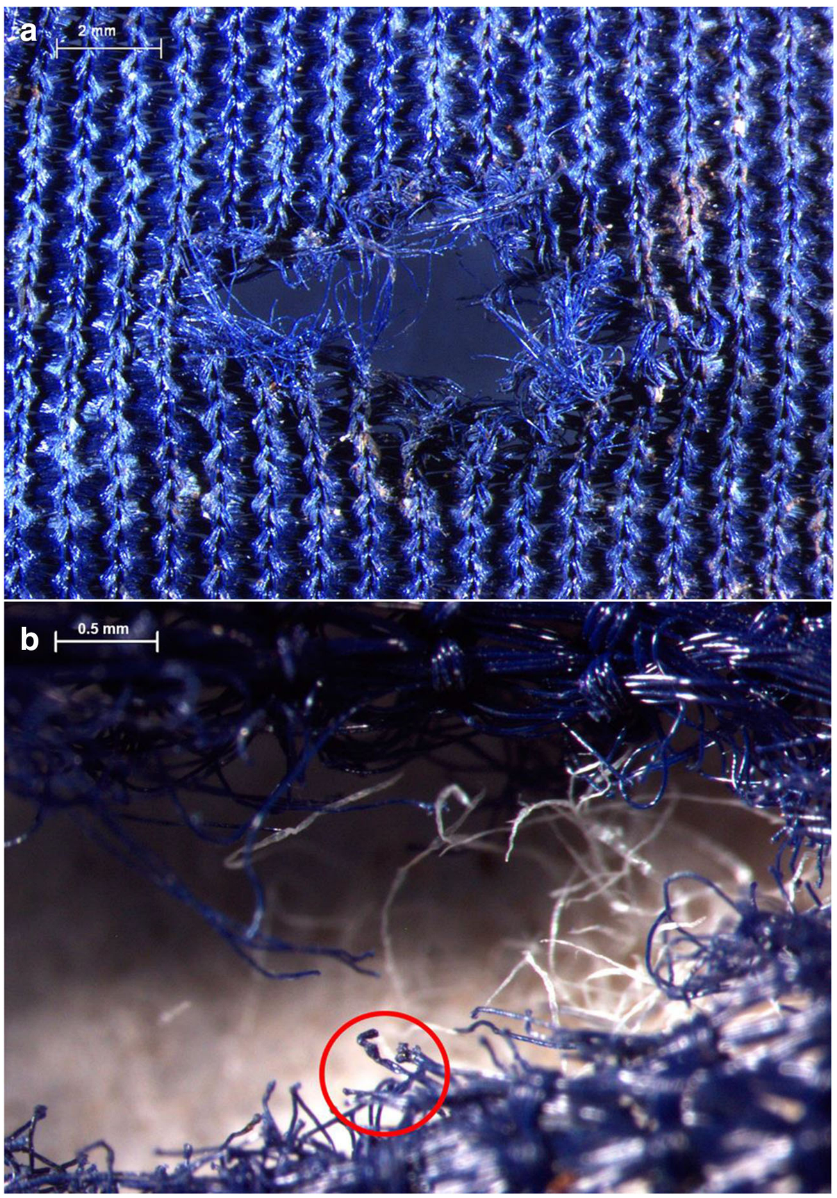
In general, at a higher magnification (× 150–× 230), all the fibres became wider at the end and thickened, often taking the form of a bulb, while the morphological structure of the remaining part of the fibres remained almost unchanged. Some broken fibre ends appeared thickened and exhibited tensile failure, cut-off fibres and a characteristic bulbous or mushroom-shaped end. In the impacted area, filaments frequently stuck together and were fused into larger clumps or a compact mass (probably fibres that had partially melted). In some fibre ends, it is also evident a melted filament of nylon, some globular and some in the form of links or bridges between filaments, that had partially melted. Finally, light microscopy showed undamaged filaments beyond 1–1.5 cm from the bullet hole (case no. 1, Fig. 1–4; case no. 5, Figs. 5–7) (see Online Resources 2, Figs. 9–20).

Discussion

To date, these are the first research in which textile remains belonging to subjects executed during the first decade of the Chilean military dictatorship period (1973–1990) were thoroughly analysed for assessing cause and manner of death.

Concerning the taphonomic damages observed in the clothing, nylon and polyester had only rust stains and some residuals of fungal growth, thus showing high resistance to biodegradation. In such cases, when the deceased has undergone decomposition, and the skeletal remains are not well preserved, the clothing may then be analysed. One area of clothing damage that is somewhat neglected is the one of firearm damages, with some very limited research being conducted [3, 4].

The presence of gunshot residues in the fibres, or bullet wipe and debris, and their association with the defect in the garment are two of the most important clues in a correct



Figs. 1-4 **a**–**d** A bullet hole in a shirt with melted fibres forming bridges (red circle and white arrows) and fibre ends with mushroom-shaped morphology (case no. 1)

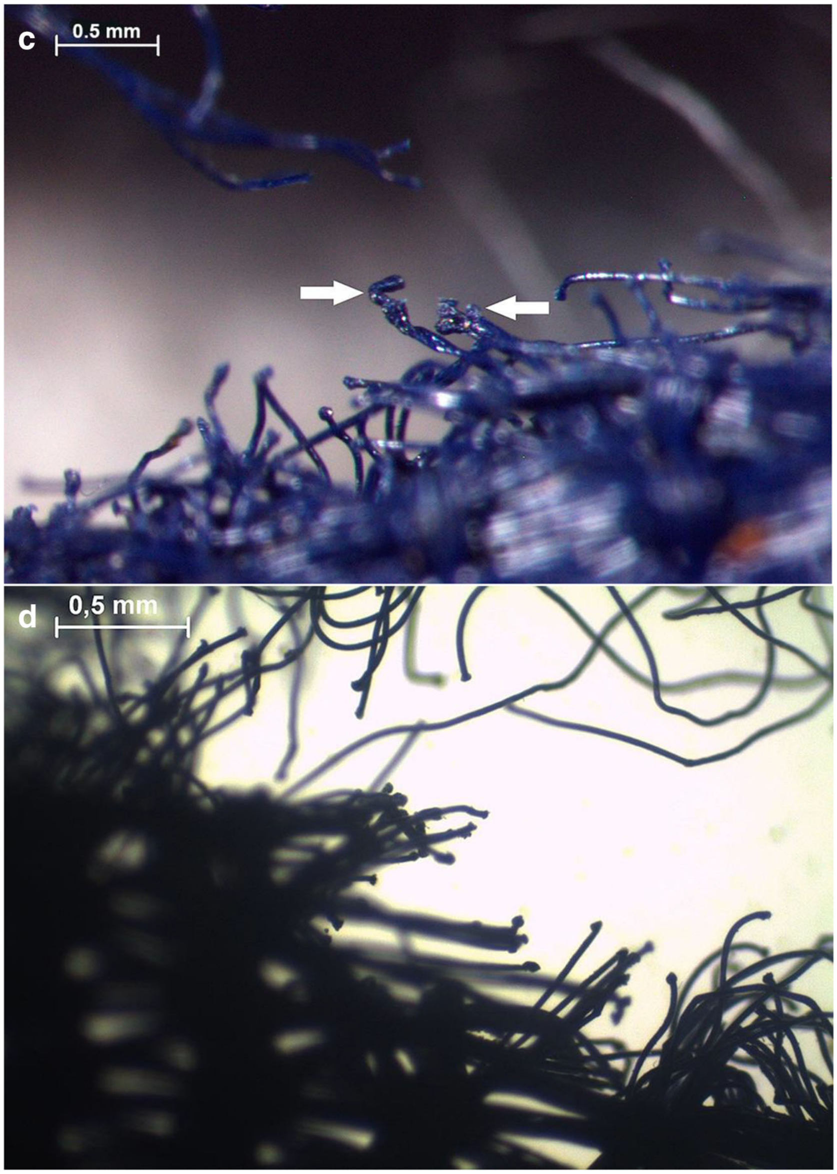
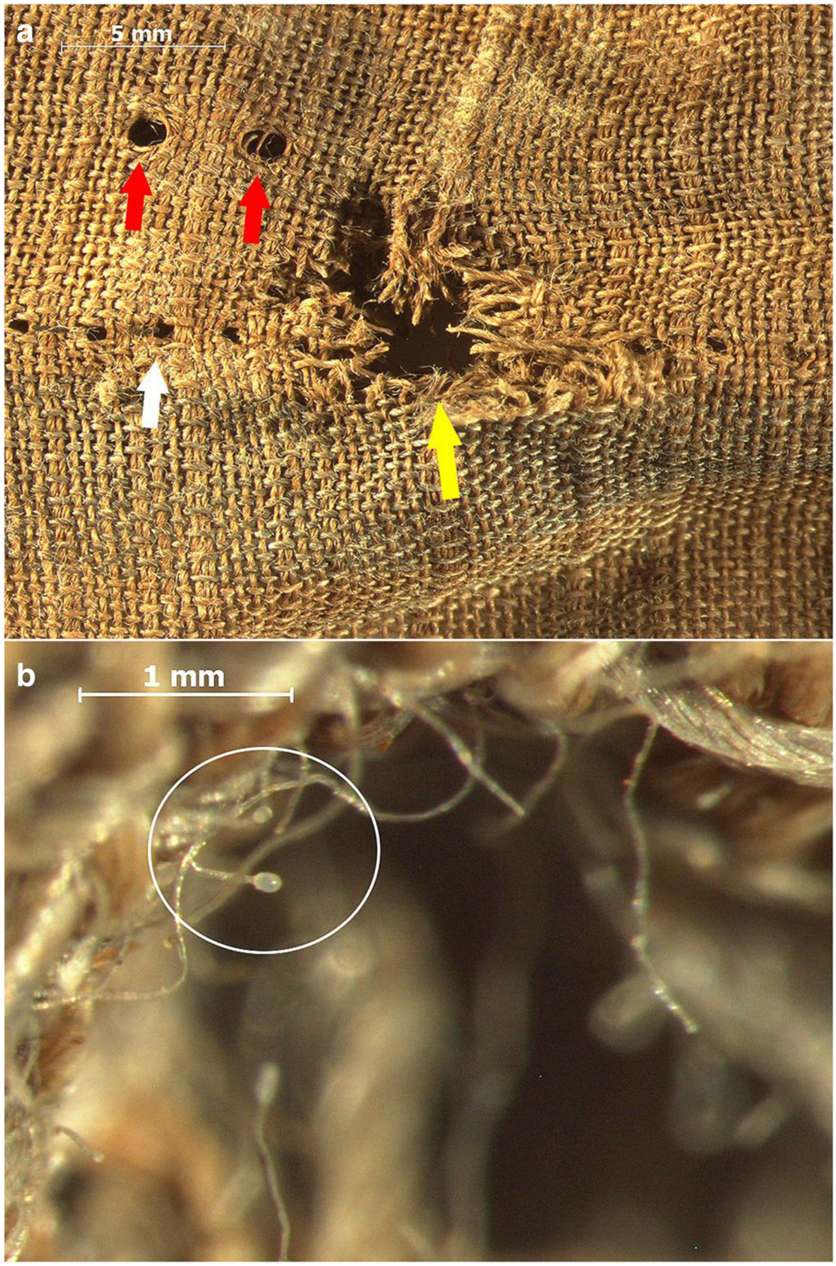


Fig. 1 (continued)

evaluation of gunshot wounds [9]. When these two characteristics have been removed or they disappeared because of the exposure to the weather elements, or the passing of time, further evidences need to be investigated, both in the biological tissues and in the fabrics. Nowadays, there are limited studies discussing damage caused to apparel fabrics by bullets [3, 4]. In them, all the authors highlighted that bullet holes in fabrics containing thermoplastic fibres, such as nylon or polyester, may have evidences of molten edges with bulbous or mushroom-shaped morphology.

In this study, light microscopy was used to evaluate the morphological characteristics of fibres and yarns in the observed bullet holes. The presence of a considerable amount of fibres with tensile failure, solidified polymer (nylon and polyester), globular fibre ends (mushroom-shaped morphology) and links or bridges of melted fibres indicated that friction, tensile strength and heat were generated in and close to the path of the ballistic projectile.

Examination of failed yarns showed that the filaments are broken at one edge as if the yarn had been cut and contracted with globular ends. This phenomenon is known as thermally stimulated shrinkage or thermal relaxation [18]: it occurred when an oriented polymer structure, such as any type of synthetic fibres, that is a dynamic structure increased the internal energy of the oriented system because of an increase in the temperature and changed their mechanical properties. Crystallites are therefore molten and the whole material is in a liquid state of high viscosity. However, this effect also works in reversal: if energy is rapidly removed from a material, then the polymer's temperature will decrease, causing the material



Figs. 5-7 **a**–**c** A bullet hole in a synthetic shirt (white arrow: seam; red arrows: button's holes; yellow arrow: bullet hole) with globular fibre ends in the margin (white circle) (case no. 5)

to contract. Therefore, the shrinkage process could be considered a recrystallization.

Nylon and PET are thermoplastic materials, and their mechanical resistances decrease at higher temperatures [18]. Their melting points are 263 °C and 295 °C, respectively [19]. In the studied cases, high temperatures were expected due to the bullet impact and because of friction between the bullet and the fibres (pathway through the fabric layers). In fact, as shown by the molten material found in the holes, the kinetic energy of the bullet was probably transformed into higher temperature during penetration. In addition, the fact that all the fibre ends, with altered tensile conditions, were in one surface indicated failure by a sharing action at the moment of bullet penetration. Roberts et al. [14] showed that the mushroom-shaped morphology and resultant modifications to the optical properties of damaged synthetic fibres indicate a high-speed fracture, which includes a bullet discharged from a firearm.

Unfortunately, limited studies discussing damages caused to apparel fabrics by bullet wound have been published so far. In general, many of these researches lacked important details about ammunition and weapon, impact velocity and fabric description. Poole and Pailthorpe [7] showed mushroom-shaped morphology in several nylon fibre ends of warp knit

Fig. 2 (continued)

slip. In a study published by Lepik and Vasiliev [10], the polyester fabric showed melting at the edges of the holes caused by the bullets. Palenik et al. [12] also noticed mushroomed polyester fibre ends in their sample.

Cotton and other cellulosic fibres do not burn or melt and would not be expected to show such features, more common in synthetic fibres. However, Carr et al. [5] observed some bullet holes with thermoplastic modifications and mushroomed-shape morphology in three fabric combinations representing common clothing made of 100% cotton. According to Palenik et al. [12], such fibres that are often blended with synthetics in a fabric could be readily identified using polarized light microscopy (PLM) or scanning electron microscopy (SEM) regarding their optical properties and morphology.

It is important to highlight that the presence of mushroom-shaped fibre ends depends not only on the fibre type, yarn structure, fabric construction and fabric orientation but also on the shooting distance as well as the type and velocity of ammunition [9].

Regarding the taphonomic and environmental effects on these fabrics, the synthetic fibres are quite resistant to biodegradation such as the alterations due to body fluids. However, some changes may be observed in nylon due to light degradation and thermo-oxidation, which can result in a moderate degree of embrittlement [20]. This type of natural damage along with careless manipulation can easily modify the relative position of fibres and yarns or remove the edges around the margin of the bullet hole. Therefore, great care must always be taken when handling these damaged historical fabrics in order to avoid further modifications of the original direction of the protruding fibres.

Conclusions

Such cases represent a valuable focus on how the clothing analysis may help in forensic investigation. According to the results of this research, the mushroom-shaped morphology, along with the other physical characteristics observed, is a first useful pattern for assessing the presence of a bullet impact in ancient and deteriorated synthetic fibres. However, high caution in interpreting the results is needed, because pitfalls can be everywhere, mostly in these cases belonging to a historical period, where the passage of time and some taphonomic processes could modify their characteristics. In addition, the limited body of research into the physical effect of firearm damages on clothing demonstrates that the interaction between the textile and the bullets is highly variable. For this reason, a great deal of quantitative studies on the same type of fabric and with different ammunitions should be carried out. With the aid of a physical human surrogate torso model (HSTM), a computational (finite element) model (FEM) and a SEM analysis, the damages observed in these cases and in the daily forensic practice could be reproduced and evaluated [3].

Authors' contribution Stefano De Luca: conceived and designed the analysis, collected the data, performed the analysis and wrote and reviewed the manuscript.

Miriam Pérez de los Ríos: conceived and designed the analysis and wrote and reviewed the manuscript.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Informed consent No informed consent required in the study.

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