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Study of the adhesion of explosive residues to the finger and transfer to clothing and luggage

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Abstract

It is important to understand the extent of transfer of explosive particles to different surfaces in order to better evaluate potential cross-contamination by explosives in crowded security controls such as those at airports. This work investigated the transfer of nine explosive residues (ANFO, dynamite, black powder, TNT, HMTD, PETN, NH_4NO_3, KNO_3, $NaClO_3$) through fingerprints from one surface to another. First, the extent of adhesion of explosive residues from different surfaces to the bare finger, nitrile and latex gloves was studied. Then, the transfer of explosive residues from one surface to another through fingerprints was investigated. Cotton fabric (hereinafter referred to as cotton) as clothing material and polycarbonate plastic (hereinafter referred to as polycarbonate) as luggage material were chosen for the experiments. These surfaces containing explosive particles were imaged using a reflex camera before and after the particles were transferred. Afterwards the images were processed in MATLAB where pixels corresponding to explosive residues were quantified. Results demonstrated that transfer of explosive residues frequently occurred with certain differences among materials. Generally, the amount of explosive particles adhered to the finger decreased in the following order: skin>latex>nitrile, while the transfer of particles from the finger to another surface was the opposite. The adhesion of explosive residues from polycarbonate to the finger was found to be better compared to cotton, while the amount of particles transferred to cotton was higher.

Keywords: explosive, adhesion, transfer, fingerprint, multispectral imaging

1. Introduction

The search for traces of explosives on people and objects (luggage, laptops) at airports and other security settings is crucial regarding counterterrorism [1]. For detection of hidden explosives at airports mainly two approaches are used: advanced imaging technologies seeking for bulk material and direct chemical identification of trace explosives on clothing, luggage, *etc.* [2]. Numerous trace explosive detectors have been developed and several are in routine use today for screening luggage and cargo at airports [2–5]. The most commonly used techniques for detection of explosives are ion mobility spectrometry (IMS), gas chromatography with electron capture or chemiluminescence detector, mass spectrometry, Raman spectroscopy, and different X-ray techniques [2–7].

Despite the significant success achieved in airport security by now, the hit rate of the respective *in situ* devices is far from being optimal. In this respect, false negative cases pose the highest threat. An explosive detection device should never fail at passenger control since the opposite case would involve a high risk of bomb explosion. Less dangerous yet equally disturbing is the high number of false positive responses, which exceptionally increase the delays at airports and upset millions of air passengers. The high false positive rate may be mainly accounted for by the existence of a great number of common interfering substances. For instance, a commercial ion mobility spectrometer may give false positive responses to explosive detection due to the presence of fertilizers, skin lotions, hand creams or even perfumes [8–10]. Besides the interfering substances, potential cross-contamination at airports is also of concern and needs to be studied. According to Levi [11], and particular incidents experienced by some of the authors of this article as regular air passengers, occasionally luggage and body scan has been done by the airport security officer with the same gloves on as when performing the scan of the anterior passenger in the line, which proved positive. This may lead to consecutive false positive responses due to cross-contamination. It is impossible that the ideal and effective prevention procedures employed in trace explosives laboratories to avoid contamination [12] are identically followed at airports. However, they should perhaps be simplified into some few essential procedures for their implementation at airports.

Fingerprints are considered one of the main means through which explosive traces are transferred to different surfaces. This makes fingerprints targets for sample collection when searching for a terrorist having handled an improvised explosive device [13,14]. Therefore, detection of explosive traces in fingerprints is widely studied by various techniques [15–23].

Often the detection relies on the swabbing methods from hands, which help to pick up the small explosive particles [24–26]. Explosive traces will inevitably adhere to a bomb maker's hands and be afterwards transferred to clothing, parcels, luggage, *etc.* [27,28]. Therefore, usually when studying the transfer of explosives, the adhesion of explosives is studied simultaneously. To date, very few articles have been reported on the adhesion and transfer of explosives to different materials. Oxley *et al.* [28] quantified the amount of explosive residues remaining in the primary work area and in secondary transfer points during simple manipulation process. Some authors have investigated the adhesion of explosives to surfaces by using scanning techniques such as atomic force microscopy (AFM) [27,29,30]. For instance, Yu *et al.* [30] investigated the adhesion of explosives 2,4,6-trinitrotoluene (TNT), pentaerythritol tetranitrate (PETN), 1,3,5-trinitroperhydro-1,3,5-triazine (RDX) to a variety of textile and non-textile surfaces by using AFM. Based on the obtained results, the researchers found that explosive crystals display a higher adhesion to smoother, non-textile surfaces, particularly glass. However, to our knowledge, no research on the adhesion of explosive traces to the finger or gloves made of different materials the security officers at airports have on has been reported before, although the topic is highly important. Regarding transfer, Choi and Son [31] used IMS to detect RDX and TNT after being transferred to three smear matrices – stainless steel mesh, cellulose paper, and cotton fabric, using a poly(tetrafluoroethylene) (PTFE) sheet. The investigators prepared the samples of solid state explosives by dropping the respective solutions on the PTFE sheet. Afterwards, the solid explosive particles deposited on the PTFE sheet were transferred to the smear matrix using a stainless steel roller. Their workgroup found that the order of the transfer and detection efficiencies of TNT and RDX according to the smear matrix material type was cotton fabric>stainless steel mesh>cellulose paper. Turano [32] studied the transfer of NH_4NO_3 and $KClO_3$ in ten consecutive fingerprints to three different surface materials – filter paper, polypropylene and polyurethane, using ion chromatography. He noticed that there were differences in the transfer not only based on the transferred substance but also on the materials studied. NH_4NO_3, due to its hygroscopic nature, exhibited better adhesion to filter paper, while $KClO_3$ adhered more firmly to polypropylene.

Multispectral imaging (MSI) is a fast, non-contact, non-destructive and non-invasive technique [33]. These, in turn, are required mandatory features to study the transfer of explosive residues since the sample before transferring the residues has to be first analyzed without being altered. The reflex camera is the simplest MSI device using red-green-blue (RGB) wavelengths. This simple MSI approach employing a reflex camera was recently tested by Dr. García-Ruiz's

research group as a suitable technique for studying the transfer of explosive residues to different surfaces [34]. Other studies employing imaging techniques for the detection of explosive residues also revealed the advantages of imaging [35–41]. For instance, Fernández de la Ossa *et al.* [39,40] analyzed explosive residues on human handprints using near infrared hyperspectral imaging combined with chemometrics. The researchers pointed out that their proposed method had the advantage of simplicity, minimal sample pre-treatment procedure and non-contact, non-invasive and non-destructive measurements, which are optimal technological features for its portable use in public places such as airports and stations.

This work aimed to study and compare the adhesion of residues of different explosives to different glove materials and the bare finger after the fingertip had picked up explosive particles from either textile or non-textile surfaces. Another goal of the research was to prove that explosive residues were transferred from one surface to another through fingerprints, with hands gloved or not. Moreover, the research provided some knowledge to elucidate the surfaces to which the adhesion and transfer of residues of different explosives were favored. In addition, the study endeavored to explore the possibility of cross-contamination of explosive traces at airports through contaminated hands.

2. Material and methods

2.1 Explosives and materials

In the current research, the transfer of residues of the nine different explosives reported in previous work of Lees *et al.* [34] were investigated. Three inorganic oxidizing salts, including NH_4NO_3, KNO_3 and $NaClO_3$, and three inorganic explosive mixtures, including ANFO (90% ammonium nitrate + 10% diesel), dynamite (66% ammonium nitrate + 29% ethylene glycol dinitrate + 1% nitrocellulose + 2.5% dibutyl phthalate + 1.2% sawdust + 0.3% calcium carbonate), and black powder (75% potassium nitrate + 15% charcoal + 10% sulfur) were tested. In addition, three organic explosives were included – TNT, hexamethylene triperoxide diamine (HMTD) and PETN. All the above explosives, except TNT and dynamite, were obtained in powdered form and were used as received. The pretreatment procedure for powdering TNT and dynamite is outlined in similar previous work [34]. Briefly, the substances were dissolved in acetonitrile or powdered mechanically in mortar to obtain microscopic particles. Standards of inorganic salts were obtained from Sigma-Aldrich in ACS reagent grade (>99.0%), while all the other explosives were obtained from Spanish Explosive Ordnance Disposal (TEDAX).

To ensure an adequate area for printing an index finger, 3 cm × 3 cm pieces of cotton fabric and polycarbonate plastic were used as surfaces in the experiments. Cotton fabric and polycarbonate plastic are the most common clothing and luggage materials, also at airports. The authors investigated the transfer of explosive residues from polycarbonate to polycarbonate, polycarbonate to cotton, cotton to cotton and cotton to polycarbonate.

Additionally, gloves made of the two most common materials – nitrile and latex (Sempercare®, Singapore), the security officers at airports have on were used in the study. In addition, the adhesion of explosive residues to the bare finger (hereinafter referred to as skin) was investigated.

2.2 Instrumentation and data treatment (image processing)

A Nikon D5000 Digital SLR Camera equipped with a 12.9 megapixel DX-format CMOS sensor and an AF-S DX Zoom-Nikkor 18-55 mm f/3.5-5.6G ED II lens was used for imaging the samples. Each sample was photographed in three parallels in a purpose-built photo studio using remote control. Then the images were processed in MATLAB R2017a (The MathWorks, Inc., USA) where pixels belonging to the explosive residues were counted. It is important to point out that the number of pixels did not exactly correspond with the number of particles, yet the results were not affected by this as they were expressed as a percentage. The image processing used in this study is described in more detail in previous work of Lees *et al.* [34]. Briefly, three RGB frames of each image were compared and the frame that provided the sharpest contrast between the explosive and the background material was selected. Raw images contained 2848 × 4288 pixels × 3 wavelengths, but after the selection of region of interest (ROI) in the correct frame, the images were converted to the 1000 × 1000 matrix. The spatial resolution of each pixel was approximately 20 µm × 20 µm. The pixels that exceeded the specific value of intensity in the specific frame were quantified. Different intensity values were tested by controlling the intensities in the blank sample and assuring visually that no false pixels from the background were counted by the program.

A DXR confocal Raman microscope from Thermo scientific (Waltham, MA) was finally employed to confirm the identification of the transferred explosive particles on surfaces. Raman spectra were collected from 2000 to 200 cm^{-1} using a 785 nm laser at 10 mW power, 10 scans and 5 s per scan. Magnification objectives of 10×, 20× or 50× were used depending on the size of the explosive particle.

2.3 Procedure

Explosive particles were balanced directly onto the first surface (cotton fabric or polycarbonate plastic) from where these were picked up by the fingertip and transferred to the second surface. In all the experiments, the initial amount of explosive residues was weighed to be 10.00 mg by using an Ohaus DV215CD analytical balance.

One subject pressed his/her index finger on the first surface and transferred the explosive residues that were adhered to his/her fingertip to the second surface. A controlled procedure with a pressing time of 3 sec and an applied force of 1 kg was followed. Three replicates were prepared for each of the nine explosives, each surface combination (from cotton to cotton, cotton to polycarbonate, polycarbonate to polycarbonate, polycarbonate to cotton) and each material (nitrile, latex, skin). Thus, a total of 324 transfers were performed. For instance, three replicates were made for the transfer of TNT from cotton to cotton using latex gloves, *etc*. For each replicate, three images were collected before the transfer and three images after the transfer. Thus, including all the explosives, a total of 1944 images were collected. The average number of pixels containing explosive residues was calculated for the three replicate images.

The adhesion of explosives was defined as the amount of explosive residues picked up by the finger after pressing it on the first surface. It should be noted that adhesion does not refer in this study to the molecular forces occurring between a molecule and a surface (physics), but the result of explosive residues adhering to the finger. In order to quantify the extent of such adhesion from the images, the amount of picked-up explosive residues was determined by subtracting the amount of pixels containing remaining explosive residues after pressing the finger on the surface (*i.e.* the amount of explosive residues left on the surface) from the total number of pixels containing explosive residues before pressing the finger on the surface. The final percentage of adhesion was calculated by dividing the value obtained by the total number of pixels containing explosive residues before pressing the finger on the surface and multiplying this value by 100%, as illustrated in Fig. 1.
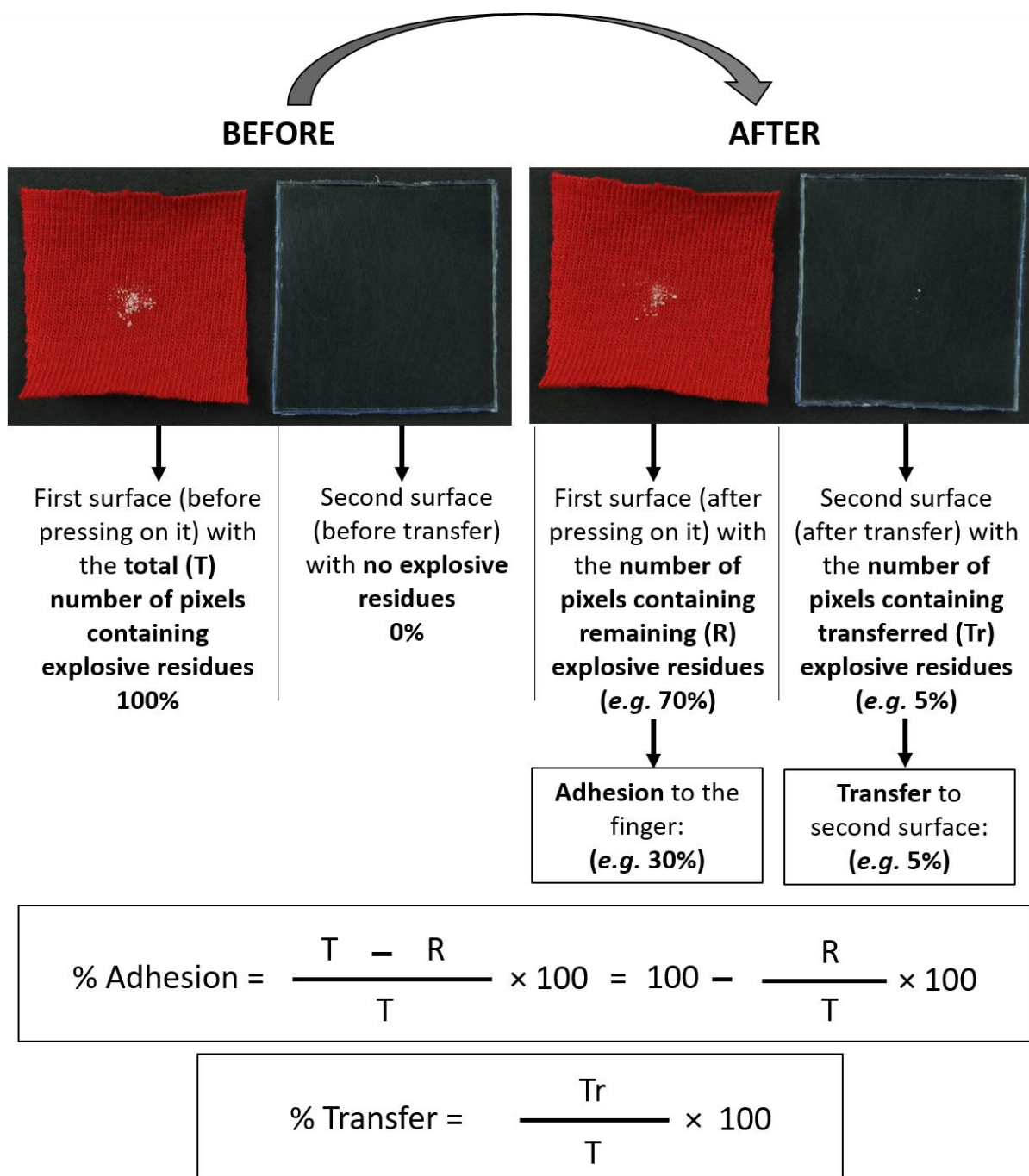
Fig. 1. Scheme of calculation of the percentage of adhesion and transfer of explosive residues from images. Abbreviations: T – the total initial number of pixels containing explosive residues on first surface, R – the number of pixels containing the remaining explosive residues on first surface (after pressing the finger), Tr – the number of pixels containing the transferred explosive residues on the second surface (after transfer).

The degree of transfer of explosives was defined as the amount of explosive residues transferred to the second surface, *i.e.* the number of pixels containing explosive residues in the image of the second surface after transfer. For comparison, the degree of transfer was calculated in

percentage. The percentage value was calculated by dividing the number of pixels containing transferred explosive residues in the image of the second surface by the total number of pixels containing explosive residues before pressing on the first surface and multiplying this value by 100, as illustrated in Fig. 1.

Six replicates were analyzed to determine the adhesion of residues of each explosive from each surface (cotton, polycarbonate) to each material (skin, latex, nitrile). At the same time, three replicates were analyzed to study the transfer of residues of each explosive from the first surface to the second by using all materials – skin, latex and nitrile. For the study of adhesion more replicates were analyzed because explosive residues were transferred either from one surface to the same or other surface which enabled the particles adhesion to the finger to be studied more thoroughly, *i.e.* 3+3 replicates.

3. Results and Discussion

3.1 Adhesion of explosive residues to the finger from cotton or polycarbonate surface after one touch

As a first step, the adhesion of explosive residues to the finger was evaluated by visual inspection of the surface before and after pressing on it with the finger. Pictures of one replicate illustrating the adhesion of residues of NH_4NO_3, dynamite and PETN from cotton and polycarbonate to skin, latex and nitrile gloves are displayed in Fig. 2. The adhesion of explosive particles to the finger can be visually estimated by the decrease in the particles amount in the image before and after the impression.
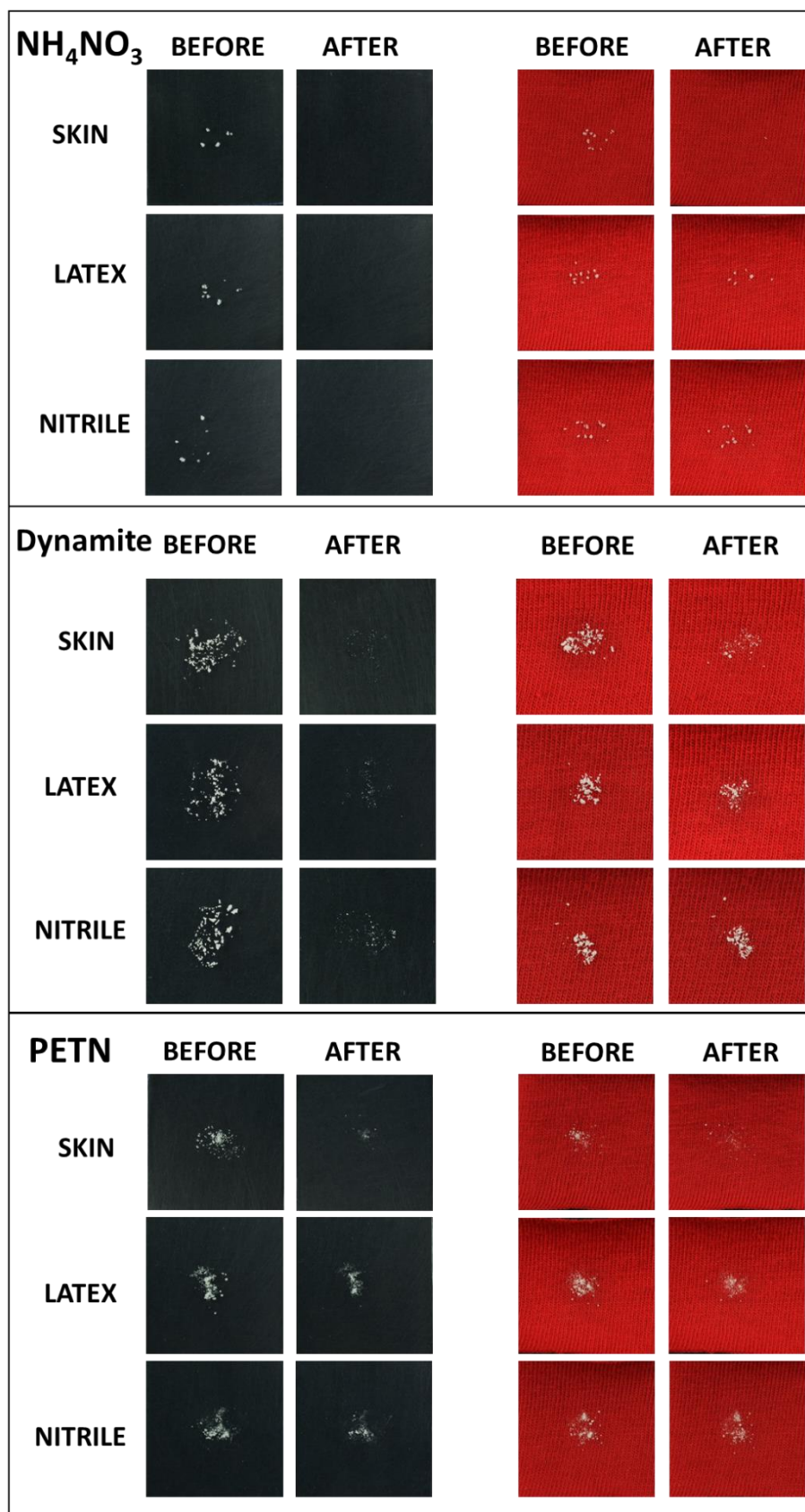
Fig. 2. Pictures (one of the replicates) of the residues of NH_4NO_3, dynamite and PETN on polycarbonate plastic (left – dark background) and cotton fabric (right – red background) before and after pressing on the surface with the fingertip (skin, latex, nitrile).

Visual comparison of the pictures shows that the residues of NH_4NO_3 present on polycarbonate almost entirely adhered to the finger, with hands gloved or not (adhesion almost 100%). Similarly, no residues of NH_4NO_3 visually remained on cotton after pressing on it with the bare finger (skin) (adhesion almost 100%). However, some amount of residues remained on cotton when latex gloves were used, and almost the entire amount of residues remained on this surface when nitrile gloves were used. Similar results were observed for the other inorganic salts and explosives. However, there always remained a certain amount of residues of organic explosives and explosive mixtures on polycarbonate and cotton, as shown in Fig. 2 for dynamite and PETN. Based on these findings, cotton seemed to retain a higher amount of explosive residues than polycarbonate and the adhesion of the residues to the finger seemed to decrease in the order: skin>latex>nitrile.

The adhesion of explosive residues to the fingertip was subsequently determined through the quantification of pixels containing the residues in the images, as described in experimental section. The adhesion of residues of nine explosives from polycarbonate and cotton to the bare finger (skin) or latex and nitrile gloves is depicted in Fig. 3.
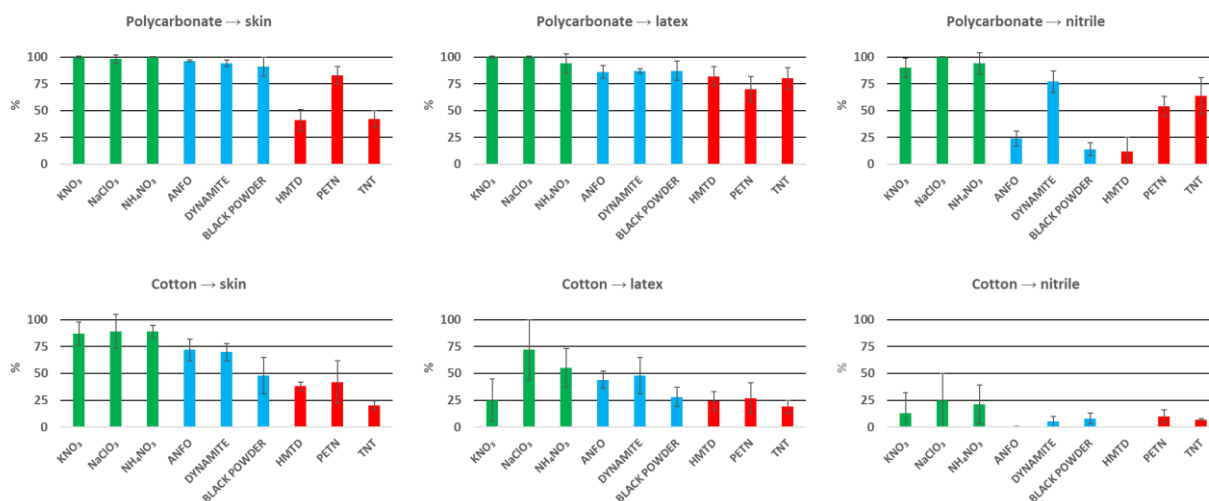

Fig. 3. Adhesion of residues of inorganic salts, explosive mixtures and organic explosives from polycarbonate or cotton to skin, latex and nitrile gloves (n=6). Green – inorganic salts, blue – explosive mixtures, red – organic explosives. Error bars represent the standard deviation for six replicates.

Residues of all explosives present on polycarbonate were picked up by skin or latex gloves almost entirely. The lowest degree of adhesion of particles from polycarbonate to the skin was with residues of organic explosives HMTD and TNT (about 40%), while to latex gloves

occurred with residues of PETN (about 70%). Residues of inorganic salts (KNO_3, $NaClO_3$, NH_4NO_3) and dynamite present on polycarbonate adhered to nitrile gloves almost entirely, respectively 90–100%, and about 80%. The amount of residues of ANFO, black powder and HMTD present on polycarbonate picked up by hands with nitrile gloves on was low, 10–25%. In general, the extent of adhesion of residues from polycarbonate was higher to skin or latex gloves than to nitrile gloves, being between 40 and 100% for skin and latex gloves, and from 10 to 100% for nitrile gloves. Therefore, the degree of adhesion of explosive residues to nitrile gloves was the lowest among the three materials under study, while the extent of adhesion of the residues to skin and latex gloves was similar. Nevertheless, there were noticed some exceptions to this tendency. For example, the extent of adhesion of TNT residues to skin was the lowest, about 40%, and the highest to latex gloves, about 80%.

The degree of adhesion of explosive residues picked up from cotton by gloves or the bare finger was more variable. Around 90% of the amount of inorganic salts residues present on cotton adhered to skin. Such a high degree of adhesion to skin may be explained by the hygroscopic nature of these inorganic salts, which enabled their easy adhesion to the warm bare finger (skin). The degree of adhesion of inorganic salts residues from cotton to latex gloves was higher than to nitrile gloves. Regarding all explosives, the adhesion of residues to skin was higher than to nitrile or latex gloves. Less than 25% of the amount of residues of all explosives present on cotton adhered to nitrile gloves. Therefore, nitrile was considered the material with least adhesion. The adhesion of the explosive residues from cotton to latex gloves was between 20 and 70%, to skin, from 20 to 90%. Thus, the explosive residues adhesion to fingertip from cotton took place in the following descending order: skin>latex>nitrile (Fig. 3).

Regarding the comparison of both surfaces, the quantity of explosive particles picked up by the fingertip from polycarbonate was higher. This may be explained by the smoother surface of polycarbonate plastic, unlike the fibrous surface of cotton fabric, in case of which the explosive particles remain between the fabric fibers rather than stick to the finger.

3.2 Transfer of explosive residues from one surface to another through various materials

The transfer of inorganic salts residues from polycarbonate or cotton by skin or nitrile/latex gloves is illustrated in Fig. 4. A considerable amount of the salts residues was transferred by nitrile and latex gloves to cotton (polycarbonate→cotton or cotton→cotton), being in case of polycarbonate→cotton transfer 25-75%. As an example, the transfer of KNO_3 residues from polycarbonate to cotton (about 75%) and the transfer of $NaClO_3$ residues from cotton to cotton

(about 35%) by nitrile gloves is illustrated in Fig. 4. A small amount of inorganic salts residues, <10%, was transferred to polycarbonate (polycarbonate→polycarbonate or cotton→polycarbonate) regardless of the material used for transfer. In general, only a small amount of residues was transferred by skin (gray bars in Fig. 4), *i.e.* less than 7% of their initial amount on the surface; despite the fact that a large amount of particles of inorganic salts was picked up by skin (Fig. 3). As an example, the transfer of NH_4NO_3 residues from polycarbonate to polycarbonate by skin ($\leq 0.1\%$ which is obtained from the fine dust of NH_4NO_3) is displayed in Fig. 4. It should be noted that the remaining 99.9% of residues persisted on the fingertip since no residues remained on the first surface (almost 100% adhesion).
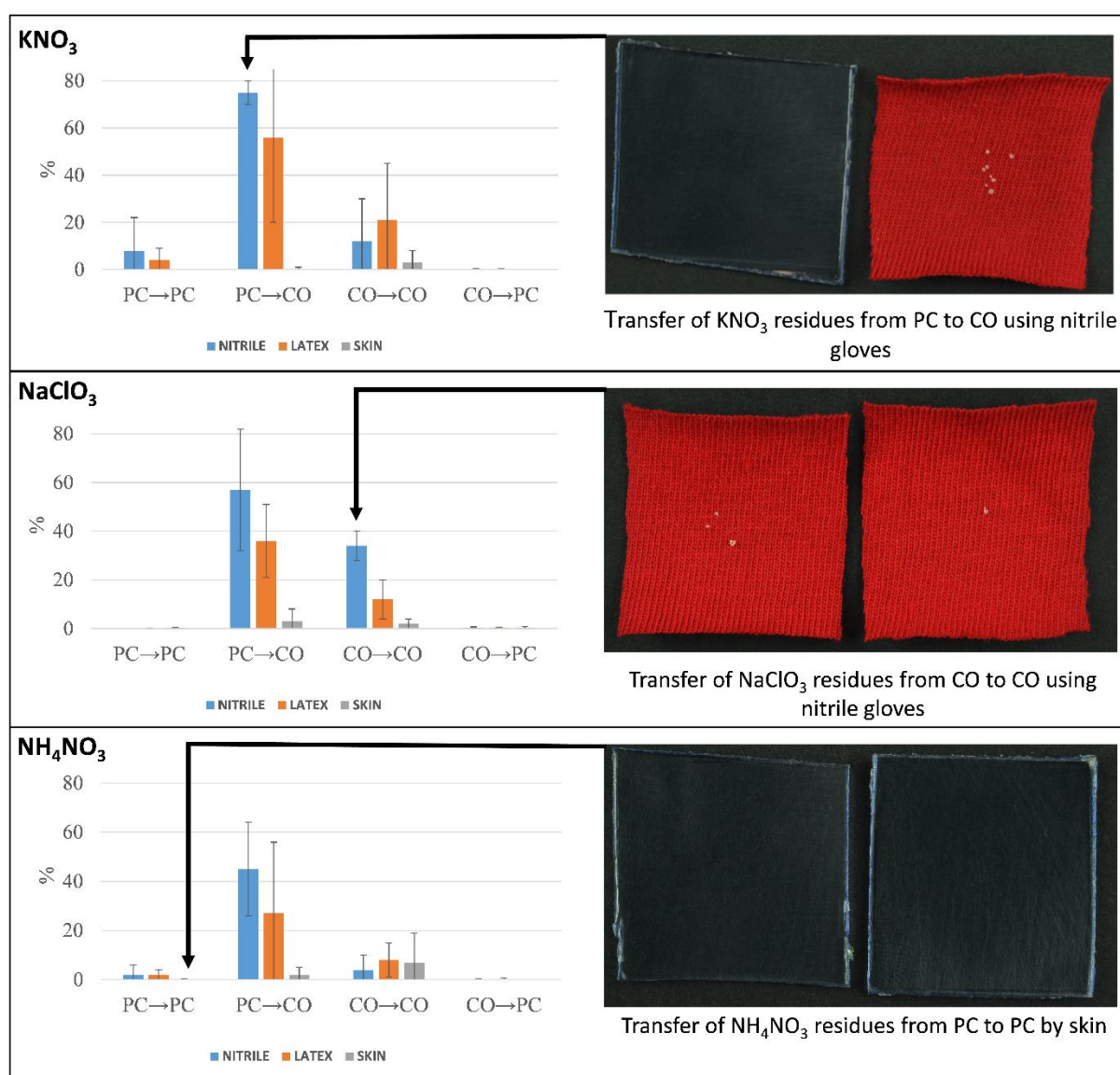

Transfer of KNO_3 residues from PC to CO using nitrile gloves

Transfer of $NaClO_3$ residues from CO to CO using nitrile gloves

Transfer of NH_4NO_3 residues from PC to PC by skin

Fig. 4. Transfer of different inorganic salts (KNO_3, $NaClO_3$ and NH_4NO_3) from polycarbonate/cotton to polycarbonate/cotton by nitrile, latex or skin (n=3). As an example, one picture per inorganic salt of the first and second surface after transfer is displayed.

Abbreviations: PC – polycarbonate plastic, CO – cotton fabric. Error bars represent the standard deviation for three replicates.

Although there were significant differences in some replicates of inorganic salts (NH_4NO_3, KNO_3 and $NaClO_3$), as seen in Fig. 4 through the large standard deviation (up to 50% in some cases), this was actually associated to a very small number of big particles (1-3 particles).

The transfer of residues of explosive mixtures ANFO, dynamite and black powder from polycarbonate or cotton by skin or nitrile/latex gloves is depicted in Fig. 5. Similarly to the inorganic salts, the residues of explosive mixtures were transferred the most from polycarbonate to cotton. This is clearly seen in the case of transfer of ANFO and dynamite residues. On the contrary, black powder was the least transferred explosive under study – its transfer was always below 8%. However, the transfer of several particles of black powder (about 1%) was observed even when using the nitrile gloves (Fig. 5), despite the fact that only a small amount of black powder particles was picked up by nitrile gloves (Fig. 3). As shown in Fig. 5, the transfer of the three explosives by skin to all surfaces under study was below 8%. As an example, the transfer of ANFO residues from polycarbonate to polycarbonate by skin (1-2%) is depicted in Fig. 5. In contrast, 30-40% of the amount of ANFO residues was transferred from polycarbonate to cotton by both, nitrile and latex gloves. However, less than 5% of the amount of ANFO residues was transferred from cotton to either cotton or polycarbonate either by skin, latex or nitrile gloves. At the same time, approximately 30-60% of the amount of dynamite residues was transferred from polycarbonate to cotton by nitrile or latex gloves whereas the degree of transfer using any other surface combinations remained below 10%.
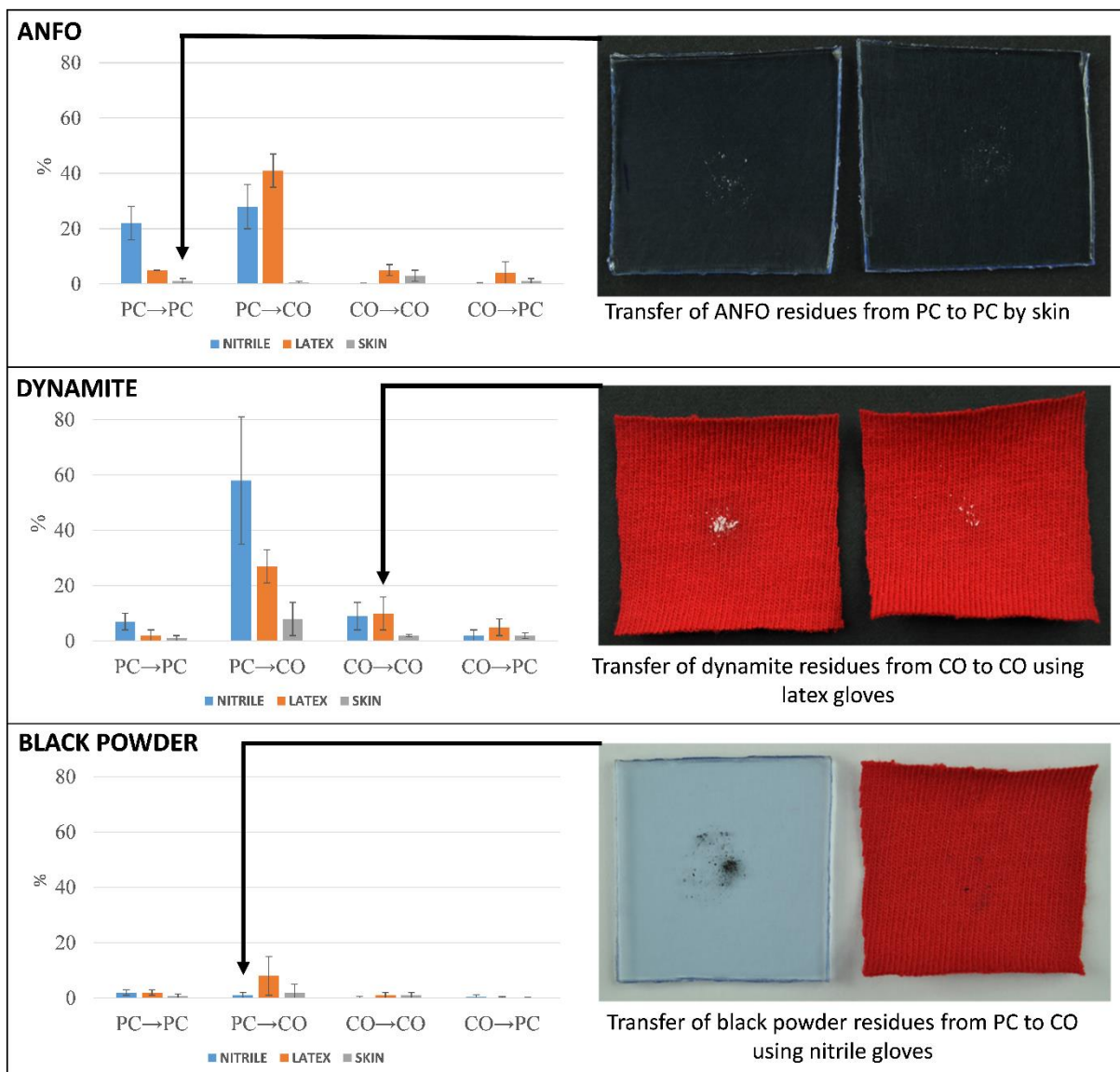
Fig. 5. Transfer of explosive mixtures (ANFO, dynamite and black powder) from polycarbonate/cotton to polycarbonate/cotton by skin, latex or nitrile (n=3). One picture per explosive mixture of the first and second surface after transfer is displayed as an example. Abbreviations as in Fig. 4. Error bars represent the standard deviation for three replicates.

The transfer of the residues of organic explosives HMTD, PETN and TNT from polycarbonate or cotton by skin or nitrile/latex gloves is depicted in Fig. 6. Compared to inorganic salts (Fig. 4) and explosive mixtures (Fig. 5), generally the amount of transferred residues of organic explosives was higher. In fact, their residues were transferred also by skin in amounts up to 26%. The higher degree of transfer of organic explosives may be explained by their smaller particle size compared to inorganic salts and explosive mixtures. The average particle diameter of organic explosives was in the range of 20–75 µm, while that of all other explosives varied between 300 and 500 µm. Among all the explosives studied, TNT was one of the most

transferred explosives: 10–70% of its residues were transferred (considering all possible transfer combinations). The amount of TNT residues transferred from polycarbonate to cotton using gloves was the highest, over 60% (Fig. 6). The degree of transfer of HMTD residues was also quite high, however, the transfer was poor when nitrile gloves were used. This was not surprising because only very few particles of HMTD adhered to nitrile gloves, as shown in Fig. 3. Unexpectedly, the degree of transfer of HMTD particles from polycarbonate to polycarbonate by using latex gloves was the highest, about 70%. The amount of HMTD residues transferred by skin and latex gloves was between 10 and 70%. Of the three organic explosives, the amount of transferred residues of PETN was the lowest. 30% of the initial amount of its residues was transferred from polycarbonate to cotton by using nitrile and latex gloves, while in the case of all other combinations the amount transferred remained below 12%.
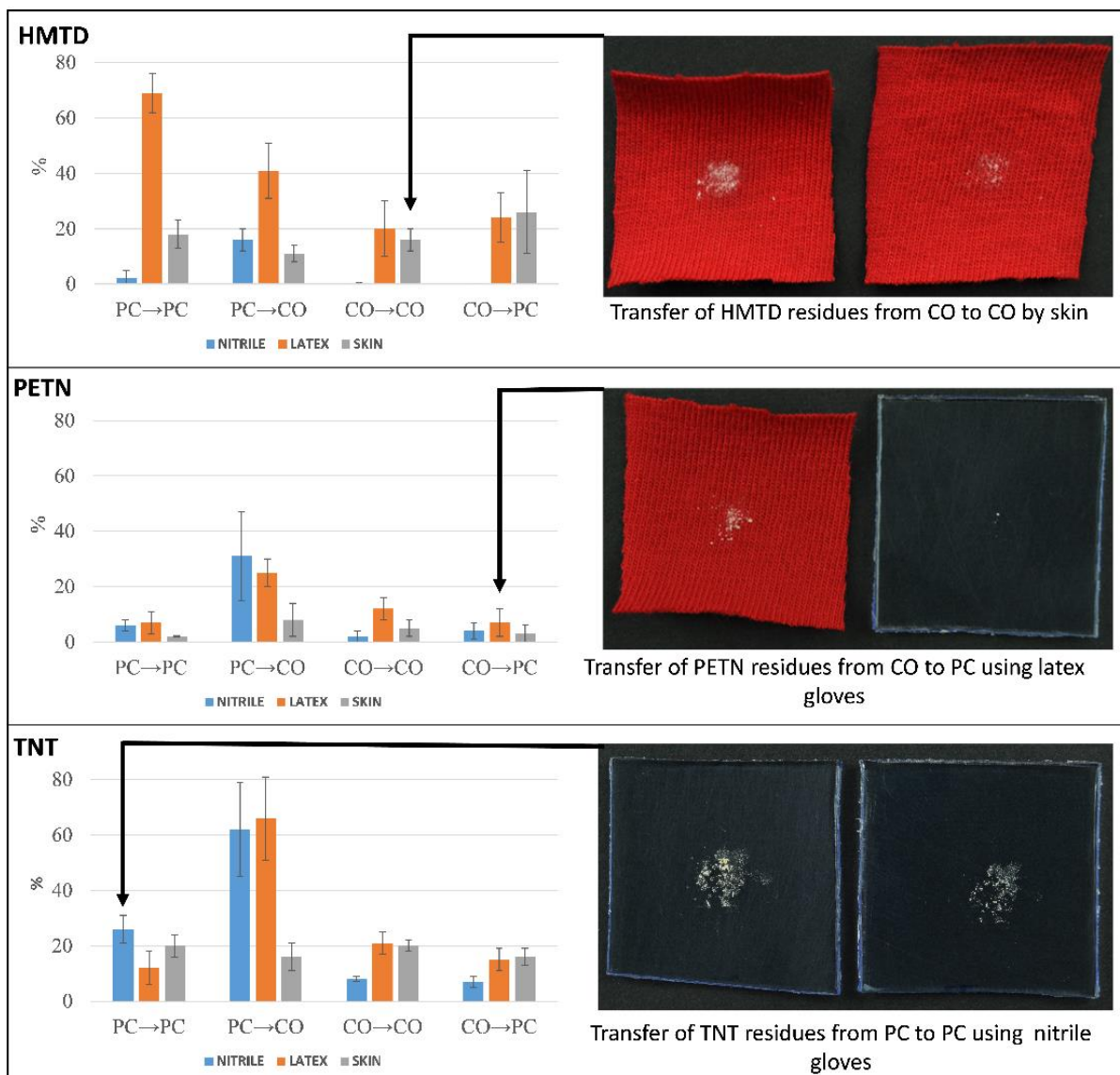
Fig. 6. Transfer of organic explosives (HMTD, PETN and TNT) from polycarbonate/cotton to polycarbonate/cotton by skin, latex or nitrile (n=3). One picture per explosive of the first and second surface after transfer is displayed as an example. Abbreviations as in Fig. 4. Error bars represent the standard deviation for three replicates.

The overall analysis of the transfer patterns of residues of inorganic salts, explosive mixtures and organic explosives revealed some general tendencies.

First, the degree of transfer of the residues of almost all explosives from polycarbonate to cotton using latex or nitrile gloves was the highest, between 25 and 75% of their initial amounts. There were two reasons for this. Firstly, as explained in Section 3.1, explosive particles adhered more easily to skin/latex/nitrile from polycarbonate than from cotton. Secondly, cotton fabric was the best surface for transfer, but not for picking up the residues from. The higher degree of transfer

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of explosive particles to cotton fabric could be explained by their easy trapping to the fine fibers of cotton. Unlike the surface of polycarbonate plastic, the surface of cotton fabric is rough.

Secondly, while polycarbonate→cotton was the best surface combination for transferring explosive residues by a fingertip, the smallest amounts were transferred to polycarbonate surface. Particularly, the amount of explosive residues transferred from cotton to polycarbonate was the lowest. This happened for the following two reasons: a) overall, smaller amounts of explosive residues were adhered from cotton to fingertip than from polycarbonate and b) the residue amount transferred to the smooth polycarbonate surface was lower than to the fibrous cotton surface. In this respect, small amounts of residues of inorganic salts and explosive mixtures were transferred – less than 5% in all cases.

Thirdly, the lowest amount of residues was transferred by the bare finger, the degree of transfer was always below 26% (see Figures 4-6). As explained in Section 3.1, the amount of explosive particles adhered to the fingertip decreased in the order skin>latex>nitrile, while the amount of explosive particles transferred to the second surface, in general, decreased in the opposite order: nitrile>latex>skin. Particularly, this difference was evident in the case of the surface combination polycarbonate→cotton. Usually a higher amount of residues was transferred using nitrile gloves than by skin, because the particles got stuck to the bare finger instead of being transferred to another surface. This was the main reason why the amount of explosive particles transferred by skin was low, evidencing the higher degree of explosive particles adhesion to skin compared to other surfaces (even cotton). Thus, using all combinations of materials and surfaces, the adhesion of residues was subjected to the following order: skin>cotton>latex>nitrile>polycarbonate.

Lastly, it should be mentioned that even if the amount of transferred residues was often low, the transfer of several small microscopic particles still took place, which will be potentially detected by those analytical techniques used for trace explosives detection. In fact, the identification of the transferred explosive particles on both studied surfaces was proved in this study using Raman spectroscopy. The Raman spectra of transferred particles on each surface are displayed in Supporting Information. Thus, these kinds of sensitive trace explosive detectors used at airports would also detect these transferred explosive traces produced by cross-contamination, providing evidence for a false accusation of the passenger at airport controls.

Conclusions

In general, a higher amount of explosives residues was picked up by the fingertip from polycarbonate plastic than from cotton fabric. The highest amounts of residues of almost all explosives were transferred from polycarbonate plastic to cotton fabric, *i.e.* from luggage to clothing. The amount of residues transferred to the smooth polycarbonate surface was lower (combinations polycarbonate→polycarbonate or cotton→polycarbonate).

This research evidenced that the explosive particles can adhere to a fingertip from surfaces under study in large percentage (especially in the case of inorganic salts, which are known as the main components of a wide variety of improvised explosive devices). The amount of explosive residues adhered to the finger decreased in the following order: skin>latex>nitrile. Thus, a higher amount of explosive residues was adhered to skin (bare finger) than to glove materials. At the same time, the transfer of explosive residues from polycarbonate to cotton surface decreased in the opposite order: nitrile>latex>skin. Therefore, the amount of explosive residues transferred by nitrile gloves was the highest and by skin the lowest. This was because explosive particles stuck to the bare finger, instead of being transferred to another surface.

In some cases, the amount of transferred explosive residues (from the initial 10 mg) was very small, especially by skin. However, such small amounts of transferred explosive residues were detected by Raman microscopy (since the size of explosive particles was in the μm range). Thus, the transfer of these microscopic explosive particles (or even smaller) would be easily detected by using sensitive trace explosive detectors.

This research demonstrated that the transfer of explosive residues occurred from one surface to another, despite gloves on or not. Based on the results of this pioneering study, it can be reasonably assumed that cross-contamination may take place at airports through contaminated gloves, or hands. However, further experiments studying different scenarios in real airports are necessary to confirm this assumption since a predefined laboratory procedure of pressing and transfer was followed in this study to ensure reproducibility and comparison of explosives, which is not that realistic to the situation at airports. Even so, in the light of these experiments and results, two main recommendations should be contemplated: a periodic auto-checking of the security officers; and the removal and exchange of gloves after a positive detection of explosives in one passenger's belongings.

Conflicts of interest

The authors have declared no conflicts of interest.

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