Trace evidence dynamics of cocaine on banknotes: A comparison study of paper and polymer banknotes

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Abstract

It is well established that a large proportion of paper banknotes in circulation contain traces of cocaine. Being able to discriminate between the innocent transfer of illicit drug particles acquired through everyday interactions with surfaces such as banknotes, as opposed to transfer resulting from criminal activities can provide valuable intelligence that can inform an investigation. With many countries adopting polymer banknotes as legal tender, it is important to consider the transfer of cocaine from these surfaces as well as the retention of these particulates on polymer banknotes for evaluative interpretation in crime reconstruction. This comparison study assessed three contact variables (force, time, and rotation) on the transfer of cocaine particulates from paper and polymer banknotes onto a human skin proxy. The persistence of cocaine particulates was assessed through a realistic scenario which mimicked a cash transaction. Quantifiable amounts of cocaine were transferred onto the human skin proxy across all of the contacts assessed, with a greater transfer observed with contacts involving polymer banknotes and those contacts which involved rotation. Following extensive handling, cocaine persisted on both banknote types, with paper banknotes retaining larger amounts of cocaine than polymer banknotes. These findings show that cocaine can persist on both paper and polymer banknotes for extended periods of time following handling and is therefore available for transfer. This transfer then readily occurs, even when contact is brief and involves relatively small forces. A key distinction between the banknote types was that cocaine particulates are more likely to transfer from polymer banknotes due to the lower retention rate of particulates on this surface. Such insights can aid in evaluating the relevance of illicit drug particles identified on items or persons of interest in crime reconstruction approaches.

Keywords

Forensic science; Experimental studies; Transfer; Persistence; Crime reconstruction; Instron ElectroPuls

1. Introduction

In 2019, an estimated 20 million people worldwide used cocaine (0.4% of the total population between 15 and 64 years old) [1]. Over the same period, cocaine (benzoylmethylecgonine) was the second most commonly used illicit drug in Europe, with 3.5 million users (1.2% of the total population aged 15 to 64) [2]. Cocaine, a Class A drug under the UK Misuse of Drugs Act (1971), is a common environmental contaminate, with cocaine traces found on approximately 13% of fingerprints from self-reported drug-free volunteers [3] and on many paper banknotes in circulation [4,5,6,7,8,9,10,11]. A person handling adulterated banknotes is therefore likely to receive traces of drugs onto their hands. Historically, banknotes have been made from cotton and linen papers (cellulose fibres), a porous substrate [12] but since Australia replaced paper banknotes with polymer banknotes in 1996 [13], other countries have either adopted, or have started to adopt, polymer banknotes as legal tender [14,15,16,17]. These polymer banknotes are commonly produced using biaxially oriented polypropylene (BOPP), a non-porous substrate [18].
Despite the decline of cash economy [19], cash is still often used in organised crime transactions [20], and the change from paper to polymer banknotes is likely to impact upon the transfer and persistence of cocaine traces on and to these surfaces. Being able to discriminate between the innocent transfer of drug traces acquired from contaminated surfaces, such as banknotes, as opposed to transfer resulting from illicit activities is of relevance to crime reconstructions as particle traces provide valuable intelligence that can inform an investigation [21]. It is important to be able to identify traces, and also to understand the dynamics of those traces to establish how and when they have been transferred to an object or a person [22,23]. Empirical studies assessing the dynamics of how these traces may have been transferred, under what conditions they may persist, and over what timescales can these traces persist, can provide contextual information and enable robust crime reconstructions [24,25].

This paper presents an experimental study which was designed to compare the transfer and persistence of cocaine particulates on paper and polymer banknotes that were intentionally adulterated with controlled amounts of cocaine. A reductionist approach was taken to understand the individual impact that time, force, and rotation have on the percentage of cocaine transferred from paper and polymer banknotes onto a human skin proxy. The duration of contact, force of contact, and rotation applied during contact were controlled using an Instron ElectroPuls E3000, a method previously used to characterise transfer of explosive particulates [26]. To assess persistence, paper and polymer banknotes were handled up to fifty times, and the amount of cocaine present on each banknote quantified following each prescribed handling period. Results from studies such as this can aid in developing an understanding of the proportion of cocaine that can be transferred by direct handling of adulterated banknotes under different testing parameters as well as how long these particulates will persist on banknotes following repeated handling. These insights can then be used to create an evidence based approach for the interpretation of trace particles such as cocaine in crime reconstructions.

2. Materials and Methods

2.1 Banknotes

Foreign currency banknotes were drawn over the counter from a local Eurochange (Crickhowell, UK). For this study, paper United States one-dollar banknotes and polymer Vietnamese twenty thousand đồng banknotes were used (see **Fig. 1**). Of the paper currency issued in the United States, the one-dollar banknote, made from a blend of 25% linen and 75% cotton, is the most common banknote in circulation [27]. Vietnam was an early large-scale adopter of polymer banknotes [28,29] and the twenty thousand đồng banknote, made from BOPP, was selected as having an approximate equivalent value (~ $0.9 USD). To remove any previously transferred particulates each note was twice washed with isopropyl alcohol [30], and subsequently allowed to dry, before the experiment was undertaken; cocaine was not detectable in the negative controls.

Fig. 1. United States one-dollar (1 USD) paper banknote (left) and Vietnamese twenty thousand đồng (20,000 VND) polymer banknote (right) used in this study.

2.2 Transfer Study

With such a high number of banknotes in circulation adulterated with cocaine traces, coupled with the frequency with which banknotes are handled in society, drug traces are likely to be transferred onto the hands of individuals who make contact with banknotes. As such, this study was designed to quantify the amount of cocaine transferred onto a human skin proxy from paper and polymer banknotes following a controlled contact. Chamois leather (Amazon, UK) was used as a proxy for human skin and was preconditioned by wearing under clothing for a period of eight hours to transfer dermal oils. This material was chosen as it has been shown to mimic both the mechanical and frictional contact behaviour of human skin [31, 32]. All leather samples were cut into 1 cm^2 circles (n = 90).

2.2.1 Adulteration of Banknotes with Cocaine Hydrochloride

A 1,000 mg/L working solution of cocaine hydrochloride (HCl) (≥ 97.5% purity; Sigma Aldrich, Gillingham, Dorset, UK) was prepared by dissolving 0.1 grams of cocaine HCl powder in 100 cm^3 of methanol (HPLC grade; Sigma Aldrich, Gillingham, Dorset, UK). Each banknote was subdivided into ten approximately equal sections (**Fig. 2**). To the centre of each section, 250 µL of the working solution was spotted. Banknotes were then left to air dry for one hour to allow the solvent (methanol) to evaporate and the solute (cocaine HCl) to recrystallize onto the surface.

Fig. 2. Exemplar template of how each banknote was subdivided into ten sections.

2.2.2 Controlled Contact

An Instron ElectroPuls E3000 material testing instrument (Instron, High Wycombe, UK) was used to control the duration of contact, force of contact, and extent of rotation applied during contact (**Table 1**). In each run, the adulterated banknote was affixed to the dynamic load cell and the leather recipient surface was affixed to the static load cell of the instrument. Operation was controlled through Instron WaveMatrix software using a three-step method. The first step brought the banknote and leather recipient surface into contact at a speed of 0.05 mm/s. Once contact occurred, the second step controlled the time and force at which the surfaces were held under compression. Rotation was applied by delivering a fixed angular velocity for 4, 8, or 12 s to provide rotation of 120, 240, or 360 degrees. The third step broke the contact between the two surfaces, moving the surfaces away from one another at a speed of 0.05 mm/s. Each experimental run was assessed five times and the mean and standard deviation calculated.

Table 1
The control factors and variables tested in each experimental run. A ±250 N Dynacell (dynamic load cell) was fitted for experiments one through twelve (those assessing the impact of force and time) and a ±5 kN Dynacell, with a torsional range of ±25 Nm, fitted for experiments thirteen through eighteen (those assessing the impact of rotation).

Experiment	**Control Factors**			**Variables**	
	Force (N)	**Rotation (°)**	**Recipient Surface**	**Transfer Surface**	**Time (s)**
1	100	0	Chamois leather	Paper banknote	2
2					60
3					300
4				Polymer banknote	2
5					60
6					300
Experiment	**Control Factors**			**Variables**	
	Time (s)	**Rotation (°)**	**Recipient Surface**	**Transfer Surface**	**Force (N)**
7	30	0	Chamois leather	Paper banknote	10
8					120
9					240
10				Polymer banknote	10
11					120
12					240
Experiment	**Control Factors**			**Variables**	
	Time (s)	**Force (N)**	**Recipient Surface**	**Transfer Surface**	**Rotation (°)**
13	30	100	Chamois leather	Paper banknote	120
14					240
15					360
16				Polymer banknote	120
17					240
18					360

2.2.3 Extraction of Cocaine Hydrochloride

To extract the cocaine from each of the leather samples, 1 cm^3 of methanol was added and the samples were then agitated at 70 rpm for 30 minutes using a Cole-Parmer Stuart See-Saw Rocker. Following this, the leather samples were wrung dry (using forceps that were cleaned between samples) and the extracts transferred into 2 cm^3 autosampler vials. The amount of cocaine present in extract was quantified using gas chromatography with a flame ionization detector as outlined in **Section 2.4**. The extraction efficiency of the method was assessed by spotting five leather samples with 100 µL of the stock solution of cocaine HCl and quantifying the amount recovered following extraction.

2.3 Persistence Study

A further study was designed to compare the persistence of cocaine on adulterated paper and polymer banknotes following handling. A realistic scenario was designed to mimic an everyday cash transaction whereby cash is removed from, and returned to, a wallet.

2.3.1 Adulteration of Banknotes with Cocaine Hydrochloride

Each banknote was divided into five sections (**Fig. 3**) and 250 µL of the working solution of cocaine HCl (1,000 mg/L) spotted onto the centre point of each section. The banknotes were left to air dry for one hour, to allow for the solvent (methanol) to evaporate and the drug (cocaine HCl) to recrystallise on the surface.

Fig. 3. Exemplar template of how each banknote was subdivided into five sections.

2.3.2 Handling

To assess the persistence of cocaine on banknotes following handling, an adulterated banknote was placed inside a billfold wallet, which was then folded, and subsequently placed inside a trouser pocket. The wallet was then removed from the pocket, unfolded, and the banknote taken out. This process was repeated ten times after which the first section of the banknote was sampled. Subsequent sections of banknote were sampled following the note being handled twenty, thirty, forty, and fifty times. The whole experiment was then replicated to generate data across five runs for each banknote type (paper and polymer). Each banknote type was assessed independently, and a new banknote used for each replicate (a total of five of each type of banknote). A new billfold wallet was used for each experimental run (total of 10 wallets).

2.3.3 Recovery of Cocaine Hydrochloride

Following the method outlined by Amaral et al. [33], a sampling gel was prepared by combining gelatine powder, arrowroot powder, glycerine, and water in a mass ratio of 3:1:1:5. Using a disposable plastic syringe, a thin layer of gel was applied over the surface area of the banknote section being sampled (~19 cm^2). The gel was left to dry for 15 minutes, before being peeled from the surface using forceps, and placed into a beaker. The gel was dissolved in 25 cm^3 of water at 75°C with 0.6 g of powdered bromelain added to prevent re-solidification. Cocaine HCl was isolated from the gelatine-based matrix using solid-phase extraction (SPE) (**Fig. 4**) following which the eluates were dried under a stream of nitrogen gas and reconstituted in 1 cm^3 of methanol prior to analysis. The recovery efficiency of the method was assessed by spotting five sections of a paper and polymer banknote with 250 µL of the stock solution of cocaine HCl, applying the gel to each section and then isolating cocaine HCl from the gel matrix using SPE. Cotton wool swabs wetted with methanol were used to sample the billfold wallets for cocaine.

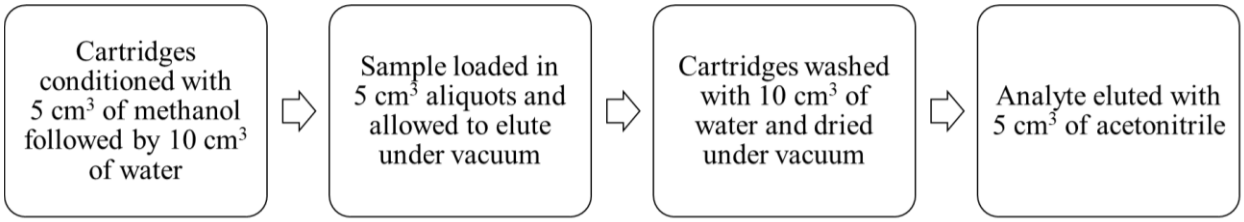

Fig. 4. SPE method used to isolate cocaine HCl from the gelatine-based matrix.

2.4 Analysis and Quantification

All analyses were carried out using a Shimadzu Nexis GC-2030 gas chromatograph with an AOC-20i Plus auto injector and flame ionization detector. The method used was adapted from the United Nations Office on Drugs and Crime (**Table 2**) [34]. Analysis of a standard solution of cocaine HCl yielded two resolved Gaussian peaks: a solvent peak at 1.7 mins and an analyte peak at 5.2 mins.

Table 2
Gas chromatograph operating conditions used for identification and quantification of cocaine HCl.

Detector:	FID
Column:	SH-Rxi-5ms, 30 m length, 0.25 mm ID, 0.25 µm film thickness
Carrier gas:	Helium 1.14 mL/min
Injector temperature:	280°C
Detector temperature:	280°C
Oven temperature:	250°C
Injection volume:	2 µL
Split ratio:	25:1
Run time:	7 min

To quantify the amount of cocaine HCl present in each extract, a ten-point calibration curve was established (concentration range: 1 mg/L to 1,000 mg/L). Each of the calibration standards were injected onto the column in triplicate, and the average peak area calculated. This was then plotted against the concentration of each calibrator and the linearity evaluated. The resultant coefficient of determination (R^2 = .99) indicted a linear relationship over the concentration range tested. Using the established line equation, y = 374.71(x) – 7142.87, the concentration of cocaine HCl in each extract was calculated by correlating its resultant peak area (y) to a concentration (x).

2.5 Statistical Analyses

Data was analysed using IBM SPSS Statistics (version 26). The Shapiro-Wilk test was used to determine whether the data followed the Normal distribution or not. In all instances, the tests did not show evidence of non-normality ($p > 0.05$). Based on this, and the visual examination of the Q-Q plots, parametric tests were used. A one-way analysis of variance (ANOVA) was conducted to determine if the mean amount of cocaine HCl transferred depended on the duration of contact, force of contact, or extent of rotation applied. The strength of the relationship between the contact parameters (time, force, and rotation) and the amount of cocaine HCl transferred was then assessed using Pearson product-moment correlation coefficients. Based on the regression models, a two-sample *t*-test (assuming unequal variances) was carried out to compare the mean amount of cocaine HCl transferred when contact involved rotation, to those contacts that did not involve rotation. The impact of banknote type (paper and polymer) on the transfer of cocaine transferred was also assessed using a two-sample *t*-test (assuming unequal variances).

The relationship between the number of times a banknote was handled and the amount of cocaine present on the banknote was evaluated using the Pearson product-moment correlation coefficient. A two-sample *t*-test (assuming unequal variance) was then carried out to compare the mean amount of cocaine recovered from a billfold wallet containing an adulterated polymer banknote to the recovery of cocaine from a wallet containing an adulterated paper banknote.

Cohen's *d*, the standardised mean difference, was used to measure the effect size (values >0.8 indicated a large effect size, where the results are likely to show a meaningful difference between the two groups [35]). The means +/- 1 standard deviation, along with the coefficients of variation, are presented throughout. An alpha level of .05 (5%) was used for all statistical tests.

3. Results

3.1 Transfer Study

The recovery efficiency of the extraction technique employed to liberate cocaine HCl from the recipient surface (chamois leather) was determined to be 20.4 ± 0.9%. Even though the percentage recovery was relatively low, the recovery was consistent (%CV = 4.2%). To provide a more accurate representation of the actual amount of cocaine HCl transferred, the measured amount of cocaine HCl in each sample was adjusted to account for the average percentage lost (79.6%) in the recovery process.

Across the three parameters tested (the duration of contact, force of contact, and extent of rotation applied during contact), polymer banknotes consistently transferred more cocaine HCl to the skin proxy than paper banknotes. This finding was significant ($t(88) = 15.91$, $p < .001$, $d = 3.35$), and substantial, with approximately twice the amount of cocaine HCl transferred to skin from a polymer banknote than a paper note. The amount of cocaine HCl transferred from paper banknotes did not depend on the duration or force of contact (time: $R^2 = .19$, $F(1, 13) = 3.04$, $p = .105$; force: $R^2 = .08$, $F(1, 13) = 1.08$, $p = .318$). With contacts occurring with polymer banknotes, larger contact forces resulted in a greater transfer of cocaine HCl, $R^2 = .75$, $F(1, 13) = 39.25$, $p < .001$. No trend was observed for the duration of contact, $R^2 = .02$, $F(1, 13) = 0.25$, $p = .623$ (see **Fig. 5)**.

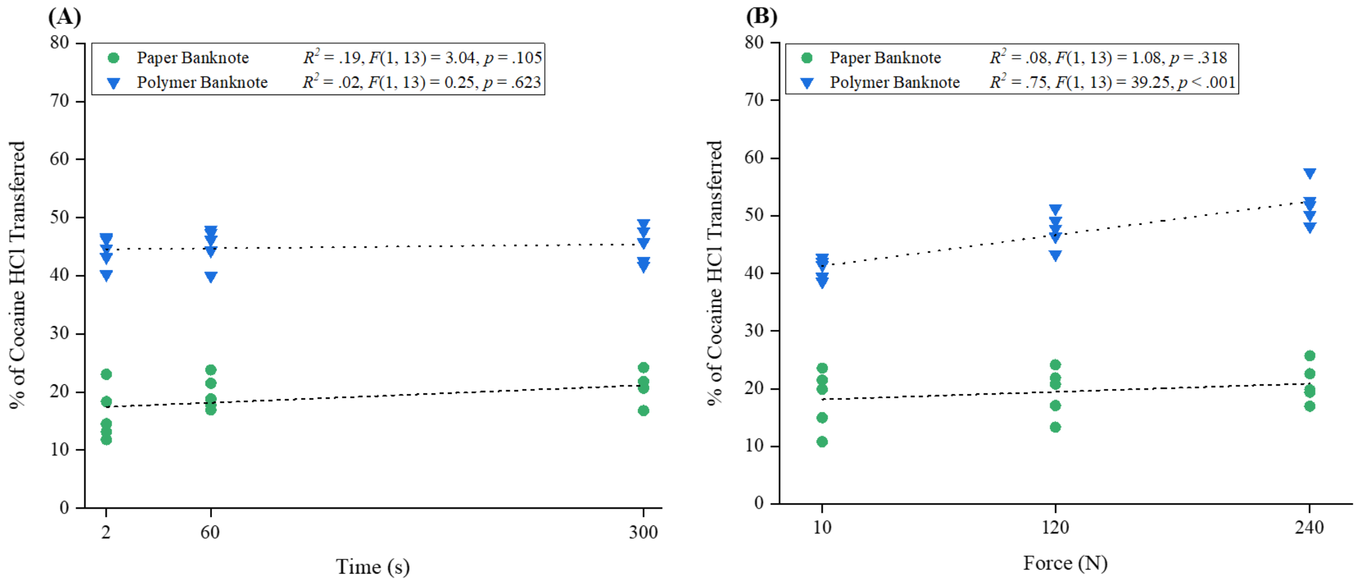

Fig. 5. The percentage of cocaine HCl transferred from adulterated paper and polymer banknotes onto the recipient surface following contacts occurring at three different times (A) and forces (B).

For both polymer and paper banknotes, contact which involved rotation resulted in a larger transfer of cocaine HCl onto the recipient surface than those contacts not involving rotation (paper: $t(43) = 9.25$, $p < .001$, $d = 2.93$; polymer: $t(43) = 7.80$, $p < .001$, $d = 2.47$). With paper banknotes, increasing the amount of rotation applied over the contact period resulted in an increased transfer of cocaine HCl onto the recipient surface, $R^2 = .34$, $F(1, 13) = 6.71$, $p = .022$. No trend was observed for polymer banknotes, $R^2 = .02$, $F(1, 13) = 0.22$, $p = .649$. The results are summarised in **Fig. 6**.

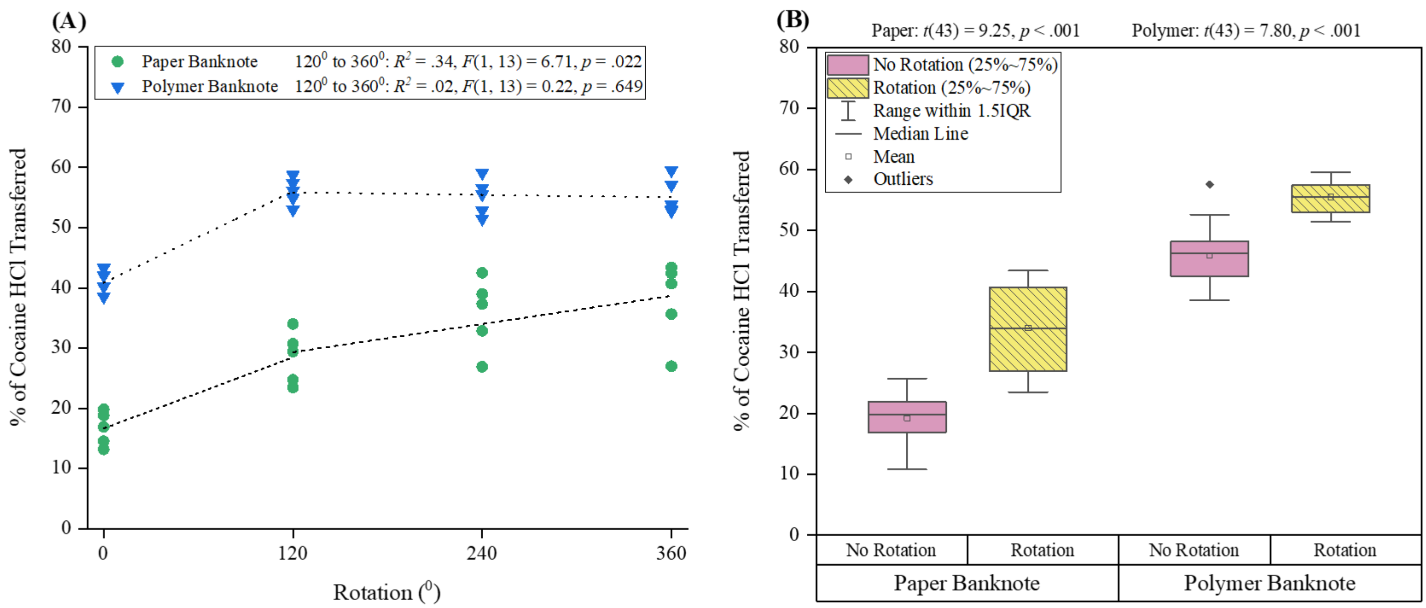

Fig. 6. (A) The percentage of cocaine HCl transferred from adulterated paper and polymer banknotes onto the recipient surface following contacts occurring without rotation and with three rotations applied during contact. (B) Box plot comparison of the amount of cocaine HCl transferred from adulterated paper and polymer banknotes across contacts occurring without rotation and those with rotation.

3.2 Persistence Study

Using the gelatine-based collection medium, the recovery of cocaine HCl from banknotes was determined to be 9.5 ± 1.3% for paper banknotes and 38.9 ± 1.8% for polymer banknotes. The recoveries of cocaine from paper banknotes yielded higher coefficients of variation (%CV = 13.6%) than those from polymer banknotes (%CV = 4.6%). As such, the percentage variability in the recovery of cocaine HCl was less from polymer banknotes. Following handling, the measured amount of cocaine present on each section of the paper and polymer banknotes was adjusted for, accounting for the average percentage recovery of the technique on both banknote types.

On average, 399.8 ± 30.3 mg/L of cocaine HCl remained on the surface of paper banknotes following handling. For polymer banknotes, the average was 158.0 ± 32.4 mg/L. Greater quantities of cocaine were therefore persisting on paper banknotes after handling. This finding was significant, $t(48) = 27.25$, $p < .001$, $d = 7.71$. With increased handling, the concentration of cocaine HCl present on polymer banknotes decreased, $R^2 = .85$, $F(1, 23) = 131.12$, $p < .001$. No trend was observed for paper banknotes, $R^2 = .02$, $F(1, 23) = 0.36$, $p = .556$ (**Fig. 7)**.

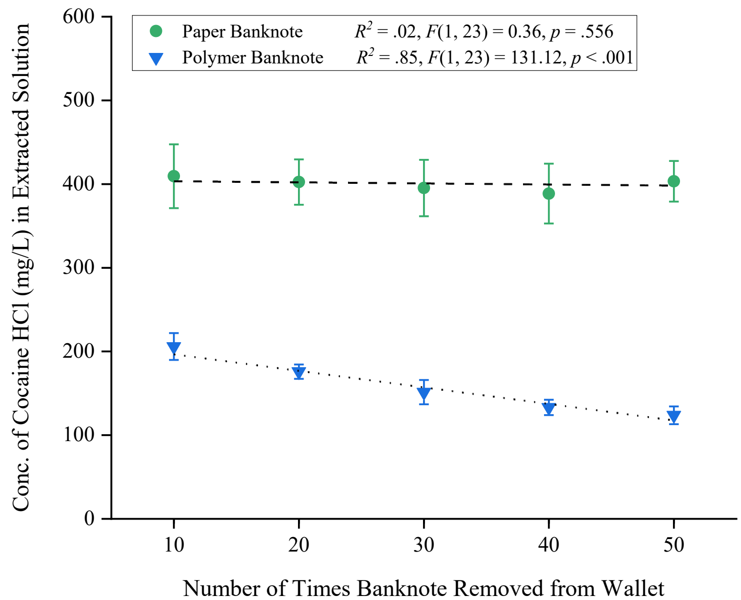

Fig. 7. The average amount of cocaine HCl quantified in the extracts. Each banknote was sampled following handling a defined number of times. Error bars represent ± one standard deviation from the mean.

Following housing adulterated banknotes, each wallet was swabbed and the amount of cocaine HCl present quantified (the recovery efficiency of the swabbing method was 39.2%). The results obtained showed that swabs from wallets which housed adulterated paper banknotes had lower concentrations of cocaine HCl than those that held adulterated polymer banknotes (**Fig. 8**). This supports the observation that there was a larger transfer of cocaine HCl from polymer banknotes to the billfold wallet than from paper banknotes, $t(8) = 9.09$, $p < .001$, $d = 5.75$.

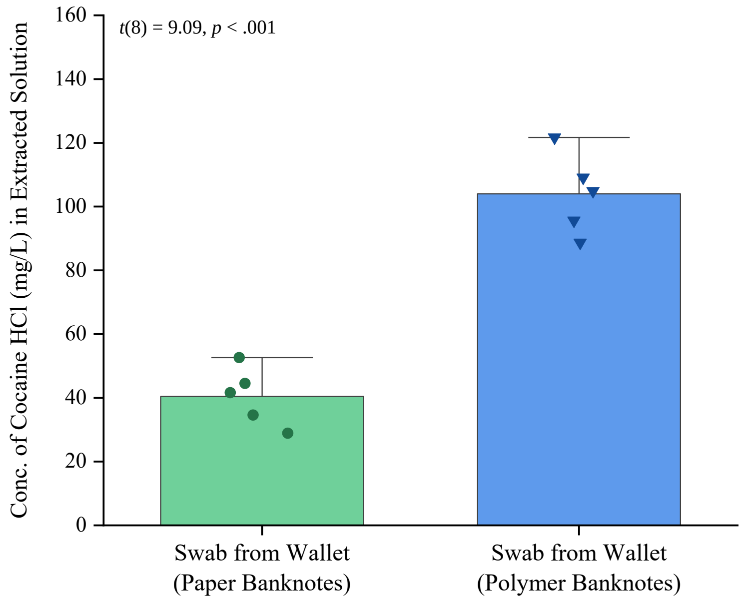

Fig. 8. Comparison of the amount of cocaine HCl quantified in the extracts after sampling the billfold wallets that housed either adulterated paper or polymer banknotes. Data points represent the amount of cocaine HCl quantified on each swab after sampling the billfold wallets which housed each banknote type.

4. Discussion

Chamois leather as a material which could mimic the mechanical and frictional contact behaviour of skin [31, 32] provided a suitable proxy to assess the mechanics of transfer. However, the properties of human skin are complex and continuously changing due to different factors [31]. As such, this needs to be taken into account when considering the results of this study and how they can be applied to situations of transfer of particles to human skin. The extraction method to recover cocaine from the recipient surface (preconditioned chamois leather) provided consistent results (%CV = 4.2%) and as such, offered insights for meaningful comparisons with respect to the transfer of cocaine (expressed as a percentage) from paper and polymer banknotes under different testing parameters. It was found that cocaine was readily transferred from adulterated paper and polymer banknotes onto a proxy for human skin across all testing parameters. A greater number of cocaine particulates were transferred from polymer banknotes than from paper banknotes. This is likely due to the differences in the surface topography (as shown in the SEM micrographs (**Fig. 9**)). The results suggest that cocaine particulates are more likely to be retained within the porous matrix of paper banknotes while having a lower retention on non-porous polymer banknotes. This was an expected result and is in agreement with other studies that have assessed the impact of surface type on the transfer of trace forensic materials such as DNA [36,37].

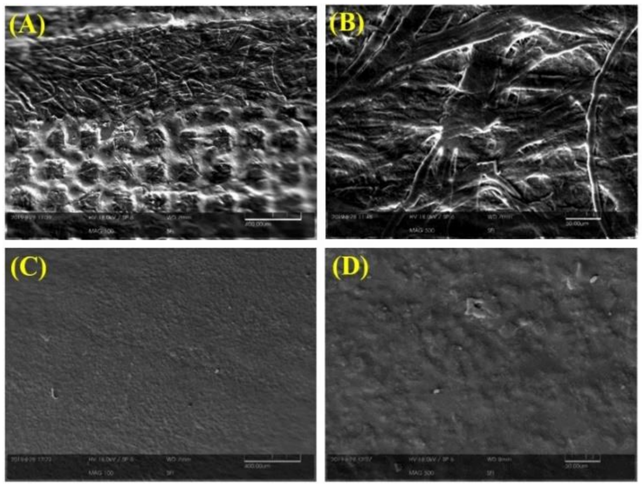

Fig. 9. SEM micrographs. US one dollar paper banknote (A) 100x magnification and (B) 1,000x magnification. Vietnamese twenty thousand đồng polymer banknote (C) 100x magnification and (D) 1,000x magnification. Micrographs acquired using a Pemtron PS-230 scanning electron microscope (Pemtron, Seoul, South Korea) fitted with an Oxford Instruments X-act energy-dispersive X-ray spectrometer system (Oxford Instruments, Abingdon, UK).

The results indicate that the transfer of cocaine was independent of the duration of contact. A similar finding was noted by Amaral et al. [26] with respect to the transfer of explosive residues. Conversely, contact time has been shown to have an impact on the transfer of fragrances [38]. As such, there is evidence to suggest that the transfer of volatile organic compounds increases with prolonged contact whilst the transfer of solid particulates is independent of contact time. The impact of the type of evidence being transferred therefore needs to be considered as a factor and warrants further exploration.

Contacts which occurred at higher forces resulted in a larger transfer of cocaine from polymer banknotes whereas force did not impact the amount of transfer from paper banknotes. It is probable that higher contact forces are able to dislodge cocaine particulates from low porosity surfaces more readily than from higher porosity surfaces where there is a higher likelihood of the particulates being trapped within the pores of the surface. The force applied over a given surface area (pressure) has been reported to have an influence on the transfer of trace DNA [39] but not on the transfer of explosive residues [26]. Again, this highlights the complexity of evidence transfer and the need for further research to address evidence dynamics of relevant traces.

All contacts which involved rotation resulted in greater quantities of cocaine being transferred when compared to contact not involving rotation. Increasing the amount of rotation applied over the contact period resulted in a greater transfer from paper banknotes. This suggests that a larger proportion of cocaine particles are being liberated from the paper matrix of banknotes as the amount of rotation applied during contact increases. For polymer banknotes, only the application of rotation resulted in an increased transfer; the amount of rotation applied was not found to impact upon the amount transferred from polymer banknotes. Although there is limited published research on the impact of rotation on the transfer of forensic materials, a recent study by Amaral et al. [26] reported similar findings whereby contacts which involved rotation transferred more ammonium nitrate onto the recipient surface than contacts occurring without rotation.

A solution deposition was used to seed the banknotes with cocaine HCl in order to achieve accurate control over the concentration. Additionally, this form of deposition allowed for the percentage of cocaine transferred to be calculated from the concentration of cocaine HCl quantified in the extracts from the recipient surface. An important consideration is that the crystallisation of cocaine from the solvent will be likely to exhibit differences from the dry powdered form. The findings are therefore more relevant to damp environment conditions and in situations where adulterated banknotes have taken on moisture and then subsequently dried. Building upon the contact parameters assessed in this reductionist approach, the interaction of cocaine particulates with the surface, such as the electrostatic forces involved, should be considered.

Using a gelatine-based sampling medium, the average recovery of cocaine from polymer banknotes (38.9 ± 1.8%) was comparable to the recovery results reported by Amaral et al. [33] for explosive residues on acrylonitrile butadiene styrene (ABS) surfaces (38.6%). For paper banknotes, the average recovery (9.5 ± 1.3%) obtained was higher than previously reported recoveries from porous surfaces (wood: 1.1%, fabric: 1.6%, and carpet: 6.8%) [33]. As this recovery method had previously only been used to sample explosive residues [33] we expand upon the application of this technique as a viable method to also sample drug residues.

The trend in persistence was important to assess rather than the raw amount of cocaine HCl present on the banknote following handling. As such, the differences in the efficiencies of the recovery method for paper and polymer banknotes did not impact upon the ability to assess these trends. With successive handling, a continual decrease in the amount of cocaine present on polymer banknotes was observed. The observed trend was linear and departed from the two-stage model of decay curve first reported by Pounds and Smalldon [40] for fibre evidence and subsequently identified for other evidence types including: glass [41], pollen [42], hair [43], foam [44], fragrances [45], and diatoms [46]. However, these studies all assessed the persistence over time whereas this research assessed persistence following activity (the handling of banknotes). For paper banknotes, the amount of cocaine recovered remained relatively stable following handling. Therefore, cocaine is likely to persist on paper banknotes for longer periods of time following handling than for polymer banknotes. Following handling, the billfold wallet used to house each banknote was sampled for cocaine residues. A greater amount of cocaine was recovered from wallets that contained adulterated polymer banknotes than from those containing adulterated paper banknotes. This supports the finding that cocaine is more readily lost from polymer banknotes.

5. Conclusion

This study compared the transfer and persistence of cocaine on paper and polymer banknotes. The independent impact of three contact variables (time, force, and rotation) on the transfer of cocaine onto a human skin proxy was assessed. Automated control of the parameters in which contact between a given banknote and the recipient surface occurred was achieved using an Instron ElectroPuls E3000. To assess persistence, a realistic scenario was constructed to mimic an everyday cash transaction whereby cash was removed from, and returned to, a wallet. Each banknote was sampled after defined handling periods. The amount of cocaine transferred onto the recipient surface, as well as the amount of cocaine present on each banknote following handling, was quantified using GC-FID. The results from this study demonstrated that:

1) cocaine is readily transferred from both paper and polymer banknotes through contact;
2) a greater transfer of cocaine occurred from polymer banknotes;
3) contacts which involved rotation resulted in a larger transfer of cocaine than contacts not involving rotation;
4) cocaine persisted on both banknote types following extensive handling;
5) following handling, cocaine is more easily lost from polymer banknotes.

The results from this study provide empirical data that offer insights into the factors which underpin the transfer of cocaine from banknotes as well as persistence behaviour of cocaine on paper and polymer banknotes following handling. This study highlights that cocaine is readily transferred from banknotes through contact, even with the smallest forces and shortest contact times. Additionally, cocaine persists on all banknotes for extended periods of time following handling and is therefore available for transfer onto persons. Polymer banknotes were found to have a lower retention rate of cocaine particulates than paper banknotes. As such, cocaine particulates are more available for transfer from polymer banknotes and contact with adulterated polymer banknotes is therefore likely to result in larger quantities of cocaine being transferred onto individuals. Such findings are important for investigators when assessing the probability of innocent transfer of drug traces acquired from contaminated surfaces, such as banknotes, as opposed to those transfers resulting from illicit activities. These are valuable data that address the likelihood, and likely quantities, of transfers in the course of handling banknotes. These insights have potential to assist with evaluating the relevance of illicit drug particles identified on items or persons of interest in crime reconstruction approaches.

CRediT authorship contribution statement

M.A. Amaral: Conceptualisation, Methodology, Formal analysis, Investigation, Writing – original draft

A.P. Gibson: Project administration, Supervision, Writing – review & editing

R.M. Morgan: Project administration, Supervision, Writing – review & editing

Acknowledgements

The authors would like to thank Eve Hatten for the generous use of laboratory space as well as her invaluable assistance in setting up the ElectroPuls E3000 for the application required in this study. The authors would also like to thank Francisco Coelho for his assistance and support.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

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