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Authors

Poupko, Jay M
Hearn, William Lee
Rossano, Federico

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CRITICAL REVIEW

CRIMINALISTICS

Jay M. Poupko,[1] *Ph.D.; William Lee Hearn*,[2] *Ph.D.; and Federico Rossano*,[3] *Ph.D.*

Drug Contamination of U.S. Paper Currency and Forensic Relevance of Canine Alert to Paper Currency: A Critical Review of the Scientific Literature*

ABSTRACT: Several studies have reported on wide-spread contamination of U.S. paper currency with cocaine and to a lesser extent other illicit drugs. Canines are trained and employed to search for and alert to drugs. Canine alert to currency has been used as evidence that currency has been directly involved in illicit drug trafficking to justify currency seizure and forfeiture. This assertion, particularly when the only evidence is based upon canine alert, has been challenged in the courts considering that most currency in circulation is contaminated with cocaine. Comprehensive review of the scientific literature establishes that (i) 67–100% of circulated U.S. currency is contaminated with cocaine ranging from a few nanograms to over one milligram/bill (ii) various biological and environmental parameters impact canine alert to drugs. It is concluded that canine alert to U.S. currency is not sufficiently reliable to determine that currency was directly used in an illicit drug transaction.

KEYWORDS: forensic science, cocaine, currency contamination, canine alert, forensic relevance, critical review

Several scientific studies published from the late 1980s through 2013 have reported that most U.S. paper currency in the general circulation is contaminated with cocaine and to lesser degree by other controlled substances. Governmental law enforcement agencies routinely utilize canines trained to alert to trace amounts of controlled substances such as cocaine, marijuana, and heroin by detecting odors associated with these substances. Canine alert to currency is frequently used as forensic evidence that currency was directly involved in an illegal drug transaction resulting in its seizure and forfeiture to law enforcement agencies. This assertion, particularly when the only evidence is based upon canine alert, has been challenged in the courts considering that most currency in circulation is contaminated with cocaine and possibly other controlled substances. Court decisions and legal arguments will not be analyzed, discussed, nor further mentioned here.

The purpose of this study was to review and analyze the scientific literature concerning this matter in order to ascertain the forensic relevance of canine alert to U.S. paper currency. To this end, review, analysis and discussion of published scientific studies of the following is presented: (i) contamination of U.S. currency with cocaine and other controlled substances, (ii) biological, behavioral, and environmental parameters and variables of canine alert to controlled substances, (iii) methyl benzoate as the cocaine-associated odorant in canine alert, and (iv) scientific publications on canine alert to U.S. currency. Regarding controlled substances other than cocaine, only two published studies were found on U.S. currency contamination, and no controlled studies were found on canine alert to currency contaminated with other controlled substances. Consequently, the primary focus of this meta-analysis and critical review is on cocaine. Moreover, the foregoing does not include review of studies on drug contamination of foreign paper currency because of differences in the physical and chemical composition and properties of foreign currency.

Review and Analysis of Scientific Literature on Drug Contamination of U.S. Currency

Several published studies commencing in the late 1980s through 2013 have reported that at least the majority of U.S. currency tested is contaminated with minute, invisible quantities of cocaine. The extent of cocaine contamination ranged from as low as a few nanograms to as high as several hundred micrograms per bill. Potential factors affecting the extent of contamination include collection location, changes in currency composition, denomination, time in circulation, sampling technique, and analytical methodology. Various sampling techniques employed to remove cocaine from currency included shaking, vacuuming, swiping/swabbing, and solvent extraction. The above techniques are listed in order of increasing efficiency of cocaine recovery from currency varying approximately over at least five

[1]Biology Department, Touro College, 11 Beit Hadfus St., Jerusalem 95483, Israel.
[2]1391 N.W. Saint Lucie West Blvd., #207, Port Saint Lucie, FL 34986.
[3]Cognitive Science Department, University of California San Diego, La Jolla, CA 92093-0515.
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orders of magnitude. Thus, for example, solvent extraction generally yielded on the average a few micrograms, whereas shaking yielded a few nanograms of cocaine per bill.

In 1987, a technical article by Aaron and Lewis (1) reported cocaine contamination of U.S. currency. Stacks of 100 circulated bills of various denominations collected from the Federal Reserve Bank in Baltimore were placed in polyester envelopes and subjected to a shaking procedure. The envelopes and the stacks of bills were washed with methanol and extracts were analyzed by gas chromatography/mass spectrometry (GC/MS). Cocaine was not detected in extracts from empty bags that had contained currency subjected to shaking. In contrast, extracts of three of five stacks of currency tested positive for cocaine. No quantitation or limit of detection was reported though the authors note that microgram quantities deliberately transferred from fingertips to the bills yielded positive results.

The first quantitative study of cocaine contamination of currency was reported by Hearn in 1989 (2). One hundred and thirty-five bills in $1–100 denominations were collected from 12 U.S. cities. Bills were extracted in methanol and analyzed by full spectrum and selected ion monitoring (SIM) GC/MS. Of those, 131 (97%) tested positive for cocaine with an average of 7.3 μg (microgram) per bill.

In 1996, Oyler et al. (3) reported on analysis of a total of 134 $1 denomination bills collected from 14 U.S. cities. The bills were extracted initially with methanol followed by (SPE) solid-phase column extraction, qualitatively analyzed by full scan GC/MS, and quantitatively by SIM GC/MS. The LOQ (limit of quantitation) was 12.5 ng, and recovery was >95%. Extracts of uncirculated currency tested negative for cocaine. The percent of bills contaminated varied at different locations from 50% to 100%. Overall, 79% of bills had >0.1 μg and 54% >1.0 μg of cocaine with a range of contamination of 0.5–1327 μg/bill. Seventeen percent of the bills were also contaminated with benzoylecgonine, a cocaine hydrolysis product. The authors concluded "that cocaine is present as a contaminant in the majority of all circulated United States paper currency." They further asserted that "the results from this study suggest that the presence of cocaine in amounts up to 1 mg (milligram) per bill does not signify that the currency was involved in a drug transaction."

In 1998, Negrusz et al. (4) reported results on ten $20 bills collected from Rockford, IL and four $1 bills collected from Chicago. Bills were initially extracted with 0.1 M hydrochloric acid followed by SPE. Cocaine was identified by full scan GC/MS and quantitated by SIM GC/MS. The limit of detection (LOD) was 1 ng/bill and LOQ 50 ng. Cocaine was identified in 92.8% of the bills. All $20 bills tested positive ranging from 0.14 to 10.02 μg/bill. Two of the four $1 bills were positive at 0.31 and 2.99 μg, respectively, one tested positive below the LOQ and no cocaine detected in the fourth bill. Four uncirculated $1 bills obtained from the Federal Reserve tested negative. The authors concluded based upon previous studies and their results that "it is accurate to say that the entire population of various denominations of United States currency is contaminated to a significant degree with illicit cocaine."

Jenkins published a study in 2001 (5) reporting results of a total of fifty $1 bills collected from the general circulation from three continental U.S. cities as well as Honolulu and San Juan, Puerto Rico. Individual bills were extracted with acetonitrile followed by SPE and quantitatively analyzed for cocaine, heroin, 6-acetylmorphine 6-AM), codeine, methamphetamine, amphetamine, and phencyclidine (PCP) by SIM GC/MS. The LOD and LOQ were 1 ng/bill. Ninety-two percent of all bills tested positive for cocaine with a mean amount of 28.75 ± 139.07 and a median of 1.37 ranging from 0.01 to 922.72 μg/bill. Some of the cocaine-contaminated bills also were contaminated with other controlled substances. Heroin was detected in seven bills at a range of 0.03–168.50 μg. 6-AM and morphine were detected in 3 bills; methamphetamine and amphetamine in three and one bills, respectively, and PCP was detected in two bills. Cocaine-negative bills were also negative for other controlled substances.

Lavins et al. (6) reported on detection of the cannabinoids: Δ9-tetrahydrocannabinol (THC), cannabinol (CBN) and cannabidiol (CBD) on 125 $1 bills collected from 12 U.S. cities. Bills were chemically extracted and derivatized extracts analyzed by SIM GC/MS. About 1.6% of bills were contaminated with THC at 0.085–0.146 μg/bill, 10.3% with CBN at 0.014–0.774 (mean 0.166) μg/bill, and 1.6% with CBD at 0.032–0.086 μg/bill. Overall, the lower percent currency contamination and concentration found for drugs other than cocaine may be related to differences in the drug's physical–chemical characteristics, mode and extent of use in the population and the degree of contact with currency.

In 2008, Zuo et al. (7) presented results for cocaine analysis of a total of 31 bills in general circulation in denominations of $1, $5, $10, $20, $50, and $100 collected from three cities in Southeastern Massachusetts. Individual bills were sonicated in water followed by cocaine extraction by SPE. Extracts were analyzed by capillary GC using a FID detector for cocaine identification and quantification. Cocaine identification was confirmed by full scan MS. The LOQ was 4 ng, and the LOD was not specified. Sixty-seven percent of the bills tested positive for cocaine ranging from trace (below LOQ) to 49.4 μg/bill. All $5, $10, $20, and $50 denominations tested positive. None of the $1 bills tested positive, and one of four $100 bills tested positive. All uncirculated bills were reported as nondetected.

By far, the most comprehensive study of cocaine contamination of U.S. currency was a study by Jourdan et al. (8). Results were presented for total of 4174 bills of various denominations in general circulation collected between 1993 and 2009 from 90 U.S. locations including 66 cities in 43 States and the District of Columbia. Data were also presented for bills associated with criminal investigations. The latter were first qualitatively screened for cocaine by ion mobility spectroscopy (IMS) as follows: bills were sampled by vacuuming the surface, trapping particulate matter on a filter which was then screened for cocaine by IMS. If the bill screened positive by IMS, a second set of bills from the same source was sampled as described above and the filter quantitatively analyzed by GC/MS, LC/MS, or LC/MS/MS. The administrative LOD and LOQ were 0.05 and approximately 0.2 ng/bill, respectively. No recovery data were presented. Approximately 97% of the bills were positive for cocaine. The national average was 2.34 ± 0.08 ng/bill. Variability in contamination level between denominations was minimal. Early samples (1993–2002) displayed higher levels with a mean value of 3.62 ng/bill compared to later samples (2003–2009) that had a mean of 0.61 ng/bill though the authors speculate that skewing of results due to different sample sizes for the two periods may have accounted for this difference. An alternate explanation of differences in early and late samples may be a result of changes in the physical and/or chemical composition of paper currency in circulation during these two periods. There were also examples of significant variability between cities/establishments in close proximity (e.g., Miami vs. Ft. Lauderdale, FL). Approximately half of general circulation samples

tested (N = 418) were contaminated at <0.5 ng/bill, whereas half of the samples associated with criminal cases (N = 68) exhibited contamination up to 20 ng/bill. Employing a statistical model, the probability of cocaine contamination for any given bill in the general circulation at a particular cocaine level was calculated and ranged from about 0.8 for <20 ng/bill and 0.0009 for 300 ng/bill.

The results of drug contamination of currency studies are summarized in Table 1. It is particularly noteworthy that the level of cocaine contamination reported in the Jourdan et al. study was at least three orders of magnitude less (ng vs. μg/bill) than four of the five other studies reviewed (2–5). Only one other study (1) reported ng/bill levels. One likely explanation for this discrepancy is the difference in sampling method. Whereas the four studies reporting μg/bill levels (2–5,7) employed solvent extraction, the other two either vacuumed the surface (8) or used shaking to physically remove material from the bill (1). Consequently, it remains to be determined whether the differences found for vacuum-sampled currency collected and analyzed during different collection periods or differences between currency in general circulation vs. criminal cases may be extrapolated to currency sampled by chemical extraction. It also remains to be resolved whether cocaine residue recovered by vacuum sampling constitutes a drug subpopulation representative of cocaine recovered by chemical extraction.

Review and Analysis of Scientific Literature on Canine Alert to Drugs

Canines have long been utilized by man for their innate, highly sensitive, and discriminative sense of olfaction and their ability to be trained to detect illicit drugs as well as other substances such as explosives. Quignon et al. (9) reported that the keen ability of canines to smell is largely due to their large olfactory epithelium and their olfactory receptor genes repertoire, which is over 1000 and outnumbers the 600–900 olfactory receptor genes in the human genome. With their keen sense of smell, trained canine teams have been utilized to detect and follow volatile organic compounds (VOCs) of various controlled substances such as cocaine, marijuana, heroin, and MDMA (Ecstasy). An extensive review of canine olfaction, substance detection training and applications to forensics, conservation and medicine may be found in Jezierski et al. (10).

However, accurate detection appears to be dependent on drug type, and various biological, environmental, behavioral, and physiological factors. For example, Jezierski et al. (11) reported on variables affecting the false alert rate. A significantly lower % false alert rate was observed for marijuana compared to amphetamine, cocaine, or heroin (11). English cocker spaniels displayed significantly fewer false alerts than terriers. Canines were more accurate alerting outdoors than around and inside automobiles (11). Lit et al. (12) observed that handler beliefs of the presence of a drug or explosive scent (where no substance was actually present) resulted in a significant number of false alerts. Sargisson and McLean (13) found that the false alert rate for explosive detection is dependent on positive reinforcement. In addition, physiologic factors appear to affect canine alert such as presearch strenuous exercise (14) and diet (15).

Cocaine and Methyl Benzoate

In a controlled laboratory study published by Waggoner et al. (16), the threshold for canine detection of methyl benzoate (MB) present in illicit cocaine samples ranged from 0.02 to 0.04 ppb, whereas the threshold for detection of pure methyl benzoate ranged from 5 to 27 ppb. The percent false-positive alert for both illicit cocaine and pure MB was <10%. Sensitivity and accuracy for pharmaceutical cocaine were considerably lower than illicit cocaine presumably due to the low level of MB in highly purified pharmaceutical cocaine. The authors concluded that the significantly greater sensitivity for methyl benzoate in illicit cocaine compared to pure MB suggests that canines may not be using MB solely for illicit cocaine detection and that other compounds may significantly contribute to the signature odor of cocaine.

The contention that MB may not be the primary or sole signature odor of cocaine is supported by the studies of Rice and Koziel (17–19) who reported that human odor detection thresholds for various VOCs associated with cocaine, heroin, and marijuana do not correlate with their headspace chemical concentrations. They propose that low concentrations of highly odorous compounds (i.e., very low odor detection thresholds) present in the headspace of these drugs may be primarily responsible for contributing to the overall odor of these drugs. Although their observation pertained to human rather than canine olfaction, it is possible that this finding is generally valid for canines as well. Thus, MB may not be the primary or sole

TABLE 1—*Summary of studies on contamination of U.S. paper currency with cocaine.*

Publication	Sampling Method	Analytical Method(s)	# Bills Tested	Denomination(s)	Location(s)	% Contamination	Mean/Range Contamination/Bill
Aaron and Lewis (1)	Shaking	GC/MS	Unspecified stacks	Unspecified	Unspecified	Not detected	–
Aaron and Lewis (1)	MeOH extraction	GC/MS	Unspecified stacks	Unspecifed	Unspecified	3 of 5 stacks	Unspecified
Hearn (2)	MeOH extraction	GC/MS	135	Unspecified	Unspecified	97%	7.3 μg
Oyler et al. (3)	MeOH extraction + SPE	GC/MS	134	$1s	14 US cities	79%	0.5–1327 μg
Negrussz et al. (4)	HCl+SPE	GC/MS	4	$1s	Chicago	75%	0.31–2.99 μg
Negrussz et al. (4)		GC/MS	10	$20s	Rockford, IL	100%	0.14–10.2 μg
Jenkins (5)	Acetonitrile+SPE	GC/MS	50	$1s	5 US cities	92%	28.75 ± 139.07 μg
Zuo et al. (7)	Sonication in water	GC/FID	31	$1s, 5s, 10s, 20s, 50s,100s	Southeastern, MA	67% overall average all denominations	Trace-44.9 μg
Jourdan et al. (8)	Vacuuming	GC/MS, LC/MS or LC/MS/MS	4174	$1s, 5s, 10s, 20s, 50s, 100s	90 U.S. cities	97%	2.34 ng

signature odor associated with cocaine. If, however, a canine was trained primarily on pseudococaine, whose active ingredient is MB, it likely that it will alert to the MB in an illicit cocaine sample rather than another highly volatile substance present in low concentration.

Review of Physical and Chemical Properties of Methyl Benzoate

Methyl benzoate is a colorless, volatile liquid with a pleasant aromatic odor naturally found in certain flowers such as various species of Snapdragons (Antirrhinum). It is used as a component of perfumes under its common name, oil of Niobe. Pure methyl benzoate solidifies at approximately −15°C and boils at 198 to 200°C. It is insoluble in water, but soluble in organic solvents (20).

Cocaine is the methyl ester of benzoylecgonine, which is the ecgonine ester of benzoic acid. In the presence of moisture and acid or base, cocaine undergoes a chemical reaction, transesterification, that produces the methyl ester of benzoic acid, methyl benzoate (21). Street cocaine is less purified than pharmaceutical cocaine hydrochloride, and it may be contaminated with base from the extraction of coca paste or conversion to "crack cocaine" or hydrochloric acid from preparation of the hydrochloride salt of cocaine. The transesterification reaction is accelerated as the cocaine is exposed to elevated temperatures. It is noteworthy that training of many certified drug-detector dogs often entails the use of a training material called pseudococaine whose active ingredient is MB rather than cocaine. This material does not contain the stereoisomer of cocaine also termed pseudococaine. Based upon analysis of four samples of street cocaine hydrochloride, it was reported that the average percent MB was 0.020% (w/w) with a range of 0.010–0.036% (22). In contrast, the percent MB in pharmaceutical cocaine hydrochloride was approximately 0.00069%, almost 1/30 the percent found in the street samples. Furthermore, the percent of methyl benzoate detected in solid pharmaceutical-grade cocaine hydrochloride as a function of time appears to be fairly constant decreasing only 1.5% after a week and 13% after a two-week period (22). As pointed out by Waggoner et al. (16), it is possible that canines may not be using MB solely for illicit cocaine detection and that other compounds may significantly contribute to the signature odor of cocaine.

Furton et al. (22) reported on results of a study on Miami-Dade County, Florida Police Department certified drug-detector canine responses to cocaine and various volatile cocaine byproducts. Their results confirmed earlier reports that when their drug-detector canines alerted to cocaine, they actually alerted to MB rather than cocaine itself. Using an indoor environment protocol, drug-detector canines alerted to as low as 1 μg of MB but failed to alert various other volatile cocaine byproducts. They did not exhibit a significant response to as high as 1.0 g of pharmaceutical-grade cocaine hydrochloride. In an outdoor controlled-environment protocol using spiked U.S. currency, detector dogs failed to alert to various byproducts of cocaine. Most detector dogs failed to alert to 1.0 g of pharmaceutical-grade cocaine hydrochloride though a greater percent of dogs alerted to 1.0 gm of a street cocaine sample. Overall, in approximately 50% of tests using MB-spiked U.S. currency, detector dogs alerted to as low as 1.0 μg MB and about 10% alerted to 0.1 μg MB. No data were presented in this study for <1.0 g street cocaine though in a previous publication, Furton et al. (23) reported 13.3% and 28.6% percent alert rate for 10 mg pharmaceutical-grade cocaine hydrochloride and 10 mg cocaine base, respectively. Moreover, an even lower alert threshold to street cocaine would be expected as the percent MB in street cocaine was found to be almost 30× greater than pharmaceutical grade.

A more recent study published by Jezierski et al. (11) was conducted using 164 dogs trained in accordance with Polish law enforcement protocol. Canines were evaluated for detection time to controlled substances (marijuana, hashish, methamphetamine, cocaine, heroin) as well as ability to search in previous explored versus previously unexplored rooms and inside versus outside cars. By comparing the percentage of false alerts and correct indications, generalizations were made about differences in performance between various breeds. Overall, the false-positive rate for cocaine was 5.3%. The mean time to a correct indication of cocaine was found to be 79 ± 82 s. A major issue with canine ability to detect cocaine is the evaporation rate of methyl benzoate, the presumed primary signature odor source for cocaine. The study reported a decreased ability of canines to correctly identify cocaine samples after 24 and 48 h. Additionally, after 24 h 33.3% of canines produced false alerts. Because of the loss of VOCs over time, this study highlights the importance of identifying the canine threshold for methyl benzoate detection.

It is worth noting that possible discrepancies in results between the Jezierski et al. (11) and Waggoner et al. (16) studies may be due to apparent differences in Polish and U.S. law enforcement canine training and certification protocol. In addition, the Polish study was conducted under experimental conditions that more closely simulated a realistic canine work environment.

Marijuana

In the above Jezierski et al. (11) study, canines were accurately able to detect marijuana in 91.8% of the trials, with the lowest percentage of false positives (3.8%) and false negatives (4.4%) compared to hashish, methamphetamine, cocaine, and heroin. In addition, marijuana had the shortest mean detection time of 50 ± 55 s. A significant increase in false positives, "false negatives" and detection time was observed when dogs were tested 24 and 48 h after removal of the drug sample from the test area. The signature chemicals for canine detection to marijuana have not been identified. Macias et al. (24) reported that detector dogs failed to alert to the dominant volatiles found in marijuana headspace. Concerning human olfactory detection of marijuana, Rice and Koziel (19) have presented evidence that the odor of marijuana is probably not due to volatiles present in high concentration but rather highly odorous compound present in low concentration.

Heroin

Jezierski reported that heroin detection by canines had both the longest search time of (81 ± 88 s) as well as highest percentage of false alerts (17.7%) compared to marijuana, hashish, methamphetamine, and cocaine sample detection (11). The signature odor of heroin is presumed to be acetic acid, a significantly volatile substance. Accordingly, 24 h after removal of the drug from the test area, canines alerted to heroin in only 33.4% of trials and after 48 h, canines alerted in only 8.4% of trials. Training canines to detect heroin proves to be challenging. As the signature odor of heroin can vary per seized drug amount, it is difficult to provide canines with a proper training aid. It is noteworthy and perplexing that Marcias et al. (24), observed that trained canines failed to alert to the training aid Sigma Pseudo

Heroin (proprietary composition) and that only one of 12 canines alerted to 100 μL of acetic acid on gauze.

MDMA (Ecstasy) and Methamphetamine

According to Macias and Furton, odor thresholds for MDMA vary because of differing amounts of street MDMA—(and consequently, the amount of piperonal a common starting compound for MDMA synthesis)—present in ecstasy pills (25). Pills can vary by as much as 8–25% MDMA. To examine the threshold of certified drug detection canines, a piperonal controlled odor mimic permeation device (COMPS) was used to emit different permeation rates (10, 100, 1000 ng/s) of piperonal to five canines. Of the canines that had piperonal in their training aids, 55–75% alerted to the 10 ng/sec concentrations of piperonal. At the 1000 ng/s concentration of piperonal, almost 100% of canines utilizing training aids containing piperonal alerted. Canines that were not exposed to pure piperonal during their initial trainings failed to alert at the 10 ng/s and only one dog of the two showed an alert at the 100 ng/s (25). When presented with different ratios of 3,4-methylenedioxyphenyl-2-propanone, (a common intermediate for the synthesis of MDMA) and piperonal, 83% of canines alerted to the 10 mg piperonal sample. These findings support the idea that piperonal is the primary odor signature for MDMA. Lorenzo et al. (26) reported the presence of methamphetamine in MDMA tablets and proposed that it is an adulterant or contaminant rather than a MDMA synthetic byproduct. In addition, it was found that the canines were unable to alert to 5 g of pharmaceutical grade methamphetamine, but all canines alerted to 5 g of "street" methamphetamine (26).

Studies on Canine Alert to U.S. Paper Currency Spiked with Cocaine

There are only two published experimental studies on certified drug-detector canine alert to uncirculated U.S. currency spiked with various amounts of cocaine (22,27). Poupko et al. (27) reported results of a pilot study of canine alert to U.S. paper currency using four Fayetteville, Arkansas Police Department certified drug detector canine-handler teams. Uncirculated currency was spiked with 1–5000 μg of cocaine hydrochloride. Negative controls consisted of uncirculated drug-free currency as determined by GC/MS. In the initial experimental trial, three canines alerted to drug-free currency and the alert threshold to contaminated currency varied considerably between the three dogs from 1 μg to 500 μg/bill.

Consequently, a second experimental protocol was employed using plain bond paper spiked with 5–5000 μg cocaine. All of four dogs did not alert to drug-free bond paper which served as a negative control. Two of four canines failed to alert to spiked paper at any level. A third canine alerted to paper spiked with 200 and 5000 μg cocaine. The fourth canine alerted to paper contaminated with low and high but not intermediate levels of cocaine. A third experimental trial repeated with the same group of canines yielded similar results. Based upon these preliminary studies, it was concluded that this particular group of drug-detector canines falsely alerted to drug-free currency. The bond paper experimental results showed that considerable variability exists from canine to canine with respect to threshold detection levels of cocaine. Moreover, no clear dose–response relationship was evident for this group of canines.

In the Furton et al. (22) study discussed above, 15 certified drug-detector canines were tested for their ability to alert to U.S/ currency. In an outdoor controlled-environment protocol using spiked, uncirculated U.S. currency, drug-detector canines failed to alert to various byproducts of cocaine. Most detector canines failed to alert to 1.0 g of pharmaceutical-grade cocaine hydrochloride although a greater percent of canines alerted to 1.0 g of a street cocaine sample. Overall, in approximately 50% of tests using MB-spiked U.S. currency, detector canines alerted to as low as 1.0 μg MB and about 10% alerted to 0.1 μg MB. No data were presented in this study for <1.0 g street cocaine although as noted above, in a previous publication, Furton et al. (23) reported 13.3% and 28.6% percent alert rate for 10 mg pharmaceutical-grade cocaine hydrochloride and 10 mg cocaine base, respectively. Moreover, as the percent MB in street cocaine was found to be almost 30× greater than pharmaceutical-grade cocaine, an even lower alert threshold to street cocaine would be expected. The authors concluded that as the average level of cocaine present in a single bill (10 μg) is 100,000 less than the average level required for drug-detector canine alert (1 g), "it is not plausible that innocently-contaminated US currency contains sufficiently enough quantities [sic] of cocaine and associated volatile chemicals to signal an alert from a properly-train drug detector dog."

Although this may well be the case for a single circulated bill contaminated with an average amount of cocaine, it would not necessarily be the case for a large collection of bills especially considering the significant variability in cocaine quantities found between bills in the general circulation. No doubt, one of the most critical variables that determine whether a detector dog alerts is the concentration of MB in the air which in turn is determined by several volatility variables such as exposure to air, ventilation, ambient temperature, humidity, as well as any competing and/or masking odorants.

Discussion and Conclusions

Studies published from the late 1980s through 2013 have found that between 67 and 97% of U.S. paper currency collected from the general circulation to be contaminated with cocaine. The level of contamination within a given study often ranged over 3–4 orders of magnitude. Moreover, inter-study differences in mean contamination per bill were sometimes as much as three orders of magnitude (e.g., Jenkins vs. Jourdan 2014 studies). This is most likely related to differences in methods employed to remove cocaine from currency such as vacuuming versus chemical extraction.

Most authors have proposed as a likely mechanism of contamination that a small number of bills become initially contaminated with relatively high amounts of cocaine by direct contact such as insufflation (snorting) of cocaine HCL powder via a rolled bill, and the contamination is transferred when the contaminated bill comes in direct contact with other bills or via contamination of currency-counting machines. Cocaine hydrochloride is water soluble and, in its street form, is extremely hygroscopic. Therefore, any cocaine hydrochloride powder adhering to the bill will deliquesce and absorb into the paper. This is especially likely when the bill is placed in a wallet and carried close to the body in a warm climate. Consequently, shaking and vacuuming sampling methods would be much less likely to detect cocaine after absorption. In contrast, cocaine base ("Crack") is a waxy or oily solid, water insoluble material, and is less likely to come in contact with currency as it is smoked rather than insufflated although contamination may occur by transfer through handling. If cocaine base was to adhere to

currency, it probably would not be released effectively by shaking, although more likely recovered by swabbing or vacuuming.

Currently, there is insufficient knowledge to ascertain if the probability of canine alert to currency is determined by total chemically extractable cocaine on a bill or limited to superficial cocaine that can be removed by physical means such as vacuuming. With regard to interpretation of a particular canine alert based upon extrapolation from published studies, it is important to consider biological, behavioral, and environmental variables such as breed, training, drug type, search environment, handler cues and handler interpretation of canine responses, presearch exercise (14), and diet (15) as mentioned above.

The ultimate forensically relevant question addressed in this review, whether a canine alert to U.S. currency is sufficiently reliable forensic evidence on its own to justify seizure and admissibility as evidence in criminal prosecutions, has not been conclusively resolved by studies to date. Particularly, does an alert to a large quantity of currency indicate that the currency was directly involved in drug trafficking? Clearly, the larger the number of bills, the more cocaine and methyl benzoate is present in the total currency sample, although a tight stack of bills will most likely generate less volatile methyl benzoate than a looser configuration of bills. In an attempt to resolve this matter, properly controlled studies need to be conducted in realistic field environments using large numbers of certified drug-detecting canine-handler teams from various law enforcement agencies challenged with large quantities of currency.

Based upon the limited data currently available and the considerable biological and environmental variables that may affect an outcome, it is reasonable to conclude that a canine alert to U.S. paper currency should only be considered a preliminary positive field test result that should be followed up by more specific, quantitative laboratory testing (e.g., GC/MS). Only if the laboratory result is positive at a drug level well-above an established range for currency in the general circulation should it be considered reliable scientific evidence that this currency was directly involved in an illicit drug transaction. A similar approach was recently proposed by Jourdan (28).

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Additional information and reprint requests:
Jay M. Poupko, Ph.D.
Biology Department
Touro College
11 Beit Hadfus Street
Jerusalem 95483
Israel
E-mail: toxcon@aol.com