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The Natural Sampling of Airborne Trace Signals from Explosives Concealed upon the Human Body*

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ABSTRACT: An experimental study of the natural sampling of trace signals from explosives concealed upon the human body was performed by taking proper account of the thermal behavior of the air surrounding the human body and the particles therein. Experiments were conducted in a dispersal chamber to identify variables affecting the detectibility of concealed RDX and TNT patches. Movement by human volunteers was found to enhance the available explosive trace signal above a baseline level. Clothing blocked some of this movement-generated trace signal. The detected signal levels were also found to vary significantly from volunteer to volunteer, indicating that human variability is an issue in explosive trace detection. Further, under the conditions studied here, the detectibility of RDX and TNT was dependent upon the efficient sampling of contaminated particulate matter, not the vapor phase. The present results are now being applied to the design of a practical, nonintrusive trace detection portal for aviation security screening and related applications.

KEYWORDS: forensic science, explosive detection, natural sampling, RDX, TNT, human body, human thermal plume, aerobiology, heat transfer, flow visualization

In the past 25 years, sabotage for political purposes has surpassed hijacking as the foremost threat to aviation security. Explosive devices, concealed under clothing, have been carried onboard aircraft by terrorists on a number of occasions, some of which have resulted in disasters claiming many innocent lives. Statistics show that explosives, of either plastic (extremely low vapor pressure) or volatile (relatively higher vapor pressure) types, constitute the predominant weapon used by terrorists in aviation-related incidents (1). This has made it imperative that airport passenger security stations screen for concealed explosives as well as for metallic weapons.

Explosive trace detection for aircraft passengers raises the key issue of sampling (viz, the generation at the human body of an explosive trace signal and its efficient transport to a sensitive detector). After sampling comes the detection step, with an alarm if a sufficient explosive trace is found. The focus of this paper is the sampling and detection of both plastic (e.g., RDX) and volatile explosives (e.g., TNT) concealed upon the human body.[3]

While hand-held personnel scanners have been developed for explosive trace detection, they are too slow for general airport security use and may not be acceptable to the traveling public. A more general and less intrusive approach is an explosive detection portal (EDP), which is similar in appearance to the metal detection portals currently in use in airports. The present research aims to contribute to the technology base for a practical, effective explosive trace detection portal of this type.

In the spirit of the walk-through metal detection portal, several previous EDPs have been developed and are described in the technical and patent literature. However, these technologies are usually based upon the assumption that explosive traces are transported by molecular diffusion (2)—a process that is actually far too slow to be effective. This assumption further led to the belief that an explosive trace remains near its source unless actively disturbed. Accordingly, some investigators have advocated strong air currents or physical contact to "strip" or "scrub" trace signals from the human body and clothing, and to "dislodge stagnant boundary layers" (3–6). Such approaches ignore the natural aerodynamics and the heat- and mass-transfer characteristics of the human body. Moreover, strong air currents tend to further dilute an already weak signal.

Our approach to the development of an EDP differs from previous work in that fluid dynamics, heat transfer, and mass transfer are assumed central to the problem at hand. We believe that the prior technology of EDPs for human subjects may be improved substantially by taking proper account of the natural heat and mass transfer characteristics of the human body, especially including the human thermal plume.

Human skin, typically at 33°C during a normal activity, is approximately 9°C warmer than the surrounding air at room temperature (7). This causes continuous thermal convection from the body to the surroundings. Such convection rejects waste body heat at a rate of 80 to 100 W for a resting person, thereby helping to maintain a constant body-core temperature of 37°C. The air heated by the skin rises naturally according to Archimedes' Principle, generating a free-convection boundary layer about the body and a thermal plume above it, as illustrated by the Schlieren image shown in Fig. 1 (8).

For a person standing in quiet ambient air, the convective boundary layer begins at the ankles and travels up the legs and torso, growing thicker and faster as it moves (9). In the case of a standing, nude man roughly 1.7 m in height, the boundary layer is laminar for about

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[3] RDX is not a plastic explosive per se. However, since RDX is the primary component of plastic explosives such as C-4, it may be considered to be representative of plastic explosives for present purposes.

FIG. 1—*Schlieren photo of human thermal convection.*

1 m above floor level, and is fully turbulent above 1.5 m (mid-chest height) (10). This natural boundary layer is approximately 15 to 20 cm thick at the ears, where the maximum upward airspeed approaches 0.25 m/s (11). This upward flow separates from the shoulders and the top of the head, as the body surface becomes horizontal. The resulting human thermal plume encases the head and continues to rise above it, where it attains a typical overall flow rate between 20 and 60 L/s (11). The plume extends for a few meters above the head, headroom permitting, before it dissipates due to turbulent mixing. This natural human airflow pattern is similar for everyone despite differences in body height, weight, clothing, etc.

From this it is clear that the air in contact with the human body can never be stagnant, but rather is in a constant state of motion. The nature of this motion is such that every location on the body contributes chemical traces to the human boundary layer and eventually to the thermal plume. These include traces from explosives if concealed upon the body.

To understand the trace signal transfer mechanism, it is necessary to address the nature of explosives. Whether plastic or volatile, explosives are known to be "sticky" and are readily adsorbed upon many surfaces (12). So, it is very difficult to avoid contaminating explosive devices while they are being wrapped. When concealed beneath clothing, contaminated devices transfer trace explosives to the skin and clothing, particles and fibers of which are constantly being shed due to the abrasion caused by body motion. These particles migrate out through the pores and openings of the clothing, borne by the natural convective airflow described above, and are subsequently caught up in the motion of the human boundary layer and thermal plume. Traces of explosives concealed anywhere on the human body are thus expected to migrate naturally upward into the human thermal plume and above the head, where they may be collected and sampled by appropriate apparatus.

Normal clothing does not significantly interfere with the development of this human thermal plume (10,13). Although clothing reduces local temperature gradients and insulates the body, this does not alter the overall upward flow of the human boundary layer and plume (14), as shown by our Schlieren flow visualization images of nude, lightly- and heavily-clad human volunteers.

A critical consequence of this line of reasoning is that the human body and its natural thermal process of waste heat rejection are central to the problem of personnel explosive trace detection, and are not to be ignored. Several studies (e.g., 15) show substantially different airflows for unheated mannequins than for live human subjects. Accordingly, human volunteers have always been used in our experiments (detailed below).

This further suggests a simple and elegant approach to EDP design: any trace explosives released by a device concealed upon the human body must eventually find their way into the body's thermal plume. One should then collect the entire thermal plume shed by a human subject and interrogate all of it for trace explosives. It is detrimental to under-sample the plume, for this makes the detection task more difficult. If airjets are used to agitate the clothing and release particles, the airjets should be of brief duration and should not add significantly to the overall airflow rate of the body plume.

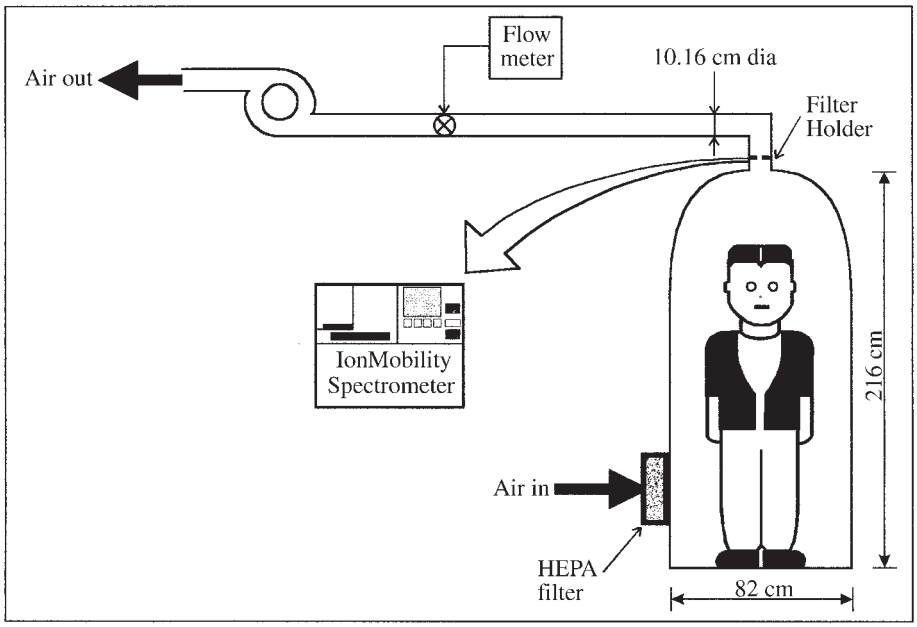

FIG. 2—*Dispersal chamber and associated apparatus.*

Here, however, arises a problem: sampling the entire human plume at roughly 40 L/s presents an "impedance mismatch" with typical explosive detectors, such as the ion mobility spectrometer, which have comparatively-miniscule input flow rates on the order of cm^3/min (16). One potential solution to this airflow impedance-matching problem is to remove the particulates from the airflow by filtering, discard the airflow, and interrogate the small remaining solid mass for trace explosives. However, this approach may neglect airborne molecular explosive traces. A better solution involves a trap that captures both particulate and molecular traces while allowing the airflow to pass through. Materials caught by such a trap are then thermally desorbed and presented to the detector via a suitably small flow rate of inert gas.

Experimental Facilities

In these experiments we collect and sample the entire thermal plume shed by a human volunteer in a dispersal chamber (Fig. 2). This is a booth-like enclosed chamber that is adapted from medical technology for counting the bacteria shed by the human body (17,18), and is the key piece of apparatus in the present experiments. It is not an EDP per se, but rather a scientific tool to gain knowledge leading to the eventual design of an EDP. Our dispersal chamber, in which the human volunteer stands, is 213 cm high, 82 cm wide and 82 cm deep with fiberglass walls and ceiling and an airtight, clear-acrylic door. It has a single air inlet at the bottom and a single outlet at the top; thus insuring that the entire airflow around the human body within is contained and captured. The airflow through the chamber is adjusted to be comparable to the 40 L/s flow rate of the human thermal plume, so there is neither an accumulation nor a dilution of the volunteer's thermal plume within the chamber. At the inlet, the air is drawn through a HEPA filter to eliminate any incoming airborne particulates. The exhaust air is filtered at the chamber outlet to trap all airborne particulates of a size greater than 15 μm. A fibrous Teflon filter is used for this purpose.

The samples collected on these filters are then analyzed using an Ion Mobility Spectrometer, or IMS (Barringer IonScan 400). Ion mobility spectrometry has been applied extensively to the detection of plastic explosives, and is widely accepted in the security community for its dependability and rapidity of analysis. However, as a scientific instrument it suffers a relatively small linear measuring range, especially for RDX (~1.5 orders of magnitude); it cannot be reliably used for quantitation outside this range. Consequently, the explosive trace levels presented here are given in terms of "cumulative amplitude" in digital units (du), the direct output of the IMS, rather than quantitative mass units. No attempt is made here to convert this output to actual mass of trace explosive, thus the results are valid only on a comparative basis. However, despite the limitations of the IMS as a laboratory instrument, we felt it was important to use this device for sample analysis since it is typical of those actually employed in the field for aviation security screening.

Protocol for Experiments

The protocol was essentially held constant for both RDX and TNT experiments in the dispersal chamber. (Differences in protocol will be duly noted and explained.) For reasons explained above, human volunteers were used in all experiments.[4] On the day of the experiment, volunteers were issued clean coveralls made of 65% polyester and 35% cotton. Under the coveralls, female volunteers wore only jogging bras and shorts, while male volunteers wore only shorts.

Immediately preceding the arrival of the volunteer at the laboratory, the explosive signal source was prepared. Depending on the explosive under investigation, a known amount of RDX or TNT was deposited on a sterile 100%-cotton gauze patch measuring 7.6 cm × 7.6 cm. At the start of the experiment, the contaminated patch was attached to the abdomen of the human volunteer using athletic tape. The volunteer pursued normal daily activities for a 2-hr "soak period,"[5] and was then brought to the dispersal chamber for testing.

[4] Human volunteers were used in full compliance with Penn State University's policy on ethics in research.

[5] The soak period is the duration of time when the volunteer is carrying, but not being tested for, the explosive signal source.

Once in the chamber, a K-type thermocouple was taped to the volunteer's abdomen and used to record skin temperature during testing. The following six tests, of five minutes (RDX) or three minutes (TNT) duration each, were then conducted:[6]

Test #1: Volunteer standing still in the chamber, seminude (i.e., undergarments only).
Test #2: Volunteer running in place in the chamber at 160 beats per minute, seminude.
Test #3: Volunteer exits dispersal chamber. A blank test is conducted to verify that there is no residual contamination.
Test #4: Volunteer standing still in the chamber, wearing coveralls.
Test #5: Volunteer running in place in the chamber at 160 beats per minute, wearing coveralls.
Test #6: Volunteer exits dispersal chamber. A final blank test is conducted to verify that there is no residual contamination.

During each test, the temperature and relative humidity inside the dispersal chamber were recorded.

Despite efforts to maintain consistency in test protocol, one significant difference between the RDX and TNT experiments was required. In the case of the former, 5 mg of RDX dissolved in 1 mL of acetone were used to contaminate the gauze patches. The acetone evaporated at room temperature, leaving behind RDX crystals on the patch. However, in the case of TNT, powder was used to create the signal source. This variation was necessary because patches created using a TNT solution were not consistently detectable in the dispersal chamber, even at a maximum patch strength of 100 mg.

This can be attributed to the sorption properties of TNT upon cellulose (cotton). When the explosives are deposited in a solvent and then the solvent is evaporated, the explosive molecules make direct contact with the cellulose surface and build up intermolecular interactions with this surface. The fact that RDX but not TNT was detectable from patches prepared by this method suggests that the two explosives have different sorption properties with respect to cellulose. The reasons for these differences may be ascribed to one or both of the following (19):

- TNT is planar and can more closely approach the cellulose surface than the nonplanar RDX;
- TNT is a distinct electron-acceptor and can form electron donor-acceptor complexes with surfaces that are able to donate electrons. When this happens, very strong bonds are formed between the TNT and the cellulose. RDX is not expected to form these complexes.

Thus, to create a TNT patch, solid TNT beads were crushed into a fine powder, using a ceramic mortar and pestle, and ground into the patch. For the present dispersal chamber experiments, 25 mg of TNT per patch were deemed sufficient for detection.

Results

The present series of experiments in the dispersal chamber primarily addresses the effects of "agitation" and clothing on the signal transfer and detection process. These data also reveal the effects of miscellaneous variables such as room temperature, relative humidity, volunteer gender, body mass, surface area, skin temperature, and skin type.

While these variables play an important role in the sampling process, the key to designing an effective explosive detection system is to identify the nature (i.e., molecular or particulate) of the signal being sampled. The present experiments also directly address the nature of the explosive signal being detected at the outlet of the dispersal chamber. Furthermore, they provide insight into differences, if any, between the sampling of volatile and plastic explosives in the dispersal chamber.

The results of the dispersal chamber experiments for RDX and TNT are presented in graphical form. In each case, the direct IMS output, cumulative amplitude, is shown on the ordinate. The RDX data are presented on semi-log plots to accommodate the large signals detected in the case of seminude volunteers running in place. The TNT data, however, when presented exclusively, are shown on linear plots. Three male and three female volunteers were used for these experiments, and each was tested five times. No volunteer was tested more than once each day. The data presented in Figs. 3, 4, 5, and 6 represent the average values of five experiments for each volunteer. All 60 individual data points are shown for each test in Figs. 7 and 8.

Consider first the effects of agitation, caused by the volunteer running in place in Tests 2 and 5,[7] as shown in Figs. 3 (RDX) and 4 (TNT). Agitation was found to increase the detectable explosive trace signal by as much as two orders of magnitude for seminude volunteers (Tests 1 and 2) wearing RDX patches, and one order of magnitude for those with TNT patches. For clothed volunteers (Tests 4 and 5), the detected signal increases due to agitation by an order of magnitude for RDX and TNT alike, save for Male 1 and Female 1 with TNT patches.

Next, consider the effects of clothing on signal detectibility, also shown in Figs. 3 (RDX) and 4 (TNT). As expected, clothing reduces the detectable explosive trace signal. When the patch was agitated by volunteer motion (Tests 2 and 5), clothing reduced the RDX and TNT signals by one order of magnitude. However, in almost all cases, clothing caused no discernible reduction in the signal detected from either the RDX or the TNT patches worn by volunteers standing still (Tests 1 and 4), within error bounds defined by the data scatter of the experiment.

As seen in Figs. 3 and 4, these data also reveal a marked variability in the signal levels from volunteer to volunteer. The IMS response varied by as much as an order of magnitude for different volunteers. It should be noted, however, that while there was such variation in the results between individuals, the motion and clothing results discussed above were nonetheless relatively consistent and repeatable over time for each volunteer.

To evaluate this between-volunteer variability in IMS response, the data from the dispersal chamber experiments were evaluated in light of some of the observable differences between the volunteers—such as gender, skin oiliness, skin temperature, body mass, and skin surface area. However, no such correlations were found. For example, see Figs. 5 (body mass) and 6 (skin surface area). The surface area of each volunteer was determined from the following formula presented by DuBois and Dubois (20), which relates the surface area (A) in m^2 to the height (H) in centimeter and weight (W) in kg:

$$A = 0.00718 \cdot W^{0.425} \cdot H^{0.725}$$

[6] These sampling times are long compared to those that are practical in a portal at a security station. However, because steady-state conditions were preferred for these studies of the sampling process, longer sampling times were required.

[7] Refer to previous section titled "Protocol for Experiments" for descriptions of Tests 1 to 6.

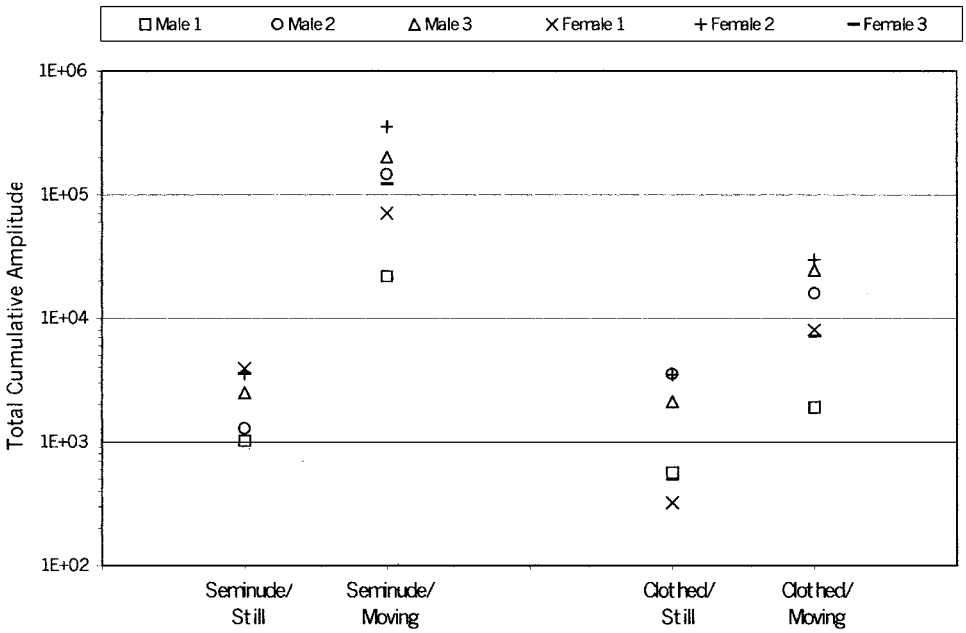

FIG. 3—*Summary of dispersal chamber experiments with 5 mg RDX patches.*

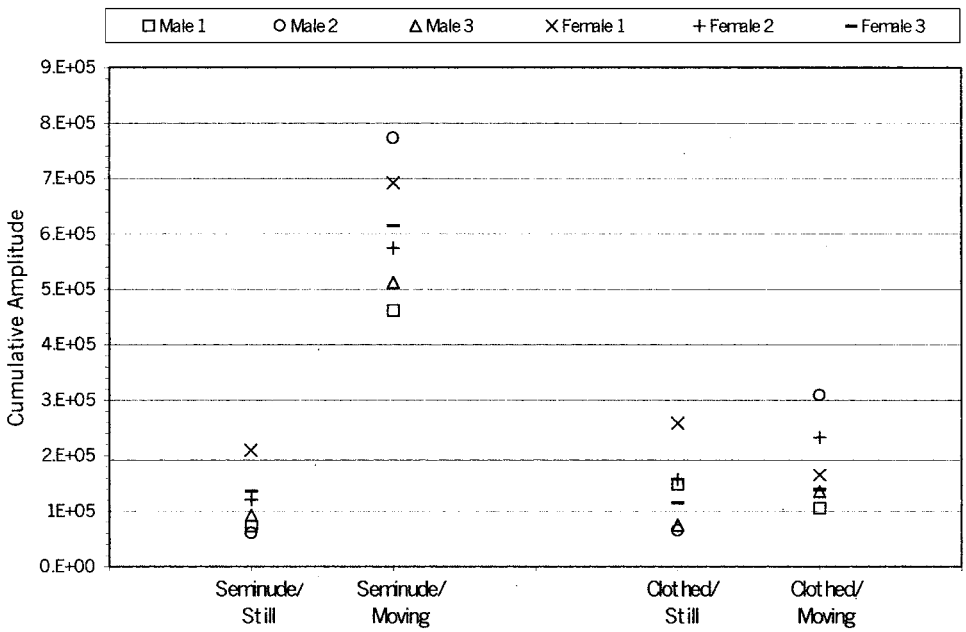

FIG. 4—*Summary of dispersal chamber experiments with 25 mg TNT patches.*

In both figures the previously noted trends with clothing and motion can be identified, but no trends with volunteer body parameters emerge.

In addition to the effects of agitation, clothing, and body parameters the data from the dispersal chamber experiments were used to evaluate the effects of ambient temperature and relative humidity. As seen in Figs. 7 (room temperature) and 8 (relative humidity), neither parameter was found to have an appreciable effect on the detection of either explosive within the tested ranges of 19 to 29°C and 21% to 68% RH.

Discussion

These results demonstrate that there is a baseline signal in the plume of a contaminated human subject that is available for detection, and that can be enhanced by agitating the source. Of course, aircraft passengers are not expected to exercise deliberately in order to facilitate the detection of concealed contraband. On the other hand, terrorists and their "mules," who are posing as passengers, are likewise not expected to remain inactive from the time the explosives are concealed until they walk through a security check-

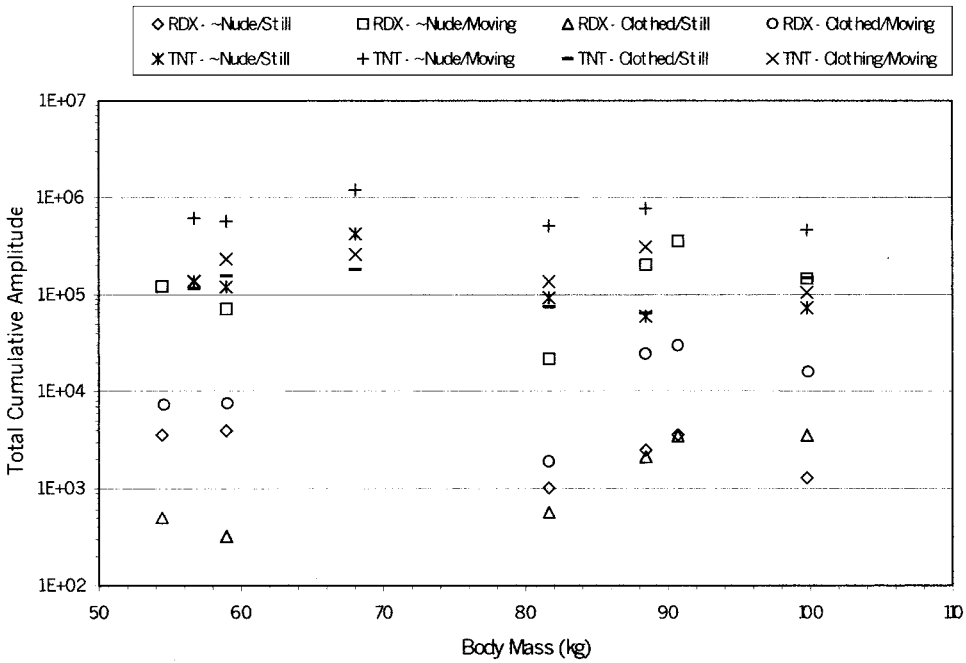

FIG. 5—*Effects of volunteer body mass on explosive signal detectibility.*

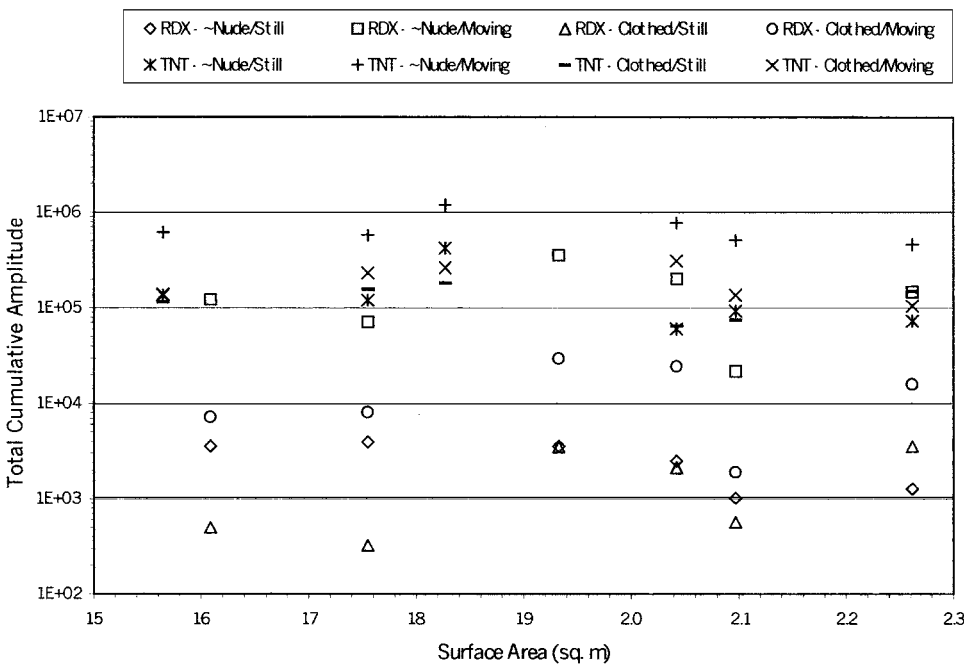

FIG. 6—*Effects of volunteer skin surface area on explosive signal detectibility.*

point. Their normal movements, walking, and carrying luggage naturally agitate the concealed explosives and contaminated clothing, releasing detectable traces into the thermal microenvironment of the human body.

As for the unexplained between-volunteer variation observed here, there is much evidence of such variability in the literature. Prior experiments with human volunteers frequently noted between-volunteer variation and day-to-day variation for an individual volunteer (18,21,22). Whyte et al., who studied the rate of dispersal of bacteria through gowns worn in operating theatres, noticed a large difference in the rate of dispersion between volunteers, as well as a difference from day-to-day for a given volunteer (18). Additionally, Lloyd (21) reported experiments to detect explosives from swabs collected from hands previously in contact with the explosive nitroglycerine. He reported that these experiments were "liable to a high level of between-subject variation." Finally, Hattis et

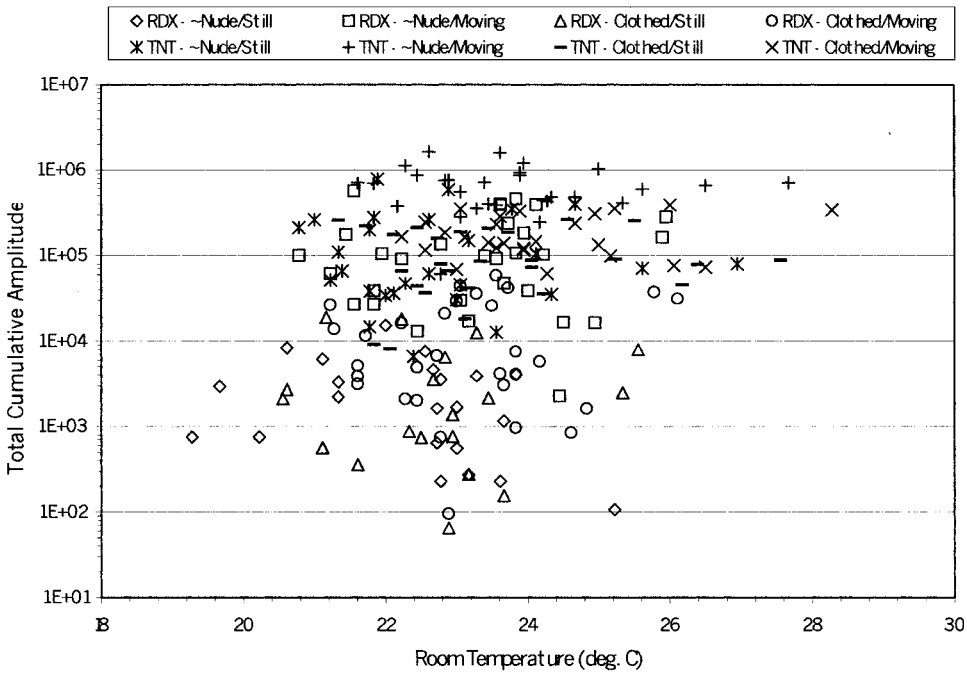

FIG. 7—*Effects of room temperature on explosive signal detectibility.*

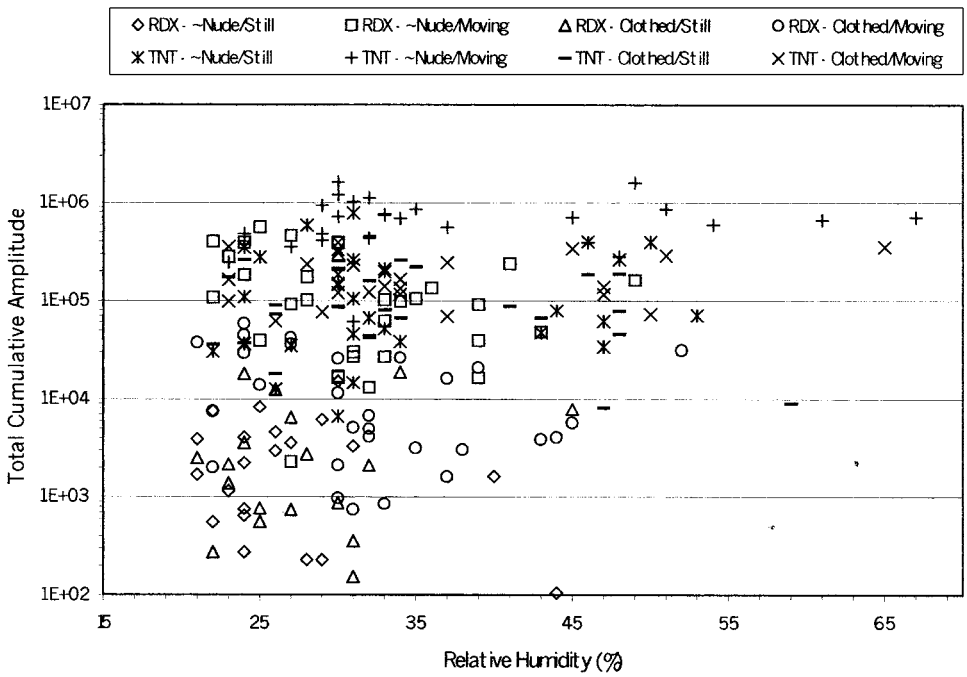

FIG. 8—*Effects of relative humidity on explosive signal detectibility.*

al. (22) noted a substantial variability (from 2.5 to 9 standard deviations from the mean) in human susceptibility to drug toxicity, which was largely ascribed to the complexity of human physiology. This breadth of variability helps to put in context the seemingly large scatter in the present data. It also suggests that the detectibility of concealed explosives in the field can be expected to vary significantly between individuals. Individuals presenting weak signals should be sought and the underlying reasons studied in further research, since these are the most difficult explosive carriers to detect.

Another significant conclusion can be drawn from the analysis of the effects of room temperature and relative humidity on signal detectibility. Since RDX is known to have very low vapor pressure, it was expected at the outset that detectable RDX traces would be

transported mainly on contaminated particulate matter. Therefore, ambient temperature and relative humidity were not anticipated to have a significant effect on RDX detectibility. This hypothesis was not made for TNT, however, since it is much more volatile. At least some of the TNT signal may be supposed to transport as a molecular trace. Humidity and especially temperature are then expected to influence the level of such a trace by way of its source strength. Since this was not observed, the present results suggest that the signal detected from gauze patches, contaminated with either RDX or TNT, is probably transported and sampled as particulate matter, not vapor. Further investigations (19), including an analytical treatment of the evaporation of TNT, confirmed that the detected signals were due to contaminated particulates and not to molecular traces in our dispersal chamber experiments. This knowledge is critical to the design and development of an effective EDP for personnel screening.

Concluding Remarks

The knowledge gained in the present dispersal chamber experiments is currently being used to design a commercial walk-through portal for aviation security screening purposes (23). This requires nonideal airflow patterns to be considered. Under the ideal conditions of a motionless person in still air, shown in Fig. 1, the human thermal plume is vertically oriented and is not difficult to collect. While walking, however, we shed our thermal plume behind us in the form of a human thermal wake. Moreover, when a walking subject comes to an abrupt halt, the airflow in the wake continues to move past the body and interferes temporarily with the re-establishment and stabilization of the vertical free-convective plume (13). Such more-realistic airflows, both due to human motion and ambient air currents, are being studied with regard to practical explosive detection portal design.

Finally, while the primary application of this research is a walk-through portal for aviation security, there are broader implications of the science behind the sampling of the human thermal plume. Other security applications may include the detection of narcotics and chemical and biological warfare agents. A related approach could be useful in medicine, where it is used to rapidly screen patients for a wide variety of diseases such as diabetes and tuberculosis, which are known to produce telltale airborne trace signals.

Acknowledgments

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