The UC Berkeley Time-Activity Monitoring System (UCB-TAMS) was developed to measure time-activity in exposure studies. The system consists of small, light, inexpensive battery-operated 40-kHz ultrasound transmitters (tags) worn by participants and an ultrasound receiver (locator) attached to a datalogger fixed in an indoor location. Presence or absence of participants is monitored by distinguishing the unique ultrasound ID of each tag. Efficacy tests in rural households of highland Guatemala showed the system to be comparable to the gold-standard time-activity measure of direct observation by researchers, with an accuracy of predicting time-weighted averages of 90–95%, minute-by-minute accuracy of 80–85%, and sensitivity/specificity values of 86–89%/71–74% for one-minute readings on children 3–8 years-old. Additional controlled tests in modern buildings and in rural Guatemalan homes confirmed the performance of the system with the presence of other ultrasound sources, with multiple tags, covered by clothing, and in other non-ideal circumstances. Key words: Exposure assessment; datalogging; indoor air pollution; efficacy; RESPIRE; Guatemala

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Monitoring personal exposure to airborne pollutants is not practical or even possible in many populations, due to cost, intrusiveness, and/or lack of appropriate technology. Consequently, investigators often rely on micro-environmental monitoring combined with time-activity assessment.1 Unfortunately, however, the social science methods for time-activity assessment (questionnaire, diary, observation) do not work well in some circumstances and themselves can be expensive and intrusive.2 Time stamped voice-recorded activity-location data3,4 and video analysis5 have proven to be useful techniques, but their transcription and interpretation are time consuming. Consequently, there have been efforts to develop more precise, objective, and less intrusive means of time-activity assessment,6 often using devices derived from the information technology revolution, such as GPS,7,8 and more recently in combination with other devices like accelerometers9 and radio frequency identification.10

In our studies of indoor air pollution in developing-country households in remote settings, we required a method that was inexpensive, reliable, deployable on a routine basis over multiple years by lightly trained personnel, sufficiently non-intrusive to be applied with every population group including infants, and with output easily linked to that from datalogging pollution monitors in the micro-environments of interest (usually rooms within the households). On the other hand, we did not need to know the location of participants at all times, but only when they were in the rooms where pollution was being monitored. Indeed, there would likely be ethical issues raised by deploying devices that reveal people’s locations over 24 hours.

Research needs reduced time-activity to a binary function: inside the room or not. We thus worked to develop a system consisting of two components. First, a stationary “locator” mounted in the microenvironment in question. Second, one or more “tags,” each with a signature indicating the identity of the participant wearing it, that could be worn on the clothing of study participants and sense and log when the tag is in the microenvironment.

Three types of wireless technology were tested for the system: infrared, radio, and ultrasound. Infrared has the advantage of line-of-sight propagation (it is not able to pass through walls), making it attractive with regards to our binary (in-out) model. Unfortunately, since the tags could become covered by one or more layers of clothing during daily activities, an infrared signal would have a good chance of being cut off. Radio, on the other hand, is too penetrating, easily passing through walls. There-

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Disclosures: The authors declare no conflict of interest.
fore, someone outside could be mistaken for someone inside the room. Ultrasound signals, in contrast, are able to go around corners and through clothes, and are not powerful enough to easily penetrate walls. Available ultrasound technologies are somewhat more expensive than infrared and radio, but not enough to pose a serious handicap.

**THE UCB ULTRASOUND TIME-ACTIVITY MONITORING SYSTEM (UCB-TAMS)**

Each UCB-TAMS system consists of ultrasound transmitting “tags,” and an ultrasound receiving “locator.” Each tag has its own identifying signature (ID), represented by a sequence of beeps, and is worn by a particular study participant. The locator, usually mounted on the wall of the room of interest, “listens” for the ultrasound emitting tags. The locator datalogger tallies the number of times the locator receives a particular tag signal during the course of each minute. At the end of a minute, the datalogger records the date/time and the number of times each tag ID has been received by the locator. The process then repeats for the next minute. In this manner, the time-activity of study participants within the microenvironment of interest can be assessed on a minute-to-minute basis over extended periods, as long as the tags are worn by participants as intended.

The UCB-TAMS is inexpensive, reliable and requires a relatively small amount of attention from researchers. It operates above the hearing range of humans and terrestrial animals, and thus is not noticed by domestic animals such as dogs, cats, chickens, etc. As there are no moving parts, sharp edges, or radiation, the system is safe for widespread use. It appears to be a good alternative to more traditional time-activity measurements, especially in cases where a binary inside/outside measurement will suffice. For our purposes, the UCB-TAMS gives more precise results than would a conventional GPS device, which does not have sufficient resolution to measure presence in most indoor locations.

Here, after a brief discussion of the way the system operates, we describe tests undertaken in controlled conditions and efficacy tests during actual household activities to validate the accuracy and reliability of the UCB-TAMS system. Field testing took place at our research site in highland Guatemala in households using wood for cooking that were part of the RESPIRE study of woodsmoke and health. Standard consents were taken from participants for the field test according to the approval obtained from UC Berkeley’s Committee for Protection of Human Subjects.

**Ultrasound ID Transmitters (“Tags”)**

Each tag consists of a piezoelectric 40 kHz ultrasound transmitter powered by a commonly available 220 milliamp-hour capacity CR2032 LiMgO2 3-V lithium coin-cell battery. The CR2032 battery is mounted under a spring clip and can be replaced in the field. The UCB-TAMS tag sleeps between each transmission, so that the average current drain from the battery is 200 microamps, and expected battery life is near 1000 hours. The piezoelectric transducer is driven to a level of twice the battery voltage and a sound pressure level of approximately 105dbm by a differential drive circuit. At 25 g and 5.3 × 3.5 × 1.5 cm, the tags are unobtrusive as well as rugged (Figure 1).

Each tag is programmed with a distinct binary code (ID) that distinguishes it from other tags. The codes are transmitted as approximately 0.6 second, 40Khz ultrasound “beeps” at random intervals between 0 and 7 seconds. Each “beep” consists of six periods of sound and silence that act to create a binary “on-off” pattern. Each “bit” of the binary codes is approximately 100 milliseconds (ms) in duration. The bit duration is chosen to produce the shortest possible signal transmission time while ensuring integrity of each bit. The signals are emitted at random to minimize interference from multiple tags (Figure 2).

**Ultrasound Locator (“Locator”)**

The ultrasound locator unit has a size and construction much like that of the tag. It consists of a 40 kHz ultrasound receiving transducer and a processing circuit that filters, amplifies and detects tag signals using a phase lock loop. Raw data is in the form of voltage levels that represent the “ones” and “zeros” of the detected ultrasound. The locator and datalogger are typically mounted on a wall in a room, preferably not facing a doorway in order to avoid receiving tag signals from outside the room. The datalogger decodes the bit pattern carried in the ultrasound signal and thereby identifies the tag. In order to simplify data analysis, an

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*Figure 1—UCB-TAMS Ultrasound Transmitter (“tag”). Note the small size. The enclosure is ABS plastic. The circular metal protrusion is the ultrasound transducer. The receiver is nearly the same size.*
algorithm has been developed that transforms each minute’s tally of detected tag IDs into “present” or “absent.” The algorithm employs a user-selectable threshold (typically 2–5 times a minute) to make this decision as a safeguard against false positives. False positives are reduced by rejecting codes that do not correspond to any of the deployed tags. The cost of parts and labor for a package consisting of 3 tags and one locator is about $80 in lots of 100.

**VALIDATION STUDIES**

Three sets of validation tests were carried out: first in buildings in Berkeley, California to test physical operating conditions; the second set extended these controlled tests to typical households in our Guatemala site; and the third set of “efficacy” tests were conducted in households undertaking normal daily activities, but still under partly artificial conditions due to the presence of a trained observer from the research team. As such, they also did not test compliance by the householders, since the observer served to make sure the tags were used properly. Three or more receptions per minute was the threshold used to categorize a tag as present in the results reported for all the studies here, except Test 11.

**Performance Tests in Controlled Settings**

The first set of seven tests was conducted in Berkeley by the authors.

1) **Performance of the system under optimal conditions.** A tag was mounted 1.5 m high on a wall and 3.5 m directly across from 3 wall-mounted locator/data-logger units. The test was carried out for 24 hours each using 2 different tags.

   **Results.** All locators successfully recorded the two tags’ presence for each minute of the 24-hour test interval (100% accuracy). In all, there were 8 false positives and 120 “junk” one-minute readings, making a gross error rate of about 1.5% (n=8640 locator-tag-min). Junk readings are defined as those recorded as tag ID1. These readings are separated from other false positive readings as no real ID1 tag is ever used, and therefore could be easily distinguished and discarded if recorded in the field. Thus, the irresolvable error rate was <0.1%.

2) **Distance, straight line.** This test was carried out in a medium-foot-traffic hallway, ~30 m in length. Two locators were attached at 1.6 m height at one end, and two tags were held at shoulder height and pointed directly...
toward the locators. The tags were moved ~1.5 m at a time away from the locators over the entire hall length, being held at each distance for 4 min.

Results. Signals from both tags were received in each of the 4-minute test periods at each measured distance, up to 22.5 m. False negatives and false positives became frequent when the distance was greater than 22.5 m. Above 28 m, the tag signals were no longer received correctly during any of the minutes tested; instead, false negatives and false positives made up all locator receptions. Outdoors the maximum range is less than 15 m and the tag must be facing the locator.

3) Penetration through common materials. A tag was wrapped in various materials every 8–16 min with a focus on differing layers of clothing. In order to simulate usage in field conditions, another tag was placed in a pouch made of cloth traditional to rural Guatemala. A third unclothed tag operated as a positive control. All three tags were placed in line approximately 1.25 m from the floor, 3 m from two operating locators.

Results. These tests showed that the UCB-TAMS tag signals can effectively penetrate through several layers of clothing. Covering the tags with more than 7 layers of cotton cloth decreased the reception of their signals such that the locators did not always receive the requisite 3 signals in a minute. Differences between the mean count of detections in each test condition were compared, as summarized in Table 1. The mean counts of the positive control tag and the pouch tag were found not to be significantly different over all test periods (p<0.05). Similarly, for each penetration test, the significance (p<0.05) of t-test results was unchanged whether the t-tests compared the number of receptions between the test tag and the positive control tag, or between the test tag and the pouch tag. Only when the test tag was covered with 10 layers of cotton shirt, or 1 layer of cotton shirt and a windbreaker, was the test tag recorded as present less than 90% of the time and were the average receptions significantly lower than the control tags. Surprisingly, when the tag was covered in 2 layers of cotton and a windbreaker, the locator marked the test tag present for all 9 of the test min, and the mean receptions per minute from the test tag was not significantly different from the positive control.

4) Ultrasound interference from outside sources. We simulated ambient ultrasound noise by manipulating various materials known to produce ultrasound that might interfere with tag-generated ultrasound. Ultrasound noise was produced by jangling keys, crinkling a plastic bag, shaking a 1 × 0.75 m aluminum sheet and banging together two aluminum bars. Two sets of tests were carried out: 1) to investigate how the time interval between incidences of manufactured ultrasound affected the system; 2) to determine the influence of the manufactured ultrasound at differing distances from the locator and tag. For the first set of tests, the materials were manipulated at frequencies of once per 10 seconds, once per 3 seconds, and twice per second (with the duration of manipulation being approximately 1 second, 1 second, and <0.25 second, respectively). The manufactured noise was produced in line with a tag, with both the tag and the noise source facing a locator 3 m distant; the testing period included a period without noise.

For the second set of tests, each of the materials was manipulated approximately twice per second for several minutes at distances of ~3 m and ~0.5 m from two locators with no tags running. Two tags were then set up 3 m from the locators. One tag was placed in a pouch made of traditional Guatemalan material; the other was left fully open to the air. The tags were allowed to run without any intentionally produced ultrasound for 15 minutes in order to investigate the existence and level of interference the UCB-TAMS system experienced due to baseline ambient ultrasound noise. The manipulations of materials were repeated with the tags running at distances of ~6 m, ~3 m, and ~0.5 m. A negative control test period, with neither tags nor intentionally produced ultrasound noise present, was also conducted.

Results. Overall, the results of the manufactured ultrasound noise tests demonstrate that the UCB-TAMS system retains its accuracy when ambient ultrasound noise occurs at a frequency less than about once every

<table>
<thead>
<tr>
<th>Layered Clothing Combination</th>
<th>Test Mean Count</th>
<th>Pouch Mean Count</th>
<th>Open Mean Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Layer cotton shirt</td>
<td>6.50</td>
<td>6.38</td>
<td>7.25</td>
</tr>
<tr>
<td>4 Layers cotton shirt</td>
<td>6.42</td>
<td>7.00</td>
<td>7.17</td>
</tr>
<tr>
<td>7 Layers cotton shirt</td>
<td>6.09</td>
<td>6.82</td>
<td>7.00</td>
</tr>
<tr>
<td>8 Layers cotton shirt</td>
<td>6.06*</td>
<td>7.38</td>
<td>7.44</td>
</tr>
<tr>
<td>10 Layers cotton shirt</td>
<td>0.11*</td>
<td>7.78</td>
<td>7.89</td>
</tr>
<tr>
<td>1 Layer cotton shirt &amp; nylon windbreaker jacket</td>
<td>4.00*</td>
<td>6.33</td>
<td>7.33</td>
</tr>
<tr>
<td>2 Layer cotton shirt &amp; nylon windbreaker jacket</td>
<td>6.22</td>
<td>6.56</td>
<td>6.44</td>
</tr>
<tr>
<td>1 Layer cotton shirt &amp; polyester fleece jacket</td>
<td>6.18</td>
<td>6.73</td>
<td>6.91</td>
</tr>
<tr>
<td>Polyester fleece jacket &amp; nylon windbreaker jacket</td>
<td>7.36</td>
<td>7.64</td>
<td>7.09</td>
</tr>
</tbody>
</table>

*p<0.05, Paired, one-tailed tests.
3 seconds. More frequent ambient ultrasound noise, on the order of 1 sound per second or greater, however, will potentially disrupt the system. It was also determined that, generally speaking, the closer the noise source to the locator, the greater its influence on the accuracy of the system. At a frequency of 1 ultrasound noise produced every 10 seconds, the mean number of true positive detections was not significantly different than the control test period for all materials tested (two-tailed t-test, p<.05). There were slightly more junk readings and false positives during this test than in the control period. Increasing the noise interval to 1 per 3 seconds slightly decreased the mean number of correct receptions for all materials except the aluminum bars, increased the mean detections of junk readings per minute (but not the maximum number of detections), and increased the number of false positives attributable to different IDs. When the frequency of manufactured noise generation was increased to twice per second, the accuracy of the system suffered dramatically. The mean number of correct readings per minute dropped to nearly zero correctly detected per minute for all materials tested.

Detection of false positive readings attributed to almost all IDs increased by a small amount. The average and range of junk readings in this test remained similar to the levels seen in the tests of less frequent noise, except for the aluminum sheet, which produced many more junk readings at the 2 per second interval. In the cases where the time interval between manufactured ultrasound was 1 per 10 seconds and 1 per 3 seconds, the mean true positive counts were at least 4 times higher than any false positive mean count per minute. This result validates the use of a simple algorithm to filter out false positives while retaining true positives over the course of a minute. It allows a user of the UCB-TAMS system to set a threshold number of detections per minute, above which a tag ID will be recorded as “present” in the locator/data-logger memory. This threshold was optimized during field-testing of the system (see Figure 3).

Results of the second set of tests revealed that, for the most part, the closer a noise source is to the UCB-TAMS locator, the less accurate the system. Decreasing distance between noise source and sensor caused increased detections of resolvable junk and/or irresolvable false positives, and a decrease in true positive detections. This result was generally true for all materials tested. For instance, at a distance of 6 m from the locator, noise produced from each material tested caused approximately a 50% reduction in true positive receptions from the control condition (no manufactured noise), versus a >10 times reduction in detected true positives when the distance was reduced to 0.5 m between noise source and locator. Jangling keys showed a slightly different pattern of interference than the other materials, with a lower number of true positive detections per minute when the keys were jangled 6 m distant from the locator than when they were jangled 3 m distant.

5) Interference from multiple tags in a room. Because the UCB-TAMS tags emit ultrasound at a common, 40 Khz frequency, their signals can interfere to reduce the accuracy of the system (see Figure 2). The number of tags present in a given study area is directly proportional to the amount of time the space is filled with tag signals. Therefore, it is expected that the greater the number of tags present, the greater the chance of interference. This hypothesis was tested by placing three locators facing outwards at a height of 180 cm from the floor. Tags were placed side-by-side, facing the locators from 1.8 m away at the same height. The test began with a single tag running for 30 min. Then another tag was added to the test setup so that the two tags ran in parallel for another 30 min. The process was repeated, with one additional tag added at the end of each 30-min period, until 8 tags were running concurrently.

Results. With 1 or 2 tags in the room, resolvable junk and irresolvable false positives were almost non-existent, while true positives were received 100% of the time. The presence of 3 or 4 tags in the room resulted in only slightly fewer true positive results (~99% true positives),
with junk readings and false positives still occurring very rarely. Beyond this, increasing the number of tags resulted in more junk and false positive readings, with a corresponding decrease in correctly received tag signals (Figure 3). With 8 tags present, the ratio of actual hits (true positives) to expected hits dropped to a mean of 0.57 (95% Confidence Interval = 0.44–0.69). Junk readings are far less problematic than false positives because false positives may not be distinguished from true positives in the field. From the trends, it would seem risky to use more than 5 tags at once.

6) Comparison with time-activity diaries. In order to test accuracy of the system in a relatively realistic setting, two people each wore a tag for approximately 2 hours at their homes while simultaneously keeping an activity
controlled observations, which served as the “gold standard” in the analyses. A RESPIRE project fieldworker participated as the adult study subject.

7) Ideal operation. Four locators were hung in the kitchen at a height of ~1.5 m. One was placed on a wooden board fixed to the metal chimney of the plancha, another on the wall to the right and to the left of the plancha, and the last was placed on the wall opposite the plancha. The study participant wore two tags on the left shoulder to discern any differences in signal strength. She stood in the center of the room and faced each locator for 10 min, then turned 90° to face another locator. With her sweater pulled over both tags, the participant then faced one locator for 10 additional minutes. She also stood ~1 m outside the door with her shoulders perpendicular to the doorframe for 5 minutes, and then ~2 m from the doorway for another 5 minutes. This experiment was repeated with two tags, one on each shoulder, and five locators, with the additional locator placed on the wall next to the plancha.

Results. The locators at all positions recorded the participant’s presence in complete (100%) agreement with hand-recorded times when she was in the kitchen, no matter which direction she faced. When she was outside, however, there was disagreement, depending on how the locators faced the door. Locators facing the open doorway were more likely to receive a signal from outside.

8) Ideal placement on an adult. As in Test 7, four locators were hung in the kitchen, and the participant moved in 90° increments. She initially wore three tags on her left shoulder and faced a locator for 5 minutes to discern any differences in the tags’ signal strengths. Next, the three tags were placed in different locations on her body, one on the front of her left shoulder, one on the top of her right shoulder, and one roughly 3 in below her right waist. This same experiment was repeated with five locators and only two tags (one on the front of the left shoulder, other just below the right waist). The participant wore a sweater over the two tags while facing the locators on the plancha for 10 minutes. During this second trial, an additional tag was placed on the top of the participant’s right shoulder for 10 minutes.

Results. Data from each locator measuring the presence of both tags (left shoulder and right waist) were in complete (100%) agreement with the hand-recorded times, regardless of the angle at which the participant stood. When the participant wore a sweater over the tags, however, the locator on the wall opposite the plancha stovewar incorrectly recorded her as absent approximately two-thirds of the time.

9) Optimal locator height. Two locators were placed on one wall 80 cm apart (122 cm and 202 cm above the ground). No locators were placed on the other walls. The study participant wore two tags, one on her left

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shoulder and the other just below her right waist. She faced the two locators for 10 minutes and then turned 90° at a time for 10 minutes in each direction. She faced the two locators with a sweater over the tags for 10 additional minutes, and then faced the locators sweater-less and with an additional tag on her right shoulder.

**Results.** Both locators were in complete (100%) agreement with recorded times, regardless of the angle at which the participant stood. The locators detected both signals for 9 out of the 10 minutes when the participant wore a sweater over the tags. When an additional tag was added to the top of the participant’s right shoulder, both locators detected all three signals.

**Efficacy Tests**

As the first main purpose for deployment of our research was to improve exposure assessment in our study children and their mothers, efficacy tests were conducted with these groups conducting normal household activities using hand-recorded observations as the gold standard.

10) **Children 3–8 years old.** Direct observations of children occurred during the preparation and consumption of a meal. To determine the sensitivity of signal detection when a child was outdoors, the child’s proximity to the kitchen while outdoors was noted as either (1) less than 2 m from the door, or (2) more than 2 m from the door.

Direct observation followed a written protocol, which was translated into Spanish. Field workers underwent training in observation methods and the use of observation tools. Each house was visited for an average of three meals. One to two children between the ages of 3 and 8 years were recruited. In one house, a child initially refused to participate; in two others, the older child was only available for one observation because he attended school. Observations were made on 10 children, for a total of 23 observations. The length of observation varied depending on the meal. Mean meal lengths (ranges) were 76 minutes (44–112 min), 113 minutes (55–135), and 77 minutes (71–84) for breakfast, lunch and dinner, respectively. Each child wore two tags, one on his/her left shoulder and another just below his/her right waist. Children were asked to behave as if the observer were not present. If the children were asleep upon arrival, their location was noted and tags were placed on them when they awoke.

A locator was hung on the **plancha** chimney as in experiments 7–9. Another locator was hung on the wall behind the **plancha** at a similar height, and yet another on an additional wall in the kitchen. When possible, the third locator was hung on the wall to the right or left of the **plancha**, but in one house this was not possible. Instead, it was placed on the wall opposite the **plancha**.

The observer noted behaviors that might cover the tag or prevent detection of the signal by locators while in the kitchen, such as: when a child leaned against the **plancha** stove, faced a wall or window, stood in the doorway, sat or squatted on the ground, covered the tag with his or her hands, etc.

Because the locator logs data in binary form, the data from direct observation were translated into binary form for comparison (1 = present in room, 0 = absent). If a child changed locations many times during one minute, the overall location for that minute

### Box: Definitions Used in this Paper

- **TWA ACCURACY** = \((1.0 - \frac{(KLR - KDO)}{OP}) \cdot 100\)
- **MBM ACCURACY** = \(\frac{(KLR \text{ that are also } KDO + OLR \text{ that are also } ODO)}{OP}\)
- **KLR** = min in kitchen recorded by locator/locator
- **KDO** = min in kitchen recorded by direct observation
- **OLR** = min outside recorded by locator/locator
- **ODO** = min outside recorded by direct observation
- **OP** = min of observation period
- **SENSITIVITY** = \(\frac{(KLR \text{ that are also } KDO)}{KDO}\)
- **SPECIFICITY** = \(\frac{(OLR \text{ that are also } ODO)}{ODO}\)

### Table 2 Accuracy of Tag/Locator Placement Combinations with Children 3-8 Years

<table>
<thead>
<tr>
<th>Locator location</th>
<th>Tag on Left Shoulder</th>
<th>Tag on Right Waist</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Wall</td>
<td>Wall behind</td>
</tr>
<tr>
<td>TWA accuracy (%)</td>
<td>95.0</td>
<td>95.0</td>
</tr>
<tr>
<td>MbM accuracy (%)</td>
<td>84.8</td>
<td>83.9</td>
</tr>
</tbody>
</table>

TWA is the Time-weighted average. MbM is a minute-by-minute average. Both the TWA and MbM calculations consisted of n=23 observations and n=14 meals.
was considered to be the location where the child spent at least 31 of 60 seconds.

*Results.* Graphs comparing hand-recorded results and electronically collected data (Figure 4) were first assessed qualitatively. Problematic tags and/or locators and suboptimal placements of tags and/or locators (i.e., too close to a window or door, etc.) were identified.

Accuracy, defined as the percent of time during the observational period that the UCB-TAMS data was in agreement with direct observation data, was determined in two ways: minute-by-minute and time-weighted average. (See Box)

Personal Locator Technology seeks to determine the location of a person during a particular period of time. Therefore, the minute-by-minute accuracy is quite informative. The rationale behind the overall time-weighted average accuracy, which compares the total number of minutes in the kitchen as recorded by the UCB-TAMS with the total recorded by direct observation, stems from the criterion for determining location during 1 minute of direct observation. During direct observation, there may be a lag in recording the exact second at which a child changed his/her location, especially if there is more than one child. This delay in recording led to a time lag of one minute in some of the data. The overall time weighted average was determined to assess how much this time lag influenced the minute-by-minute accuracy.

Sensitivity and specificity were also calculated for each combination of locations (Table 3). Sensitivity is defined as the percent of minutes that the locator recorded the child as present in the kitchen when the child was indeed present (from direct observation). Specificity is defined as the percent of minutes that the locator recorded the child absent from the kitchen when the child was truly absent (see Box).

The combination of tag on the left shoulder and locator on **plancha** chimney resulted in the highest accuracies, both minute-by-minute (84.8%) and time-weighted average (95.0%). This same combination produced the highest sensitivity (89.0%) and lowest number of false negatives (7.8), but the lowest specificity (71.1%). A locator was placed on the wall behind the **plancha** only for the first few mealtime observations. This location resulted in the highest specificity (84.5%) and lowest number of false positives (4.4%), perhaps

![Figure 4—Direct observation vs. UCB-TAMS data for one mealtime observation. The dashes represent time that the child was in the kitchen.](image-url)

**Table 3** Sensitivity and Specificity of Tag/Locator Combinations with Children 3–8 Years

<table>
<thead>
<tr>
<th>Locator location</th>
<th>Tag on Left Shoulder</th>
<th>Tag on Right Waist</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Plancha</td>
<td>Wall</td>
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<tr>
<td>Sensitivity (%)</td>
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<tr>
<td>Specificity (%)</td>
<td>71.1</td>
<td>73.6</td>
</tr>
<tr>
<td>False Negatives*</td>
<td>7.8</td>
<td>9.9</td>
</tr>
<tr>
<td>False Positives*</td>
<td>8.2</td>
<td>10.3</td>
</tr>
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</table>

*False negatives and false positives are TWAs for each tag/locator combination.*
because of a limited number of observations. It is noteworthy that the locators on the plancha chimney and on the wall behind the plancha are in approximately the same locations yet yield quite different results, perhaps because of signal blockage by the chimney for the latter.

A linear effects model was used to determine which of the following variables contributed most to the overall variability in the minute-by-minute accuracy: house, child, locator, tag and placements of tags and locators. Initial tests revealed that the locator and tag were collinear with other variables, so they were not included in the final model. The final model revealed that tag location is the only near-significant variable in the model affecting minute-by-minute accuracy (−0.03456, p=0.0579). Placement on the right waist reduces the mean accuracy by 3.5% when compared to placement on the left shoulder. Overall variability is explained primarily by within-child variability (64.9%), rather than between-house and between-child variability (25.2% and 9.9%, respectively). Although a comparatively small sample, this result may help explain differences in between- and within-child variabilities in CO personal measurements conducted in the same children when infants.13

11) Adult woman. Further validation of the UCB-TAMS system was carried out through a second direct observation field study conducted in winter 2005. During this study, a woman was observed for 4.5 hours as she performed normal cooking and cleaning tasks around her household. She was equipped with 4 tags, and 5 locators were placed in the kitchen at different locations. As part of the direct observation, each minute a fieldworker noted whether the woman was in one of her household. She was equipped with 4 tags, and 5 locators were placed in the kitchen at different locations. As part of the direct observation, each minute a fieldworker noted whether the woman was in one of

<table>
<thead>
<tr>
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<th>Threshold Setting</th>
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<tr>
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<tr>
<td># Correct</td>
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<tr>
<td># False Positives</td>
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<td>% Correct</td>
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<td>10.2</td>
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<tr>
<td>% False Negatives</td>
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</table>

All values are an average of readings from 5 locators.

Results. A total of 35 movements between the four microenvironments occurred. Table 4 summarizes the results of this experiment, excluding one defective tag. Each minute-by-minute signal from each of the 15 tag/locator combinations was compared to the direct observation data to determine whether the signal was a false positive, false negative, or a correct signal. In addition, comparison of 1–4 hits-per-minute thresholds for defining presence in the room was conducted. As expected, increasing this threshold decreases the false positive rate and increases the false negative rate. The optimal balance was found to be 3 hits per minute, which is the value used in previous tests.

CONCLUSION

The UCB-TAMS performed well in controlled settings, both in Berkeley and Guatemala. Its line-of-sight limitation of ~22 m is actually an advantage for use in households and it seems to have no serious interferences from common sources of ultrasound. Its limitation to 5 or fewer tags in one microenvironment does not constrain its use for following activities of a mother and two children, our principal interest in this setting. The direct-observation field (efficacy) studies were conducted in more realistic settings, although these settings were not completely natural due to the presence of a trained observer. This observer may not only have influenced the activities of the householder, but also most certainly improved compliance in participants wearing and not interfering with the devices compared to what would occur in a real field application. In addition, although we use observers as the “gold standard” here, in reality it is not easy for them to keep close track of exactly when householders exit and enter the kitchen. Thus, there may be some argument that a well-operating UCB-TAMS system may actually do better.

The results of the child direct observation study (TWA=95%, MBM=85%, sensitivity=89%, and specificity=71% for combination of locator on the Plancha chimney and tag on left-shoulder), along with the low false-positive and false-negative rates (6.3% and 4.3%) found in the women’s study, however, provide convincing evidence that the UCB-TAMS can be an accurate and useful tool to measure personal time-activity, even in real-world scenarios in which participants frequently move between microenvironments. It can have significant benefits, for example, in measuring behavior changes, such as cooking behavior, associated with interventions.14 In addition, by reversing the location of the locator and tag, i.e., putting a tag in each room and having participants wear the locator, there is a
potential for a range of time-activity studies in both developed and developing countries. As a result of its potential, as validated here, we have deployed the devices as a regular part of exposure monitoring protocols at our Guatemala research site.

We thank John McCracken for advice on statistical tests, and the field staff and householders in our Guatemala project site.

References