Time–Location Analysis for Exposure Assessment Studies of Children Using a Novel Global Positioning System Instrument

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Global positioning system (GPS) technology is used widely for business and leisure activities and offers promise for human time–location studies to evaluate potential exposure to environmental contaminants. In this article we describe the development of a novel GPS instrument suitable for tracking the movements of young children. Eleven children in the Seattle area (2–8 years old) wore custom-designed data-logging GPS units integrated into clothing. Location data were transferred into geographic information systems software for map overlay, visualization, and tabular analysis. Data were grouped into five location categories (in vehicle, inside house, inside school, inside business, and outside) to determine time spent and percentage reception in each location. Additional experiments focused on spatial resolution, reception efficiency in typical environments, and sources of signal interference. Significant signal interference occurred only inside concrete/steel-frame buildings and inside a power substation. The GPS instruments provided adequate spatial resolution (typically about 2–3 m outdoors and 4–5 m indoors) to locate subjects within distinct microenvironments and distinguish a variety of human activities. Reception experiments showed that location could be tracked outside, proximal to buildings, and inside some buildings. Specific location information could identify movement in a single room inside a home, on a playground, or along a fence line. The instrument, worn in a vest or in bib overalls, was accepted by children and parents. Durability of the wiring was improved early in the study to correct breakage problems. The use of GPS technology offers a new level of accuracy for direct quantification of time–location activity patterns in exposure assessment studies. *Key words:* activity pattern, behavior, children, exposure assessment, GIS, GPS, organophosphorous pesticides, time–location, tracking. *Environ Health Perspect* 111:115–122 (2003). [Online 11 December 2002] doi:10.1289/ehp.5350 available via *http://dx.doi.org/*

Evaluation of children's exposure to environmental health hazards is essential for both epidemiology and risk assessment and has become a recent focus of national concern (*1*). An essential component of exposure assessment is knowledge of where individuals spend their time. Such time–location information can be linked with pollutant concentration data to produce exposure estimates for well-defined environments, often called microenvironments (*2*). Conventional time–location analysis has relied on interviews or diaries (*3–6*). Efforts have been made recently to improve the validity of these methods, including the "shadowing" of subjects with an observer, and use of a beeper to prompt subjects to record time–location data (*7,8*). Other methods and technologies have been explored but have not proven practical for human exposure studies (*9,10*). The purpose of the study reported in this article was to identify and test a new method for tracking preschool children throughout the course of a day.

The location of children has most often been documented through parental interviews and diaries (*11–13*). Although probably adequate for gross location analysis (home/not home), they are not considered reliable for more detailed characterizations (time indoors or outdoors at home or day care, time in vehicle). Evaluation of children's microactivities (e.g., hand-to-mouth behavior) has used videotaping at single locations (*14,15*), but this approach cannot be applied realistically to track children's locations throughout the day.

Global positioning system technology. The essential aspects of global positioning system (GPS) technology have been described in a report by the U.S. Environmental Protection Agency (*16*). A summary of how GPS units collect temporal and locational data is provided here. GPS satellites orbit the earth twice every 24 hr transmitting a 50-W signal at 1,575.42 mHz (the civilian frequency). GPS receivers on the earth can detect this signal, which contains information necessary to establish coordinates for location. The GPS signal contains three components: a "pseudorandom code," ephemeris data, and almanac data. The first identifies which satellites are "seen" by the receiver. The second contains current time and date information. The third tells the GPS receiver where each GPS satellite should be at any time throughout the day. To determine location, the GPS receiver compares the time a signal was transmitted by satellite with the time it was received on the earth. The receiver calculates how far away that particular satellite is based on this time difference. When signals from three or more satellites are received simultaneously, the receiver is able to calculate a coordinate position on the earth. With four or more satellites in view, a receiver can also provide altitude information.

The U.S. Geodetic Survey manages a network of beacons that transmit differential GPS corrections from beacons across the country. The correction data are available as public domain information on the Internet from many sources that maintain continuously operating reference stations (CORS), such as the U.S. Forest Service, the U.S. Coast Guard, and the National Oceanic and Atmospheric Administration (NOAA). Data for this study were obtained from the closest station in Seattle, Washington, operated by NOAA.

On 1 May 2000, the United States stopped the intentional degradation, known as "selective availability," of GPS signals available to the public (*17*). This change allowed civilian GPS users to receive location information that is many times more accurate than was previously possible. Differential correction is essential for improved resolution when selective availability is in effect. When selective availability is not in effect, it provides a less dramatic but still important improvement in resolution. Renewal of selective availability remains an option for the U.S. government based on security concerns.

GPS signals can be received in all weather conditions and in almost all environments. Signal reception is impossible or limited inside most buildings. Reception is generally unaffected as long as there is some line of

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sight between receiver and satellite. Satellite relative geometry can affect GPS accuracy, a problem called positional dilution of precision (PDOP). Other errors can occur because of signal deflection between the satellite and the receiver and because of extremes in upper atmospheric conditions (*16*).

Applications of GPS technology. GPS technology is now in widespread use for business and leisure activities. It is used to monitor tractors as they plant fields and apply pesticides to crops (*18*) and to measure short-term velocity of athletes (*19*) and has been employed to gather time–location data on hunters by the U.S. Forest Service (*20*). Commercial GPS units were employed recently in an attempt to validate 24-hr time–activity diaries in the Oklahoma Urban Air Toxics Study (*21*). Poor GPS instrument performance prevented collection of sufficient data to realize this goal, but the investigators concluded that GPS technology showed promise as a method for tracking research subjects in community-based exposure studies. No studies to date have employed GPS technology with children.

Data generated from GPS units can be displayed effectively with a geographic information system (GIS), a database system that contains coordinate-correct maps and locations. For example, GIS has been used to map data recorded by GPS receivers in precision agriculture to optimize fertilizer and pesticide application (*18*). GIS has also been used to predict historical exposures to agricultural chemicals in a retrospective cohort study of cancers among rural residents of Nebraska (*22*). Use of GIS and GPS technologies in tandem holds potential for new insights in the field of human exposure assessment.

The use of GPS technology to evaluate children's locations throughout the day requires equipment that differs substantially from that available from commercial vendors (*23*). No commercial GPS units meet all of these criteria at present, although technologic advances are occurring rapidly in this area.

The purpose of this study was to develop and pilot test a novel GPS unit suitable for studies of children's exposure to environmental contaminants, particularly to pesticides. Our previous work in agricultural communities has suggested that where young children spend their time can play a critical role in how and to what extent they are subject to pesticide exposure (*24*). Time–location is not used as a proxy of exposure, but rather as a way to map exposures at the intersections between humans and contaminated microenvironments. The GPS experiments reported here focused on spatial resolution, reception efficiency in several environments, and major sources of signal interference. We then employed the GPS units in a field study to determine the feasibility of using GPS technology to track the movements of young children over the course of a day.

Methods

Criteria for children's GPS unit. The following 10 features were deemed essential for an instrument to be used with young children: *a*) ability to log path data, *b*) ability to store raw pseudo-random satellite code required to postprocess differential corrections, *c*) ability to import data into GIS software, *d*) memory and battery life capable of recording at least 24 hr of data at a frequent sampling rate (at least once every 30 sec), *e*) external antenna that can be positioned to optimize signal reception, *f*) ability to be worn in a way that is acceptable to both the child and parent, *g*) light weight (< 300 g or < 0.75 lb), *h*) durable, *i*) tamperproof mechanism, and *j*) simplicity of operation. The following two performance characteristics were also considered essential to define location with sufficient accuracy and precision: *a*) resolution of 3–5 m and *b*) reception under a wide range of field conditions.

GPS instrument. Our group worked with Enertech Consultants (Campbell, CA) to design a GPS "personal acquisition logger," or GPS-PAL. The GPS-PAL unit consists of a battery pack, a central electronic unit, and an antenna (Figure 1). The cost of each unit, including software for downloading and postprocessing data, is estimated at US$1,000. All components, including batteries, weigh 280 g. Separation of the antenna from the central unit allows flexibility in antenna positioning. The unit was designed for use by a subject with no supervision required and is operated by one small on/off switch. The GPS-PAL has enough memory to store 30 hr of data when set to log data every 5 sec. Battery life at the 5-sec sampling rate is 25 hr using four AAA alkaline batteries. The GPS-PAL is not an "off-the-shelf" tool, but a standard operating procedure (SOP) was developed during the course of this pilot study to expedite these functions. Downloading, postprocessing, and mapping of data can be accomplished by a user with basic Windows software competency when using the SOP.

Operating procedures. Two GPS-PAL units were tested and used in feasibility studies. The units were allowed to prime for approximately 5 min when first switched on until a signal was received (indicated by a flashing light on the unit). The units were set to record time and location (latitude/longitude) data every 5 sec. The time–location data that are logged delineates the path traveled. The GPS-PAL automatically deletes position data that are the result of poor satellite geometry to prevent spurious points from being included in the path. At the end of each data collection period, the units were connected to a desktop computer with a communications cable, and the GPS-PAL software was used to download data. GPS-PAL software uses modules licensed by Trimble Navigation Ltd. (Sunnyvale, CA). Once downloaded, data were postprocessed to correct for errors using differential signal data obtained from the Seattle NOAA CORS found on the CORS Internet site operated by the National Geodetic Survey (*25*). The GPS-PAL software automatically links to this site, instructs the user how to download the required differential correction data from the nearest CORS site, and postprocesses the GPS path data using the appropriate corrections.

After postprocessing, the coordinate information was exported into ArcView GIS software that included the Spatial Analyst extension and the COS.Point Distance and Nearest Features scripts (version 3.2; ESRI, Redlands, CA). ArcView allows the user to highlight points on a map by simply selecting points in the data table, and vice versa. A GIS of Seattle area aerial photographic maps was used to visualize GPS-PAL data points and to analyze both reception and resolution. Maps used were U.S. Geological Survey (USGS) Digital Orthophoto Quarter Quadrangles (DOQQs) licensed by the City of Seattle to the University of Washington. They are ortho-rectified to attain the geometric properties of a map. The resolution of these maps is ± 1 m. Registration errors of these DOQQs are not expected to exceed 0.1 m and were therefore not included in our analysis.

Field studies. Adult subjects and older children wore GPS-PALs integrated into nylon vests (Figure 2). Young children (< 4 years) wore GPS-PALs integrated into cotton bib overalls, which are more durable and more difficult to remove. Both types of clothing allowed for proper horizontal positioning of the antenna, and both allowed for secure attachment of the antenna cable inside the garment. The battery and GPS unit were concealed in closed pockets on the front of the garments. Positioning of battery and GPS unit was chosen to minimally encumber normal range of motion. The antenna was placed on the top of the shoulder to optimize signal reception. This design allowed research staff to simply hand the clothing to the parent or child and prevented tampering and instrument removal.

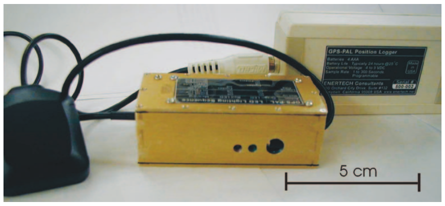

Figure 1. GPS-PAL antenna, electronics, and battery pack (left to right).

Resolution experiments. In the first experiment, GPS-PAL units were left in a stationary position for 12 hr in two urban locations: outdoors in the open and inside a single-story wood-frame house. The resulting coordinate information was analyzed in ArcView to determine what percentage of points was recorded within 2 m, 3.5 m, and 5 m of the true position of the unit. Lines were plotted from each measured point to the true position on the ortho-photo map in ArcView. The true position was the center point of a 1-m^2 landmark visible on the ortho-photo map. True position coordinates were determined in ArcView using the latitude and longitude locator function. The number of points logged by time and the resolution by time were analyzed to investigate the existence of a relationship between bias and time. The root mean square (RMS) error distance, equal to the root of the sum of the squares of all individual errors, was computed for these data. RMS is a standard expression of location error for GPS receivers (*16*).

In a second experiment, GPS-PAL units were carried by two pedestrians walking the same 4-km path on a city sidewalk. A line drawn down the center of the sidewalk was considered the true path. True path coordinates were determined in ArcView using the "line theme" function. Coordinates were analyzed to determine what percentage of points were recorded within 2, 3.5, and 5 m of the true path walked. Parallel lines of these distances on either side, known as line buffers, were drawn around the true path on the ortho-photo map in ArcView. The variable width of the sidewalk was accounted for when determining the center line.

Reception experiments. The GPS-PAL units were left stationary inside a wood-frame house and inside a concrete school building for 30 min, and were then worn by moving individuals inside these two structures for 30 min. GPS-PALs were also worn by moving individuals walking within 1–2 m of the perimeter of these buildings directly adjacent to the outside walls. The number of points logged in each situation was compared with 30-min control data logged outside in an open area. Stationary test data were compared with stationary control data; mobile test data were compared with mobile control data.

Interference experiments. Several known sources of GPS signal interference (*26*) were evaluated to test their effect on reception. Sources were evaluated on two separate days. One 10-min period was measured when the interference source was proximal to the subject wearing a GPS-PAL unit. Disruption of reception was quantified by dividing number of points received by the number of points expected during 10 min when no interference is present. Interferences were evaluated separately. The following personal interference items were tested outdoors: a wool sweater and a nylon raincoat worn over the vest containing the unit; a 900-W Amana microwave oven (Amana Appliances, Newton, IA) operating on the high setting; a Motorola Fr60 Talkabout 465 mHz two-way radio (Motorola USA, Schaumburg, IL); an Ericsson T19LX digital cellular phone receiving full signal at 1,850–1,990 mHz (Sony Ericsson USA, Plano, TX); and a V-Tech 900 mHz analog cordless telephone 5 m away from its base (V-Tech USA, Beaverton, OR). Electronic devices were operated normally for 10 min.

Feasibility study. This study was designed to evaluate child compliance and GPS-PAL functionality over the course of a day. Procedures were approved by the University of Washington Human Subjects Division. Eleven children (six female, five male) in the Seattle area 2–8 years old (mean = 5.5) wore GPS-PAL units for approximately 7–11 hr. All parents involved in the study were faculty, staff, or students in the Department of Environmental Health at the University of Washington. Recruited families responded to an announcement sent via departmental electronic mail listserver. Children selected were required to be toilet trained. Written consent was obtained from parents, and verbal assent was obtained from children. Three of the children wore units to school on a weekday; the other eight wore units on a weekend day. Parents were allowed to select their child's monitoring period. Parents were asked to record whether children complained about the weight or fit of the GPS-PAL garments. Parents were asked to switch the unit on when their child got dressed in the morning, and to turn the unit off at bedtime. Parents also provided home addresses for verifying location on the ortho-photo maps. Data from the child study were grouped by the following five location categories: in vehicle, inside house, inside school, inside business, and outside. Time spent in each location and percentage reception in each location were computed for each child.

Results

Resolution experiments. Table 1 shows the number of points logged by stationary GPS-PAL units over 12 hr and the RMS distance of the points from the true location of each unit. The units had RMS errors of 3 and 3.4 m outdoors, and 5.7 and 5.9 m inside the wood-frame house. Analysis of resolution by time showed a few short periods (< 1 min) when the distance from true location sharply increased (data not shown). Table 2 shows the number of points logged and the resolution of points logged by GPS-PAL units carried by two pedestrians during a 50-min, 4- km walk on city sidewalks. Figure 3 shows a closeup view of the true path walked, the points logged, and the line buffers that were used to determine mobile resolution. Resolution was measured by percentage of points lying within 2, 3.5, and 5 m of the true path. About 96%

Table 1. Measurement error of two stationary GPS-PAL units over 12 hr.

	Points logged[a]	Distance from true position (m)[b]			
		Mean	Median	SD	RMS[c]
Outdoors					
GPS-PAL 1	6,796	2.5	2.2	1.6	3.0
GPS-PAL 2	8,514	2.8	2.5	1.9	3.4
Indoors[d]					
GPS-PAL 1	3,920	4.8	4.0	3.2	5.7
GPS-PAL 2	4,812	4.9	4.1	3.3	5.9

[a]Units log data every 5 sec for a maximum of 8,640 data points in 12 hr. [b]True position defined by locating the coordinates of the units on the orthophotomap using GIS software. [c]Calculated by squaring each individual error, then taking the square root of the mean of these numbers. [d]Indoors = inside a single-story wood-frame building, away from windows.

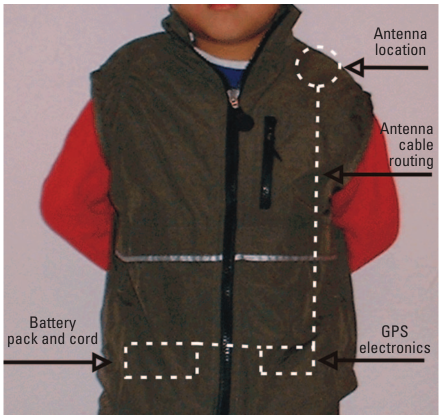

Figure 2. Child wearing GPS-PAL in a vest. Dashed lines indicate location of components inside the vest.

Table 2. Resolution of GPS-PAL units on a 4-km, 50-min walk in the city.

	Points logged[a]	Fraction of points within each buffer (%)		
		± 5 m	± 3.5 m	± 2 m
GPS-PAL 1	540	96.2	89.9	78.6
GPS-PAL 2	575	96.3	90.7	79.1

[a]Units log data every 5 sec for a maximum of 600 data points in 50 min.

of all points were logged within ± 5 m of the true path, 90% were logged within ± 3.5 m, and 79% were logged within ± 2 m.

Reception experiments. GPS-PAL reception data for a subject outdoors, inside two types of buildings and proximal to two types of buildings, are shown in Table 3. Data shown are for 30 min of operation. Better reception was attained next to a concrete/steel building than next to a wood-frame building for one unit, whereas the opposite was true for the other unit. No points were logged inside the concrete/steel frame building. Reception inside the wood-frame building was reduced almost 2-fold by moving around inside the house compared with remaining in one location.

Interference experiments. Reception interference experiment results are shown in Table 4. Walking within 20 m of power substation transformers caused a complete blockage of signal reception. Standing in front of an operating microwave oven caused a significant (32%) reduction in reception. Talking on a 900 mHz cordless phone reduced reception by 7%. Other potential interference sources had no effect or minimal effect on signal reception.

The performance of the GPS-PAL units regarding resolution, reception, and interference is illustrated in Figure 4. Figure 4A is an ortho-photo image with GPS-PAL data logged inside and proximal to a wood-frame house (points shown in green). Figure 4B is a 3:1 scale drawing of this house showing the same points. A 2-m^2 grid is superimposed on this drawing. Based on data in Table 2, this grid approximates an 80th percentile level of resolution for the GPS-PAL. Figure 4 illustrates that locations within and around a house can be defined so as to differentiate by rooms or other microenvironments in and around a residence.

Feasibility study. Data were obtained for 8 of the 11 study children. The first three subjects had no data or minimal data logged because of failure of wiring or connectors leading from the battery pack. These problems were resolved, and no further wiring problems were encountered. One parent noted that the receiver was accidentally turned off and then switched back on later, yielding only 3 hr of data. This subject was excluded from further analysis. Data from another subject were logged without incident, but postprocessing of the coordinates was not feasible because of base file differential signal errors recorded by the CORS station. The unprocessed data were not comparable with the postprocessed data and were excluded from further analysis. The 11 parents all responded that their children did not complain about the weight or restrictiveness of the GPS inside the custom clothes. Two 2-year-old children complained that they did not like the color and style of the bib overalls.

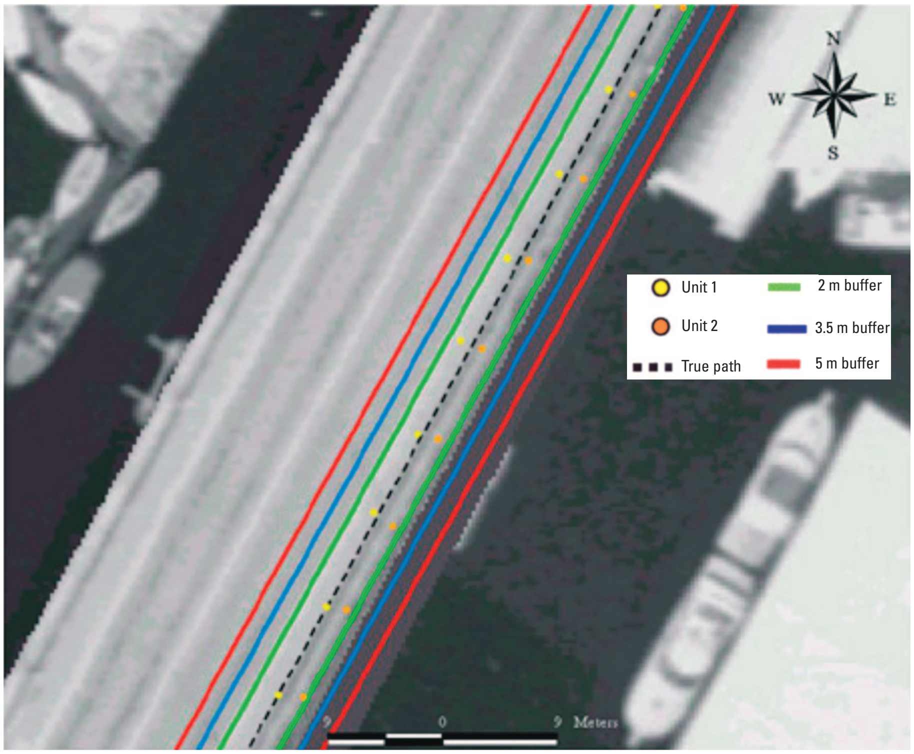

Figure 3. Sample of points logged by GPS-PAL units during the 50-min mobile test. Units were worn by two pedestrians for 4 km in the city. Nine points per unit shown along a path with ideal GPS reception: on a bridge, unobstructed. Complete 50-min data are shown in Table 2. True path is the center of the sidewalk. Variations in sidewalk width were accounted for in this analysis.

Table 3. Reception of GPS-PAL units over 30 min under stationary and mobile conditions: outdoors, indoors, and proximal to two types of buildings.

Test conditions	Location	Unit 1 reception		Unit 2 reception	
		Points logged[a]	Percent of max	Points logged[a]	Percent of max
Outdoors					
Stationary	In the open	360	100.0	360	100.0
Mobile	In the open	358	99.4	360	100.0
Mobile	Proximal to CSF building[b]	110	30.6	127	35.3
Mobile	Proximal to WF building[b]	76	21.1	170	47.2
Indoors					
Stationary	WF building	190	52.8	192	53.3
Stationary	CSF building	0	0.0	0	0.0
Mobile	WF building	113	31.4	85	23.6

CSF, concrete/steel frame; max, maximum; WF, wood frame.
[a] Units log data every 5 sec for a maximum of 360 data points in 30 min. [b] Proximal = within 1–2 m of the outside wall of the building.

Table 4. Interference to GPS-PAL unit reception.

Type of interference	Notes	Reception (% of max)[a]
None		
Outdoors, in the open	> 5 m from any building	100
Spatial		
Power substation	< 20 m from transformers	0
High-tension power lines	30 m overhead	98
Large metal reflective surface	Against galvanized steel	99
Personal		
Clothing covering antenna	Wool sweater and nylon raincoat	100
Microwave oven[b]	0.5 m from oven on "high"	68
2-Way radio[c]	Held to ear, transmit and receive	100
Digital cell phone[d]	Held to ear while talking	100
Cordless phone[e]	Held to ear while talking	93

max, maximum.
[a] Units log data every 5 sec for a maximum of 120 data points in 10 min. [b] Amana 900 w. [c] Motorola Fr60 Talkabout 465 mHz. [d] Ericsson T19LX 1,850–1,990 mHz. [e] V-Tech analog 900 mHz.

Table 5 shows the efficiency of reception by location for each child. Only two children spent appreciable time outdoors, where reception was high (79%). Reception inside homes was greater than reception inside vehicles (20% vs. 12%) and was lowest for inside schools and businesses (6% and 9%, respectively).

The fraction of time monitored for each child by location is presented in Table 6. A total of 2,964 min (49.4 hr) of data was collected for the six children, with monitoring times ranging from 387 to 700 min.

Figure 5 shows the path traveled by one child (Child 1) during the hours of a normal school day. Points on the street correspond to the child walking from the school bus to the school grounds. Points on the field near the top of the picture correspond to two distinct recess breaks. Points near the school's entrance at the center of the picture were logged before classes started in the morning and after classes were over in the afternoon. Points logged inside the school building, near the bottom of the picture, are sporadic because of the multilevel construction of the building. Figure 6 is a time line illustrating the progression of location by time for each child throughout the day. Among the two children monitored on a weekday, Child 2 spent all of her time at school indoors, whereas Child 1 went outside three times for recess. Among the four children monitored on a weekend day, distribution of time in each location varied greatly, except for Child 4 and Child 5. These two were together for most of the day they were monitored.

Discussion

Once initial wiring problems were corrected, time–location data were collected successfully for the remaining eight study participants. Data adequate for "all-day" analysis of time–location patterns were obtained from seven of these eight children. Accidental receiver shut-off, which caused the collection of only 3 hr of data from one child, was prevented in subsequent trials by covering the on/off switch. The CORS base file errors that obstructed postprocessing of one child's data are not preventable. The raw data are still readable but are lower in resolution when not postprocessed (~15% greater RMS error). It would be possible to obtain base files from a private source if higher-resolution data were deemed critical in future studies. Future GPS-PAL studies with greater numbers of subjects will incorporate solutions to data loss discovered in this pilot study. Randomization of children to either weekday or weekend sampling groups would also strengthen future studies and provide more insight into the utility of the GPS-PAL. Overall, it appears that the GPS-PAL is a practical tool for

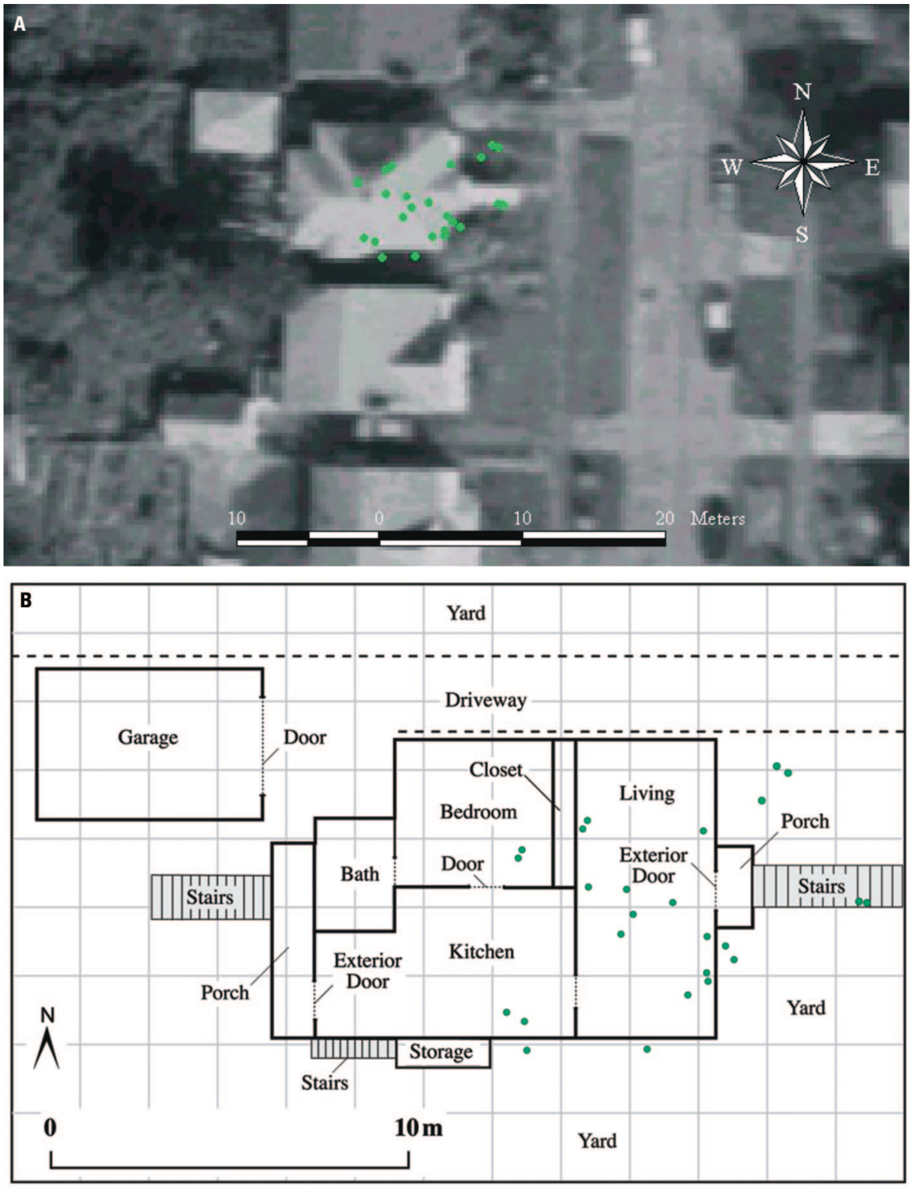

Figure 4. Representation of GPS-PAL capability to differentiate between distinct areas inside and outside a house. Aerial photo of house (*A*) and 1:3 scale drawing of house floor plan overlaid on 2 m^2 grid (*B*). GPS-PAL logged locations are shown by green circles on both photo and floor plan. Approximately 80% of points logged by GPS-PAL fall within 2 m^2. Therefore, it is possible to differentiate a person's location in distinct areas of a house and surrounding yard. Discriminating between indoors and outdoors for points close to exterior walls is accomplished by comparing the time sequence of points to the location of exterior doors.

Table 5. Reception (% of maximum) by location and monitored time for children wearing GPS-PAL units.

	Weekday		Weekend					
Location	Child 1	Child 2	Child 3	Child 4	Child 5	Child 6	Mean reception[a] by location	CV (%)[b]
Vehicle (inside)	26.9	8.8	1.1	15.9	11.0	NA	12.2	67.5
School (inside)	7.2	5.6	NA	NA	NA	NA	6.3	12.6
Home (inside)	26.1	42.5	14.3	NA	NA	20.9	19.8	43.6
Business (inside)[c]	NA[e]	NA	8.3	12.5	6.6	NA	9.3	27.0
Outdoors[d]	86.0	NA	NA	NA	NA	73.7	79.1	7.7
Mean reception[a] by child	24.2	7.7	10.8	13.2	7.3	29.7		60.1
Monitored time (min)	513	480	468	416	387	700		

[a] Units log data every 5 sec; maximum number of data points depends on monitored time for each child. [b] CV, coefficient of variation = (SD/mean) × 100%. [c] Stores, restaurants, cinemas, and other large buildings. [d] Parks, playgrounds, sidewalks, and yards. [e] NA = child spent no time in this location.

Table 6. Where children went: Fraction of monitored time (%) in each location and total monitored time for children wearing GPS-PAL units.

	Weekday		Weekend			
Location	Child 1	Child 2	Child 3	Child 4	Child 5	Child 6
Vehicle (inside)	4.8	15.0	9.7	21.4	19.0	0.0
School (inside)	52.7	80.4	0.0	0.0	0.0	0.0
Home (inside)	5.8	4.6	52.5	0.0	0.0	83.4
Business (inside)[a]	0.0	0.0	37.8	78.6	81.0	0.0
Outdoors[b]	36.7	0.0	0.0	0.0	0.0	16.6
Monitored time (min)	513	480	468	416	387	700

[a]Stores, restaurants, cinemas, and other large buildings. [b]Parks, playgrounds, sidewalks, and yards.

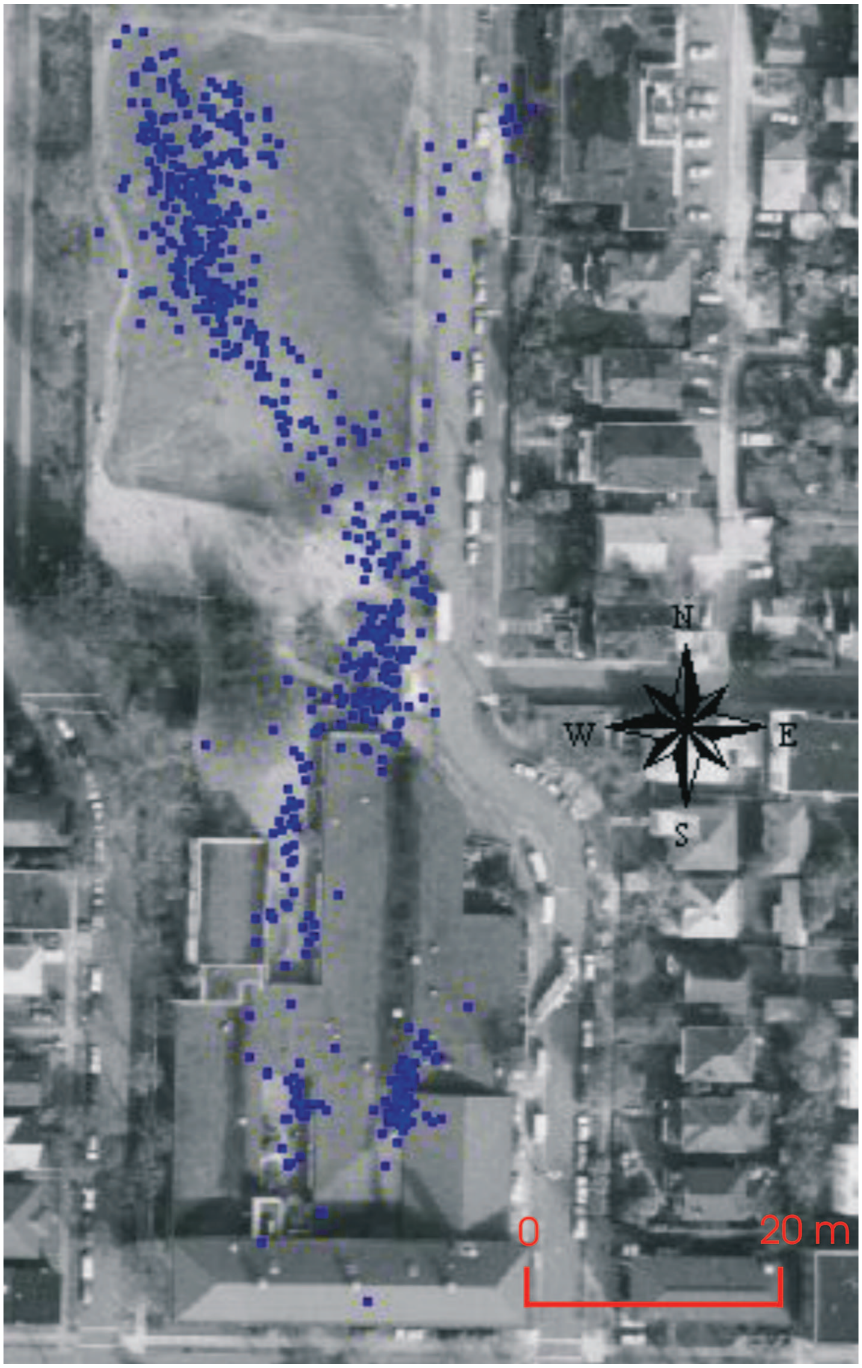

Figure 5. Path traveled by one child on a weekday during school hours. The playing field is located near the top of the picture, the school building is located near the bottom, and the main entrance is located at the center. There is a street along the right side of the school grounds.

collection of children's time–location data, and that the technical criteria for this instrument described above have been met. The performance criteria of resolution and reception are addressed below.

Resolution. A critical factor for any device intended for time–location analysis is an assessment of the instrument position accuracy. Position accuracy depends on many factors, including the satellite constellation geometry (geometric dilution of precision, or GDOP) and on biases or errors in the GPS signal components or receiver (e.g., clock errors, ephemeris, and propagation errors) (*16*). Although uniform position accuracy under all conditions is desirable, varying accuracy over time and space is unavoidable because of GDOP and loss of satellite data from interference. Often the accuracy characteristic is summarized by the range error relative to a known fixed location. Because RMS error describes the magnitude of all errors without regard to direction and because typically it is much greater than the mean error for a stationary instrument, this provides a more conservative estimate of the expected position accuracy of a GPS receiver.

An alternative measure of position accuracy is the proportion of readings that fall within a fixed range of a known location. This measure of position accuracy, as we have shown (Figure 3), can be applied to either stationary or moving subjects along a defined path. This metric is potentially more useful for time–location studies because it also can describe the ability of the instrument to correctly classify a location within a spatial boundary, such as a schoolyard or a room in a home (Figures 4 and 5).

Position accuracy is unit specific for each GPS-PAL, probably due to random clock errors in the receiver. The mean of the RMS errors for the two GPS-PAL units was 3.2 m outdoors and 5.8 m indoors, compared with a typical outdoor RMS error for most portable GPS units of 5–10 m (*23*). Published indoor RMS values were not found. Usually only large survey-quality GPS receivers are capable of attaining a lower RMS error than the GPS-PAL. The error of the map being used also must be considered as an independent factor. Thus, when GPS-PAL data was overlaid on USGS DOQQ maps (nominal 1-m resolution), overall RMS error is about 3.4 m outdoors and 5.9 m indoors, and the maximum error is 3.2 m + 1.0 m = 4.2 m outdoors, 5.8 m + 1.0 m = 6.8 m indoors. Analysis of resolution data by time (Table 1) showed a few short (< 1 min) periods where resolution waned. The existence of a relationship between bias and time can be explained by temporary loss of satellite signal or transient shifts in high atmospheric conditions (*16*).

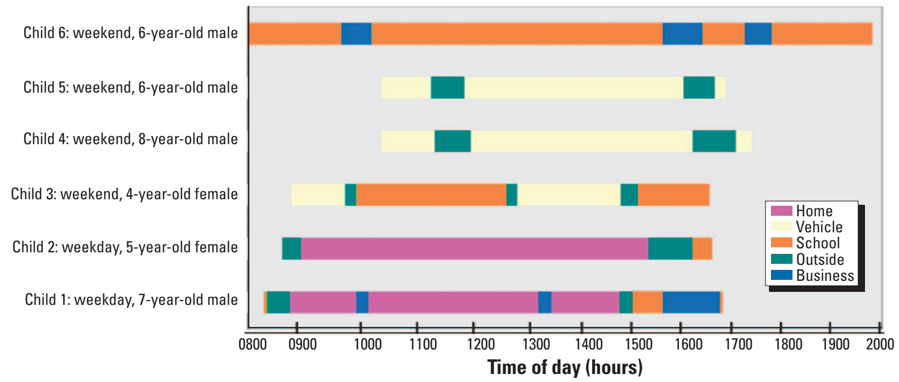

Figure 6. Children's monitored time–location during 1 day using GPS/GIS, 0800–2000 hr.

These data demonstrate that the position accuracy achieved by the GPS-PAL instrument under realistic conditions is sufficient for human time–location analysis. Note in Table 2 and Figure 3 that most points over the 4-km, 50-min test were within 2–3 m of the true path line. The 2-m grid in Figure 4 illustrates that location in and around a house can be delineated at least 80% of the time within a 2-m^2 area. At this scale, data based on position and photo maps would allow classification of activities such as entering a retail store, walking on a sidewalk, traveling by car or bus, playing on a schoolyard, or playing in and around a house. This suggests that the GPS-PAL units can locate subjects with sufficient position accuracy to correctly classify a large variety of human activities.

Reception and interference. Ideally, a GPS device for time–location studies would provide uninterrupted position data, regardless of the subject's location or activities. Certainly, buildings and other objects can compromise GPS signal reception, so tracking subjects in and around structures is constrained by the limitations of current receiver (and antenna) technology. The inconsistency of reception for different children in similar locations can be explained by the high number of variables involved, including building materials, location of a child within a building, type and location of vehicle, and proximity of a child to windows and other signal-permeable materials. This is a limitation for being able to consistently locate an individual in a specific microenvironment in exposure analysis studies. Although consistent time–location may not be feasible with GPS, the percentage reception in most locations was sufficient to define a child's time–location. The following examples using data shown in Table 3 and Figures 4 and 5 illustrate this point. In Figure 5, signal is poorly received inside the school building; however, the time and location at which this child entered and exited the building was precisely recorded, producing a clear time–activity map. Reception within wood-frame buildings and next to both wood-frame and concrete/steel buildings was adequate to characterize an individual's position in these locations (Table 3 and Figure 4). For example, because 31.4% of points were logged when the subject was moving inside the house (Figure 4), and the sampling rate was 5 sec, a location was logged about once every 16 sec. This is sufficient to detect movement between interior rooms, assuming that temporal distribution in reception for a given microenvironment is approximately uniform.

Further improvements can be gained by careful review of the logged points to account for the logical consistency of events in certain microenvironments. When data points fell close to the walls of a building (Figure 4), it was possible to differentiate indoor from outdoor environments and eliminate ambiguous data by examining the time sequence of points and the location of exterior doors. It is unlikely that a single point will fall outside a house if points logged 16 sec before and 16 sec after are logged indoors, unless an exterior door is immediately adjacent to the area.

Interference experiments examined a variety of potential sources, representing devices that have become ubiquitous in our daily environments operating at many frequencies. The results suggest that electrical power distribution equipment, or the associated electric or magnetic fields from transformers or power lines, cause a greater decrease in reception than radio frequency equipment. The lack of interference from clothing is especially important, because this allows for total concealment of the unit within garments worn by subjects.

Future applications. The GPS-PAL could be used in many settings to contribute to a refined exposure analysis of individuals. One target group for application of this technology is children living in rural agricultural communities. These subjects represent a potential high-exposure group for spatial analysis, because pesticides are used routinely in crop production and may be dispersed over wide areas. Children may come into contact with pesticides through various scenarios, such as playing in and around treated farmland, accompanying their parents into the fields, and by contact with pesticide residues brought into the home by their parents (*11,12,24*). We have also learned from more recent work that children in these communities exhibit peak exposures coincident with agricultural pesticide applications (*27*), but we do not know the pathways by which these spraying events produce elevated body burdens. GPS time–location analysis could allow us to characterize activities among these children so that we may better understand pesticide exposure pathways.

Conclusion

The GPS-PAL instrument combines high–spatial-resolution capabilities, a remote antenna, and data-logging capability into a compact size suitable for monitoring adults or children. Spatial resolution is adequate to locate people within distinct subenvironments and to distinguish a variety of human activities. Reception is adequate for position determination outside, proximal to buildings, and inside certain buildings. A subject's position can be narrowed to a single room in a home, a specific area of a playground, or one side or another of a fence line. This provides a new level of accuracy for defining time–location in relation to exposure and eliminates recall bias and reporting errors inherent with written subject-reported logs of time–location. Signal interference from common sources did not appear to limit the utility of the GPS devices in most environments. Data are readily transferred into GIS software for map overlays, allowing for linked visual and tabular analysis. Compliance was good among children 2–8 years old wearing the GPS-PAL incorporated into their clothing. The GPS-PAL is a promising new instrument for quantification of time–location activity patterns in exposure assessment studies. The application of GPS and GIS technologies is the logical next step in the characterization of human time–location patterns.

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