**Quantifying the Spatial and Temporal Variation in Dose from External Exposure to Radiation:
A New Tool for Use on Free-Ranging Wildlife**

Thomas G. Hinton^{1*}, Mike Byrne², Sarah Webster², James Beasley²

¹ Institute of Radioprotection and Nuclear Safety, Cadarache, France

² University of Georgia, Savannah River Ecology Laboratory, Aiken, South Carolina, USA

*corresponding author: tghinton@gmail.com; **Current Address:** Institute of Environmental Radioactivity, Fukushima University, 1 Kanayagawa, Fukushima, 960-1296, Japan (phone: +81-24-503-2967)

² respective email addresses of co-authors: mbyrne13@uga.edu; swebster@srel.uga.edu; beasley@srel.uga.edu

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ABSTRACT

Inadequate dosimetry is often the fundamental problem in much of the controversial research dealing with radiation effects on free-ranging wildlife. Such research is difficult because of the need to measure dose from several potential pathways of exposure (i.e., internal contamination, external irradiation, and inhalation). Difficulties in quantifying external exposures can contribute significantly to the uncertainties of dose-effect relationships. Quantifying an animal's external exposure due to spatial-temporal use of habitats that can vary by orders of magnitude in radiation levels is particularly challenging. Historically, wildlife dosimetry studies have largely ignored or been unable to accurately quantify variability in external dose because of technological limitations. The difficulties of quantifying the temporal-spatial aspects of external irradiation prompted us to develop a new dosimetry instrument for field research. We merged two existing technologies [Global Positioning Systems (GPS) and electronic dosimeters] to accommodate the restrictive conditions of having a combined unit small enough to be unobtrusively worn on the neck of a free-ranging animal, and sufficiently robust to withstand harsh environmental conditions. The GPS-dosimeter quantifies the spatial and temporal variation in external dose as wildlife traverse radioactively contaminated habitats and sends, via satellites, an animal's location and short term integrated dose to the researcher at a user-defined interval. Herein we describe: (1) the GPS-dosimeters; (2) tests to compare their uniformity of response to external irradiation under laboratory conditions; (3) field tests of their durability when worn on wildlife under natural conditions; and (4) a field application of the new technology at a radioactively contaminated site. Use of coupled GPS-dosimetry will allow, for the first time, researchers to better understand the relationship of animals to their contaminated habitats and better assess animal responses to the stress of radiological exposures.

KEY WORD

Global Positioning Systems (GPS); wildlife dose; radioecology; external irradiation

1.0 INTRODUCTION

The greatest challenge in researching the effects of radiation on free-ranging animals is the accurate quantification of absorbed dose (Hinton et al. 2013). Therefore, it is not surprising that inadequate dosimetry is a key criticism (Smith 2008; Beresford et al. 2012) in many of the controversial papers (e.g., Moller and Mousseau 2009) regarding radiation effects to wildlife. As a first step in tiered risk assessments, risk assessors are often able to bypass the need to realistically know the dose to wildlife by using model simulations with input parameters that intentionally maximize radiation exposures and the resultant dose in an elevated worst-case calculation. If this worst-case dose is below levels thought to be harmful to wildlife, the assessor is assured that the actual dose to wildlife will be lower under the real exposure conditions encountered (even when the details of the real exposure situation are not known). This approach is often used to quickly eliminate specific radionuclides or wildlife species from additional risk analyses. Subsequent, more detailed calculations in a tiered risk assessment attempt to predict more realistic dose rates.

However, the uncertainties of estimating dose from current tiered assessment models may be too large when detailed dose-effect issues arise, or when improved precision in estimating doses is needed. Such improvements are currently sought because of changes in international policy that require explicit demonstration of wildlife protection from environmental radiation exposures (ICRP 2008; IAEA 2011). The policies call for developing guidance on radiological risk assessments for wildlife, and advocate the need for specific ecological protection criteria. To establish such protection criteria it is essential to accurately determine dose-effect relationships under the field conditions in which wildlife are actually exposed (Whicker and Hinton 1996).

Determining the dose from radiation can be particularly challenging because in most cases there are two components, the dose from: (1) internal contamination (due to ingesting radioactive food or inhaling radioactive materials), and (2) external irradiation from contamination of the environment in which the animal resides. Dose to wildlife is often calculated based on exposure from the radionuclide-specific activity concentration in the animal (e.g., Bq kg⁻¹ fresh mass), and the radionuclide-specific level of radiation exposure from the environment (e.g., Bq m⁻² in dry soil).

The sources of controversy and enhanced uncertainty surrounding dose are the numerous assumptions required to quantify an animal's exposure to radiation (i.e., the parameters that feed into the dose calculations, and the values used for those parameters). For example, if the animal is not captured and its activity concentration not determined directly, then assumptions are needed to estimate its internal contamination level. Such calculations require assumptions about soil contamination levels and the propensity of radionuclides to be taken up by plants; the levels of contamination in the animal's diet; seasonal dietary preferences; the amount of inhaled contamination; and the life history and behavioral characteristics of individual species of wildlife (e.g., home range, daily activity patterns, habitat preferences and utilization). Most often such details are pragmatically ignored and empirical ratios, such as concentration ratios, are used in a simplified approach to simulate the environmental transfers of radionuclides. Empirical ratios generally vary over several orders of magnitude and thus contribute to uncertainty. Additional assumptions are needed about the exposure levels from sources external to the animal. Overlaying all these assumptions is the temporal aspects of an animal's use of diverse habitats that often have tremendous spatial variability in contaminant densities.

Current wildlife dose models and associated field measurements do not assess wildlife exposure realistically because they do not adequately consider the spatial and temporal variability in habitat use, or the large heterogeneity in levels of contamination (Hinton et al. 2013). The interplay of these parameters result in an animal's varying exposure to external irradiation as it traverses its contaminated environment. The current difficulties in quantifying the time that animals spend in various habitats with diverse contaminant levels contribute to the uncertainties of external exposure and any dose-effect relationships that are obtained.

Such uncertainties prompted us to develop a new instrument by merging two existing technologies. The instrument quantifies the spatial and temporal variations in external dose to which wildlife are exposed. For the first time, an animal's location and short-term integrated dose from external exposure to radiation can be sent to a researcher by satellites, via the use of Global Positioning Systems (GPS) coupled to electronic dosimeters. The innovative technology of the GPS-dosimeter has immense potential for aiding research programs in basic and applied radioecology. The GPS-dosimeter can produce novel information that has been challenging to collect historically from free-ranging animals in their natural environments. An important application of the GPS-dosimeter is that it will enable researchers to understand the relationship of animals to their contaminated habitats and better assess animal responses to radiation stress. Herein we describe the new GPS-dosimeter, present results from laboratory and field calibration tests, and give an example of a field application of the new GPS-dosimeter.

2.0 METHODS

2.1 Merging GPS and Dosimetry Technologies

The technology of tracking an animal's movement using satellites is well developed (Cagnacci et al. 2010). In addition to mapping an animal's location, parameters such as ambient temperature, animal activity, mortality detection, and state of hibernation are routinely obtained with modern GPS systems (Cagnacci et al. 2010). Flexible wireless data communication now exists in both directions, such that an investigator can change the GPS data collection and reporting schedules while the collar is on the animal. Most importantly, the GPS collar can also receive, store and send data that is collected wirelessly from external sensors (e.g. implanted within the animal). This capability opens the possibility for the GPS unit to communicate with an external electronic dosimeter.

Likewise, the technology of measuring dose from external exposure to radiation with electronic dosimeters is well developed. Personal Electronic Dosimeters (PEDs) are used in nuclear industries the world-over to quantify, store and alert humans to changing intensities of radiation fields. Dose from external exposures can be quantified and integrated over a time period chosen by the user, and thus permits variation in exposure conditions to be quantified.

Prior to our work, a combination of the GPS and electronic dosimeter technologies existed in situations where weight of the combined units and battery longevity were not critical issues (Runyon

et al. 1994; Paridaens 2006; Drndarevic and Bolic 2008). For example, radiation detection and GPS systems have been combined to monitor remote areas using unmanned helicopters (Okuyama et al. 2005); in car mounted systems to map radiation levels around Fukushima, Japan (Kazano et al. 2012); and to perform spatial analyses of contaminated sites (Whicker et al. 2008; He et al. 2011).

Our challenge was to adapt the current technologies to the restrictive conditions of having a small GPS-electronic dosimeter on the neck of an animal that is living under harsh environmental conditions. This was achieved in collaboration with Mirion Technologies¹, an electronic dosimeter manufacturer, and Vectronic Aerospace Limited², a firm that specializes in wildlife GPS applications. The key issues in integrating an electronic dosimeter with a GPS unit for wildlife applications were:

- adequate radiosensitivity of the dosimeter when integrated into a unit designed to sustain abuse by wildlife under a variety of field scenarios;
- sufficiently small and light that a medium-sized animal can wear the unit around its neck without interfering with its normal functions; mass of the combined GPS-dosimeter should not exceed 5% of the animal's mass in order to minimize stress (American Soc. Mammalogists 1998);
- sufficient battery longevity, particularly in sub-freezing conditions, to obtain data over several months;
- reliability of communication between the dosimeter and GPS unit;
- transmits, via satellite, cellular network, or other remote method, an animal's GPS location and short term integrated dose to the researcher's computer;
- an automatic release mechanism³ that is pre-programmed to disconnect the collar from the animal at a defined date and time, and thereby allows the GPS-dosimeter to be recovered for complete downloading of data (with the current GPS technology it is inevitable that some data are not transmitted to the satellites because of signal blockage from heavy foliage or poor satellite coverage).

Mirion's SOR/R electronic dosimeter⁴ was chosen for the GPS-dosimeter units. The SOR/R is designed for harsh conditions experienced by field military personal. The SOR/R operates under

¹ www.mirion.com

² <http://www.vectronic-aerospace.com/>

³ <http://www.vectronic-aerospace.com/wildlife.php?p=drop-off>

⁴ www.mirion.com/products/sor-electronic-radiation-dosimeter/

environmental conditions that range from -20 to +50 °C, and is resistant to drops, shocks, and vibrations. The SOR/R complies with several dosimetry standards, including IEC 1283⁵ and MIL-STD-810⁶. It provides H_p(10) dose equivalent measurements in μSv, with an energy response of $\leq \pm 20\%$ in the range of 60 keV to 2 MeV, and an accuracy of $\pm 10\%$. The H_p(10) dose equivalent represents dose at a 10 mm depth within a human torso (ICRU 1993), based on a tissue-equivalent standard of 30 cm X 30 cm X 15 cm (IAEA 1999). Because the size of the wild pigs in our study are in this same size range, and fundamentally dose to pig tissue and human tissue is the same (although the effects per dose might differ), we did not convert the dose readings to μGy. This decision was simplified by the fact that the effective dose for area monitoring [H*(10)] is the same as the H_p(10) at gamma energies equivalent to those of ¹³⁷Cs (IAEA 1999).

The SOR/R unit was dismantled and the key components placed inside the protective housing of a wildlife radio-collar manufactured by Vectronic Aerospace (GPS Plus collar)⁷, and wired to communicate with the GPS technology. This arrangement places the dosimeter in the area of an animal's throat, with the sensitive volume of the dosimeter facing downwards and outwards away from the animal's body. The dosimeter continuously integrates dose and sends data to the researcher via email at user defined intervals, via the same satellites that send the GPS location of the animal. Subtraction of the dose between two time intervals produced a mean dose (μSv) to which the unit was exposed to while in the geographical area delineated by the GPS coordinates during the same time period.

Several types of satellite or cellular communication currently are available for wildlife tracking applications, as well as units with store-on-board data capabilities. We selected GPS units equipped with Globalstar satellite communication capabilities for the purpose of this study. Spatial error of GPS locations using Globalstar average < 5m based on manufacturer specifications.

GPS units vary considerably in price depending on optional characteristics that the user chooses. The costs for our GPS units were about € 3400 each, and € 400 for each dosimeter. Additionally, satellite use charges are based on the frequency of downloading data and vary among GPS providers. We were charged € 0.13 euro per transmitted GPS location, plus a monthly subscription fee of €2 per

⁵ <http://infostore.saiglobal.com/store/details.aspx?ProductID=221648>

⁶ <http://en.wikipedia.org/wiki/MIL-STD-810>

⁷ <http://www.vectronic-aerospace.com/wildlife.php>

GPS collar. The frequency of location transmissions is a user defined parameter and is based on your research needs. It is compromised by battery longevity. The more frequently you download data the shorter the life of the GPS battery. Battery choice also affects the weight of the GPS units, as does the size of the collar to which they are attached. Collar size is dependent on the species of animal. For the wild pigs (*Sus scrofa*) in this study, the GPS units weighed 930 g, plus 55 g for the added dosimeter.

Mirion and Vectronic produced three proto-type units with our specifications. We lab tested the units for uniformity of response to external irradiation, and field tested them for durability and uniformity of response when attached to wildlife. A separate field application of the technology was then applied to a radioactively contaminated area on the U.S. Department of Energy Savannah River Site (SRS) using the same three units.

2.2 Comparison of GPS-Dosimeters under Standard Laboratory Conditions

Before attaching the GPS-dosimeters to animals, we first exposed them to a ¹³⁷Cs source at a U.S. Department of Energy calibration facility. We were interested in the accuracy of the dosimeters, and also the consistency of the three units when they were exposed under identical, well-defined laboratory conditions. Each unit was independently tested across a range of doses by exposing the collars for a specific time at a known distance from the radiation source. All collars were oriented such that placement of the dosimeter relative to the radiation source was constant among collars. Collars were programed to report a GPS position and dose measurement at 30 minute intervals. Different nominal doses were obtained (3, 5, 10, 25 and 50 µSv) by varying the time of exposure. Paired t-tests with Bonferroni adjustments were used to test if means differed at the 5% level.

2.3 Field test of GPS-Dosimeters Durability and Consistency

To test the efficacy of the prototype GPS-dosimeters in a field setting, we deployed them on wild pigs living on the U.S. Department of Energy's Savannah River Site (SRS) in Aiken, South Carolina. The SRS is a 780 km² former nuclear production facility that operated five nuclear reactors from 1951 to 1988, but now focuses on decommissioning and remediation of facilities. Production activities at SRS resulted in a heterogeneous distribution of radioactive contaminants, with most of the contamination

residing in canals, streams and reservoirs associated with effluents from the nuclear reactors (White and Gaines 2000).

Wild pigs were chosen as a test species to evaluate the durability of the GPS-dosimeters because the natural behavior of pigs would expose the units to harsh physical and environmental conditions (i.e., abuse from rooting, wallowing, and exposure to water, heat and cold). We attached the GPS-dosimeters on three young-of-the-year members of a sounder group (i.e. a social group of closely related individuals), whose mean ($\pm$ SD) mass was 46 ± 3 kg. Because members of a sounder group travel together, they would be expected to experience the same contamination levels, and to consequently accumulate similar doses. The evaluation of these units on individuals likely to exhibit substantial overlap in movement behavior was a critical means of robustly testing whether the three GPS-dosimeters responded similarly when exposed to the same doses under field conditions. The three animals were concurrently live-trapped in an area of the SRS during January 2014 where low levels of ^{137}Cs contamination exist due to global fallout from weapons testing. The pigs were trapped using Jager Pro M.I.N.E. corral traps (Jager Pro Hog Control Systems, Columbus, GA) which are designed to trap large groups of individuals. The three individuals were then anesthetized using a mixture of Telazol (4.4 mg/kg) and Xylazine (2.2 mg/kg), fitted with the GPS-dosimeter collars and released together unharmed at the site of capture. All animal handling practices were carried out in accordance with University of Georgia Animal Care and Use guidelines under protocol A2012 08-004-Y3-A4. The instruments were programmed to record a GPS location and accumulated dose reading at 30 minute intervals, with an automatic drop-off mechanism set to release after 45 days (see <http://www.vectronic-aerospace.com/wildlife.php?p=drop-off> for further information).

2.4 Field test to Distinguish Variations in Use of Contaminated Habitats

After testing the durability of the GPS-dosimeters for 45 days, the collars' automatic release mechanisms activated and the units were collected from the field. The GPS-dosimeters were refurbished by Vectronic with new batteries, collar straps and automatic release mechanisms. We then tested the ability of the GPS-dosimeters to define animals' spatial-temporal use of habitats that varied in radioactivity contamination and corresponding dose rates. To do so, we deployed the GPS-

dosimeters on one adult male and two adult female pigs using the same capture methods described above.

The adult pigs were trapped next to the dismantled R-Reactor on the SRS, an area of known radiation contamination. R-Reactor produced plutonium for the U.S. weapons program from the early 1950s to mid-1960s. The reactor was cooled by river water in a flow-through design that resulted in the contamination of several reactor effluent canals and cooling reservoirs. Due to the nature of the effluent, substantial spatial heterogeneity in contamination exists. The uplands have low levels of ^{137}Cs contamination from world-wide weapons fallout, and the riparian areas have significantly higher ^{137}Cs activity concentrations from the reactor releases. Consequently, wildlife would be expected to experience varying levels of exposure as they move among riparian and upland habitats. As such, we expected that the dose measured by the GPS-units would vary as a function of the intensity in which the pigs used the contaminated wetland areas.

The three adult pigs from R-area were trapped separately over a three week period (22-May 2014 to 17-June 2014) and fitted with GPS-dosimeter collars in a similar manner as the initial test performed on young-of-the-year pigs. The GPS-dosimeters for the adult pigs were programmed to record a GPS location and 2-hour integrated dose every 120 minutes, with a programmed release date of 29-July 2014, allowing for a minimum 42 day period of data collection. Importantly, these pigs were not members of the same social group, and were expected to travel independently of each other, thus allowing us to quantify differential spatial-temporal patterns of habitat use and corresponding dose relative to the distribution of contaminants.

To quantify habitat use we estimated the 95% and 50% utilization distribution (UD) contours for each individual adult pig from their respective GPS location data. UDs are spatial probability distributions that describe the probability of an animal occurring in a specific location during a given period of time, and are thus widely used to estimate wildlife home ranges from tracking data. The area within the 95% UD contour is commonly interpreted as representative of the animal's home range; i.e. the area traversed during normal activities of foraging, mating, caring for young, etc. (Burt 1943). The 50% contour is commonly interpreted as the animal's core area, and represents areas of intensive use (e.g., the regularly utilized foraging or resting areas within an animal's home range). UDs are constructed based on the frequency in which animals use portions of the landscape. For example, an

animal might regularly divide its time between two forest patches that are separated by a field; only entering the field briefly while crossing between the forest patches. Thus, at a given contour value we may expect two unconnected UD contours to be identified, centered on each forest patch, since that is where the animal is most likely to be at any given time. We used dynamic Brownian bridge movement models (dBBMM; Kranstauber et al. 2012; Byrne et al. 2014) to estimate UDs based on the trajectories of time-indexed GPS locations for each individual using functions available in the move package (Kranstauber and Smolla 2014) for the R statistical software package (R Core Team 2014). We chose the dBBMM method because 1) unlike traditional kernel density estimators, which are based solely on the spatial pattern of locations, spatial use is explicitly based on the movement path and behavior of the animal and 2) Brownian-bridge methods are robust to irregular GPS fix schedules and missing GPS fixes within the dataset.

We quantified the spatial distribution of radioactive contamination in the area of R-reactor using data points from an aerial ^{137}Cs survey conducted by the SRS in 2013. We interpolated a continuous surface of radiation levels from the aerial data via spatial kriging with the raster (Hijmans 2014) and gstat (Pebesma 2004) packages in R. To illustrate the ability of the GPS-dosimetry collars to capture spatial variation in radiation exposure, we also calculated 3-day UD estimates for one of the adult pigs (# 13651 – see below) in the area of R-Reactor during two 3-day periods: (1) the 3-day period when that individual received the highest dose, and (2) the 3-day period when the same animal received the lowest dose. These estimates of habitat use over the 3-day periods were then overlain with the contamination map derived from the ^{137}Cs fly-over data to see if the dosimetry readings during these periods corresponded to differences in underlying contaminant density.

3.0 RESULTS

3.1 Comparison of GPS-Dosimeters under Standard Laboratory Conditions

The three GPS-dosimeters (numbered: 1350, 1351 and 1352; **TABLE 1**) registered similar doses when exposed to the same calibrated source under laboratory conditions. All doses from the GPS-dosimeter units were greater than the nominal dose as quantified by the calibration facility using source strength, exposure time and distance calculations. These calculations did not account for the ambient background dose rate in the facility. To obtain the low doses of interest (i.e., μSv quantities) it

was necessary to have brief exposures at the calibration facility that ranged from 43.8 to 730.4 sec. However, the GPS-dosimeters were programmed to send 30-minute integrated doses to the researchers via satellites. Thus, the GPS-dosimeters continued to acquire a background dose during the 30 minute interval, after receiving the calibration dose. This additional, uncontrolled contribution may explain why the dosimeter readings were larger than the nominal calculations; additionally, dosimeters are known to over-respond (M. Holdman-Abbott, personal communication).

The 95% confidence interval of the mean for the three GPS-dosimeters included the nominal dose for all doses tested except 10 and 50 μSv (**TABLE 1**). A paired sample t-test indicated that doses of 5 and 10 μSv can be quantified and separated with 95% confidence (Bonferroni adjusted $p = 0.023$); however, with a small sample size of only three GPS-dosimeters mean doses of 3 and 5 μSv were not discernible from each other (Bonferroni adjusted $p=0.13$), thus the limit of reliable detection for the dosimeters was about 3 μSv .

This level of accuracy and precision in the GPS-dosimeters will be sufficient to address the vast majority of wildlife dose questions currently being explored by the radioecology community at contaminated sites such as Chernobyl and Fukushima.

3.2 Field test of GPS-Dosimeters Durability and Consistency on Young-of-the-Year Pigs

The GPS-dosimeters worked without problems over the 45 days that they were on the three young-of-the-year pigs. GPS and dose data were routinely received on the half-hour schedule, except when heavy foliage blocked Globalstar's communication with the satellites. Thus, the transmission of dosimetry data to the GPS system withstood the harsh conditions subjected by wild pigs living under natural conditions. We were able to ascertain that heavy foliage blocked Globalstar's communication by examining the location of GPS fixes that failed to transmit after downloading them from the unit following their recovery from the field. The collars also released from the neck of each animal on the programmed day and time as planned. All collars were recovered from the field and missing GPS data not transmitted via Globalstar were recovered off the units.

As predicted, the GPS data confirmed that the three young-of-the-year pigs captured within the same sounder mirrored their activity patterns, with nearly complete spatial-temporal concordance in movements as indicated by the 50% and 95% UD overlap for all three pigs (**FIGURE 1**).

If the dosimeters were functioning properly our expectation was that the nearly identical movements of the three pigs should result in a similar integrated dose over the entire period in which the units were deployed. This indeed was the case (**TABLE 2**); the variation in total dose among the three GPS-dosimeters over the 45 day period (CV = 3%) was less than the variation expected for a single dosimeter (10% as reported by Mirion). The results of the field test indicated that the GPS-dosimeters worked as designed, and that the novel instrument is sufficiently robust and precise for determining the location and short-term radiation dose received by free-ranging wildlife.

3.3 Field test to Distinguish Variations in Use of Contaminated Habitats by Adult Pigs

Gamma aerial survey data confirmed the spatial heterogeneity of ^{137}Cs contamination in the area of R-reactor, with the greatest contamination levels along riparian areas associated with effluent flows (**FIGURE 2**). The three adult pigs collared in this area were tracked for a total of 39, 41, and 74 days, respectively. As expected, these individuals did not travel together and exhibited different spatial use patterns (**FIGURE 3**). The highest dose rate recorded was by the female wearing collar 13650 (2.4 $\mu\text{Sv/day}$, **FIGURE 3A**). This individual made extensive use of the main effluent canal exiting the reactor during the tracking period and the distribution of points within her core area (50% UD) indicates she likely used this area often for feeding or bedding. On several occasions, pig #13650 accumulated 4 μSv over a 24 hour period, whereas the other pigs never accumulated comparable doses during any 24 hour period in which they were tracked. While a portion of the most contaminated riparian area fell within the home range (95% UD) of male 13651, this pig primarily used areas of lower contamination (**FIGURE 3B**). Thus, when averaged over the 74-day tracking period, the mean dose was lower than for female pig #13650. When we examined male 13651 at a finer temporal scale however, we clearly observed differential patterns in dose accumulation as a function of habitat use relative to contamination levels. For example, the 3-day period with the highest accumulated dose for pig 13651 was associated with use of the contaminated effluent canal; whereas, during the 3-day period in which the same individual had the lowest accumulated dose it remained in an area of lower contamination (**FIGURE 4**). This gave us confidence that changes in dose due to an animal's temporal use of habitats varying in contamination levels can be discerned by the GPS-dosimeters.

4.0 DISCUSSION

The science of measuring dose to humans exposed to ionizing radiation is well developed and involves either passive or active systems. Passive systems typically use thermoluminescent dosimeters (TLDs), which integrate dose over an extended exposure period. The TLD can be worn on clothing, or easily adapted for wildlife by attaching it to an animal in numerous ways. The use of TLDs to estimate radiation dose to wildlife began over 40 years ago (e.g., Woodhead 1973) and remains an important tool in more recent studies (e.g, Chesser et al. 2000; Beresford et al. 2008). A disadvantage of TLDs is that they must be collected and processed in a laboratory after the irradiation period. Generally, recapturing the animal is necessary, although they could be placed on GPS collars that have time released mechanisms. Regardless, TLD data provide the integrated dose received over the entire period of exposure. The TLD data provide no information on the heterogeneity of the exposure conditions during the integration period, or the amount of dose received in specific habitats that may vary tremendously in contaminant density. Thus, TLDs are not suitable for addressing questions about spatial-temporal variation in dose.

The novel approach used in this research was to integrate two existing technologies such that a free-ranging animal's location and short-term integrated dose can be determined. The results of both our laboratory and field experiments confirmed that this new tool is both sufficiently robust and accurate for use in radioecological research conducted under harsh field conditions. The GPS-dosimeters are capable of recording spatial-temporal variation in movement behavior and associated dose at a user-defined interval. These intervals can be established prior to deployment in the field, or, with some satellite applications (e.g., Iridium), can be reprogrammed from an office computer through two-way communication between the researcher and the GPS-dosimetry unit. Such flexibility permits researchers to determine the most appropriate time period over which to quantify dose, depending on the movement and behavior of their study species and research question of interest.

A challenge with this new tool is to understand what the GPS-dosimeter is actually measuring while it is attached to the animal. In addition to the goal of measuring the dose received externally from the contaminated environment, some fraction of the total dose recorded by the dosimeter is due to internal contamination of the animal (acquired through ingestion of contaminated food). We are currently exploring this potential bias in interpreting the dose reading through additional research with

the GPS-dosimeters at Chernobyl and hypothetical calculations using voxel phantoms. The problem of interpreting dosimeter readings also occurs with passive TLDs on contaminated animals (Beresford et al. 2008).

Use of coupled GPS-dosimetry will allow, for the first time, changes in external dose to be measured as animals move through habitats with heterogeneous levels of contamination, and thus should permit a finer resolution in determining variability of external dose. Such knowledge could help validate the calculations currently made by wildlife dose models. Previous wildlife dosimetry studies have largely ignored or been unable to accurately quantify variability in external dose due to technological limitations. Moreover, most wildlife dose models do not consider spatial-temporal aspects but instead use average soil contaminant densities to derive exposure and the resulting dose. This tool also permits quantification of the variation in dose received by individuals of the same population, or among different species within the same community. Such data can be used to more accurately quantify risks.

This technology is available to other researchers by working directly with GPS and dosimeter vendors. The units we designed are relatively large in size and are limited to animals whose mass > 30 kg. Future advancements in both GPS and dosimetry technologies should further increase the application and utility of GPS-dosimetry units as battery and electronic components continue to miniaturize. GPS-dosimeters will be a valuable tool that could significantly advance the science of wildlife dosimetry. Most importantly, the use of coupled GPS-dosimetry will facilitate quantification of potential sub-lethal effects as a function of the animal's more robustly determined dose.

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6.0 LITERATURE CITED

- American Society of Mammalogists Animal Care and Use Committee. 1998. Guidelines for the capture, handling, and care of mammals as approved by the American Society of Mammalogists. *J of Mammalogy* 79:1416-1431.
- Beresford N.A., Gaschak S., Barnett C., Howard B., Chizhevsky I., Strømman G., Oughton D., Wright S., Maksimenko A., and Copplestone D. 2008. Estimating the exposure of small mammals at three sites within the Chernobyl exclusion zone - a test application of the ERICA Tool. *J. Environ. Rad.* 99:1496-1502.
- Beresford N.A., Adam-Guillermine C., Bonzom J-M., Garnier-Laplace J., Hinton T., Lecomte C., Copplestone D. 2012. Comment on “Abundance of birds in Fukushima as judged by Chernobyl” by Moller et al. 2012. *Environ. Pollut.* 169:137-142.
- Burt W.H. 1943. Territoriality and home range concepts as applied to mammals. *J. of Mammalogy* 24:346-352.
- Byrne, M.E., J.C. McCoy, J.W. Hinton, M.J. Chamberlain, and B.A. Collier. 2014. Using dynamic Brownian bridge movement modelling to measure temporal patterns of habitat selection. *J. Anim. Ecol.* 83:1234-1243.
- Cagnacci F., Boitani L., Powell R., and Boyce M. 2010. Animal Ecology meets GPS-based radiotelemetry: a perfect storm of opportunities and challenges. *Philosophical Transactions of the Royal Society B.* 365:2157-2162.
- Chesser R.K., Sugg D.W., Lomakin M.D., Van Den Bussche R.A., DeWoody J.A., Jagoe C.H., Dallas C.E., Whicker F.W., Smith M.H., Holloman K. and Baker R. J. 2000. Concentrations and dose rate

estimates of ^{134,137}Cesium and ⁹⁰Strontium in small mammals at Chornobyl, Ukraine. *Environ. Tox & Chem.* 19: 305-312.

Drndarevic V., and Bolic M. 2008. Gamma radiation monitoring with internet-based sensor network. Instrumentation. *Sci. & Tech.* 36:121-133.

He H.-Y., Zhou H.-L., Zhang H.-J., Zhang S., and Weng G.-J. 2011. Radioactive source monitoring system based on RFID and GPRS. *Nuclear Electronics and Detection Tech.* 31:1223-1227.

Hijmans R.J. 2014. Raster: geographic data analysis and modeling. R package version 2.2-31. <http://CRAN.R-project.org/package=raster>

Hinton T.G., Garnier-Laplace J., Vandenhove H., Dowdall M., Adam-Guillermin C., Alonzo F., Barnett C., Beaugelin-Seiller K., Beresford N.A., Brown J., Eyrolle F., Fevrier L., Gariel, J-C., Hertel-Aas T., Horemans N., Howard B.J., Ikaheimonen T., Mora J.C, Oughton D., Real A., Salbu B., Simon-Cornu M., Steiner M., Sweeck L., and Vives i Batlle J. 2013. An invitation to contribute to a strategic research agenda in radioecology. *J. Environ. Rad.* 115:73-82.

IAEA. International Atomic Energy Agency. 1999. *Calibration of Radiation Protection Monitoring Instruments*. Safety Reports Series ISSN 1020-6450; no 16. 162pp. IAEA, Vienna, Austria.

IAEA. International Atomic Energy Agency. 2011. *Radiation Protection and safety of radiation sources: International basic safety standards Sources*. Interim Edition. General Safety Requirements Part 3 - n°GSR Part 3 (Interim). 96 pp. and annexes, IAEA, Vienna, Austria.

ICRP. International Commission on Radiological Protection. 2008. *Environmental protection: the concept and use of reference animals and plants*. ICRP Publication 108, Ann. ICRP 38, 4-6.

ICRU. International Commission on Radiation Units and Measurements. 1993. *Quantities and Units in Radiation Protection Dosimetry*, Rep. ICRU-51. Bethesda, MD.

Kawano Y., Shepard D., Shobugawa Y., Goto J., Suzuki, T. Amaya Y., Oie M., Izumikawa T., Yoshida H., Katsuragi Y., Takahashi T., Hirayama S., Saito R., and Naito M.. 2012. A map for the future: Measuring radiation levels in Fukushima, Japan. *Proceedings -2012 IEE Global Humanitarian Tech, Conf. GHTC*. ar. No. 6387021; 53-58. (ISBN: 978-076954849-4).

Kranstauber B., Kays R., LaPoint S.D., Wikelski M., and Safi K. 2012. A dynamic Brownian bridge movement model to estimate utilization distributions for heterogeneous animal movement. *J. of Animal Eco.* 81:738-746.

457 Kranstauber B. and Smolla M. 2014. Move: visualizing and analyzing animal track data. R package
 458 version 1.2.475. <http://CRAN.R-project.org/package=move>

459 Moller A.P. and Mousseau T.A. 2009. Reduced abundance of insects and spiders linked to radiation at
 460 Chernobyl 20 years after the accident. *Bio. Letters*, 5, 356-359.

461 Okuyama S., Torii T., Nawa Y., Kinoshita I., Suzuki A., Shibuya M., and Miyazaki N. 2005. Development
 462 of a remote radiation monitoring system using unmanned helicopter. *Intern. Congress Series*. 1276:
 463 422-423.

464 Paridaens J. 2006. Development of a low cost, GPS-based upgrade to a standard handheld gamma
 465 detector for mapping environmental radioactive contamination. *Applied Rad. and Isotopes*. 64:264-
 466 271.

467 Pebesma E.J. 2004. Multivariate geostatistics in S: the gstat package. *Computers and Geosciences*
 468 30:683-691.

469 R Core Team. 2014. R: A language and environment for statistical computing. R Foundation for
 470 Statistical Computing, Vienna, Austria. URL <http://www.R-project.org/>.

471 Runyon T., Hammitt R., and Lindquist R. 1994. Buried danger: integrating GIS and GPS to identify
 472 radiologically contaminated sites. *Geo Infosystems* 4:28-36.

473 Smith J. 2008. Is Chernobyl radiation really causing negative individual and population-level effects on
 474 barn swallows? *Bio. Letters* 4:63-64.

475 Vectronic Aerospace, accessed November 2014. (<http://www.vectronic-aerospace.com/>)

476 Whicker F.W. and Hinton T.G. 1996. Effects of ionising radiation on terrestrial ecosystems. IN:
 477 *Proceedings of the International Symposium on Ionising Radiation* (B. Amiro, R. Avadhanula, G.
 478 Johansson, D-M Larsson and M. Luning, Eds.) pp. 109-123. Akademtryck AB, Edsbruk, Sweden.

479 Whicker R., Cartier P., Cain J., Milmine K., and Griffin M. 2008. Radiological site characterizations:
 480 gamma surveys, gamma/226Ra correlations, and related spatial analysis. *Health Physics Operational*
 481 *Rad. Safety* 95:Supp. 5,S180-S189.

482 White D.L., and Gaines K.F. 2000. The Savannah River Site: site description, land use, and management
 483 history. *Studies Avian Bio*. 21:8-17.

484 Woodhead D. 1973. The radiation dose received by plaice (*Pleuronectes platessa*) from the waste
485 discharged into the north east Irish Sea from the fuel reprocessing plant at Windscale. *Health*
486 *Physics*. 25:115-121.
487

LIST of FIGURES

FIGURE 1. Space use estimates of three young-of-the-year wild pigs belonging to a sounder group fit with prototype GPS-dosimetry collars and tracked for 45 days. The three individuals traveled together and exhibited a high degree of overlap in their use of habitats. Estimates of home range (95% UD = thick lines) and multiple core areas (50% UD = thin lines) of frequent use for each of the three pigs are shown.

FIGURE 2. Spatial heterogeneity in ^{137}Cs contamination in the vicinity of R-Reactor based on 2013 fly-over analyses.

FIGURE 3. Estimates of home range (95% UD = thick lines) and core areas of frequent use (50% UD = thin lines), and average dose rates over the total days monitored for three adult wild pigs fitted with prototype GPS-dosimetry collars; 13650 (A), 13651 (B), and 13652 (C) in the vicinity of R-reactor, Savannah River Site, Aiken, South Carolina. The underlying heat map represents variation in ^{137}Cs contamination levels based on 2013 aerial gamma survey.

FIGURE 4. Three-day 95% (thick lines) and 50% (thin lines) UD contours for a male adult pig wearing a GPS-dosimeter in the vicinity of R reactor for: (A) the 3-day period of greatest dose accumulation, and (B) the 3-day period of lowest dose accumulation. The underlying heat map represents variation in ^{137}Cs contamination levels based on a 2013 aerial gamma survey.

TABLES

TABLE 1. Test results of three GPS-dosimeters identically exposed within a ^{137}Cs calibration facility.

Nominal Dose (μSv)	Measured Dose (μSv)			Mean	95% CI	CV (%)
	GPS-Dosimeter 13650	GPS-Dosimeter 13651	GPS-Dosimeter 13652			
3	4	5	4	4.3	2.9 – 5.8	13.3
5	5	6	7	6.0	3.5 – 8.5	16.7
10	12	12	11	11.7	10.2 – 13.1	4.9
15	17	16	16	16.3	14.9 – 17.8	3.5
25	28	29	32	29.7	24.5 – 34.8	7.0
50	57	56	57	56.7	55.2 – 58.1	1.0

TABLE 2: Comparison of total dose recorded by GPS-dosimeters deployed on three wild young-of-the-year pigs from 6 January to 20 February 2014. The pigs had the same movement patterns during the 45-day period (see Figure 1). Variation in integrated doses among the three GPS-dosimeters (CV = 3%) was less than the 10% variation expected for a single dosimeter.

Date	<u>Collar 13650</u>		<u>Collar 13651</u>		<u>Collar 13652</u>	
	μSv	Total	μSv	Total	μSv	Total
6 January	298		284		314	
20 February	384	86	365	81	398	84

Figure 1. (Color in Print and Web)

FIGURE 2 . (Color in Print and Web)