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Sequential Monitoring of Burials Containing Small Pig Cadavers Using Ground Penetrating Radar*

ABSTRACT: Ground-penetrating radar (GPR) was used to monitor 12 pig burials in Florida, each of which contained a small pig cadaver. Six of the cadavers were buried in sand at a depth of 0.50–0.60 m, and the other six were buried in sand at a depth of 1.00–1.10 m to represent deep and shallow burials that are generally encountered in forensic scenarios. Four control excavations with no pig interment were also constructed as blank graves and monitored with GPR. The burials were monitored for durations of either 13 or 21 months, and were then excavated to correlate the decomposition state of the cadaver with the GPR imagery. Overall, this study demonstrated that it may be difficult to detect small cadavers buried in sand soon after they are skeletonized because the area surrounding the body, or the grave, may not provide a strong enough contrasting area to be detected by GPR when compared to that of the surrounding undisturbed soil. Also, depth of burial appears to influence grave detection because bodies that are buried at deeper depths may be detected for a longer period of time due to reduced decomposition rates.

KEYWORDS: forensic science, ground-penetrating radar, forensic anthropology, forensic archaeology, pig cadavers

When forensic investigators are performing searches for buried bodies or evidence, a multidisciplinary approach should be implemented that incorporates multiple methods (1–4). Investigators should first begin searches by incorporating noninvasive or nondestructive methods (e.g., geophysical searches, cadaver dogs, and visual searches) to pinpoint specific areas that will require follow-up invasive or destructive testing (e.g., probes and excavating). Ground-penetrating radar (GPR) has become an important noninvasive search option for forensic investigators when site conditions are appropriate for searches involving buried bodies or evidence. In particular, examples of successful searches for burials of homicide victims have been reported in the published literature (5–9), and more recently, GPR has been used to search for avalanche victims buried in snow (10).

Controlled GPR research, most often consisting of burying a pig cadaver as a proxy for a human body in known soils and then detecting and monitoring the burial for some length of time, has been important in demonstrating the utility of this technology for grave detection (3,4,11–13). The primary purpose of these studies has been to determine if a buried body could be detected in a particular soil or environment as certain soil features will have a significant effect on GPR performance. Since the initial GPR studies performed in Colorado by NecroSearch International (3,4,11), a number of subsequent GPR studies have focused on regional approaches in the southeastern United States in locations such as Tennessee (12) and Florida (13).

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Previous forensic GPR research in Florida tested a number of important variables such as burial depth (shallow vs. deep), differing soil compositions (sand and clay), and length of interment (burial duration), all that can affect grave detection, and which may be encountered in the burial environment. For example, Schultz et al. (13) tested the efficacy of using GPR to detect controlled graves that contained large pig cadavers in central Florida. Overall, a number of important conclusions were made. While shallow cadavers buried in sand were easily detected over 21 months of monitoring and during advanced stages of decomposition, cadavers that were buried in proximity to a clay horizon became increasingly difficult to image. After the first year of interment, these burials were difficult to detect although there was extensive preservation of soft tissue structures. Blank control graves, comprising only disturbed backfill, were very important in demonstrating that the hyperbolic anomaly was primarily the result of the decomposing body or skeleton, and not the disturbed soil. Finally, it was shown that minimal processing to remove background noise of the GPR data is generally not needed for field assessments when surveying soils comprised primarily of sand. However, removing the horizontal ringing, which can mask a response from the backfill, can be helpful for grave detection because a response from the backfill may indicate the location of the grave even when there is a weak response from the body. Two issues concerning buried bodies that were not addressed by Schultz et al. (13) were the response from small-sized cadavers buried in sand and the effect of burial depth (shallow vs. deep) in sand.

The purpose of this study was to test the applicability of using GPR in Florida to detect and monitor small pig cadavers in a controlled setting. The research objectives of this study were to:

- document the changes in GPR imagery characteristics of small bodies buried in sand which result from decomposition and subsequent compaction of the backfill over approximately 21 months;

- determine if burial depth and length of interment (burial duration) were factors in producing a distinctive anomalous response;
- assess if minimal processing of the GPR profiles to remove antenna noise (known as "ringing" or multiples in the geophysical literature) was necessary for grave detection of small cadavers.

Materials and Methods

Research Site and Burial Construction

The research field site was located in unmanaged open pasture in Alachua County, Florida because it provided a number of ideal characteristics for GPR surveying of small subsurface features: the field was open with no trees or bushes in the immediate area, the ground surface and topography were flat, there was excellent drainage, and the soil represented one of the most common soil types in Florida. The soil type, an Entisol, is comprised of primarily sand horizons in the depths studied. Domestic pig (*Sus scrofa*) cadavers were used as proxies for human bodies in this study. Pig cadavers are commonly used in taphonomic experiments to replicate humans because they are easy to obtain and entomologic studies have shown that they are the most appropriate animal proxy for human decomposition (14,15). The pigs were killed in the morning by a veterinarian to ensure humane treatment, and the burial process was completed by the afternoon of the same day.

A total of 12 control graves, each containing one small pig cadaver ranging in weight from 25.9 to 33.6 kg (57–74 lbs.) with an average weight of 29.7 kg (65.4 lbs.), were constructed for this study (Table 1). The size of the pig cadavers was chosen to represent a large child or small adult. Also, the following variables were measured: the length of time a pig cadaver was interred and the depth at which a pig cadaver was buried. Six cadavers were buried at a depth of 0.50–0.60 m, and the other six were buried at a depth of 1.00–1.10 m to represent deep and shallow burials that are generally encountered in forensic scenarios. Finally, after the termination of 1 year (13 and 13.25 months), six pig burials (three deep and three shallow) were excavated to assess the decomposition state of the cadavers. The remaining six burials (three deep and three shallow) were excavated at 21 months. See Table 1 for a summary of the burial data for each cadaver. For the purposes of this paper, the overall decomposition state of each cadaver is only noted in general terms. For more in-depth descriptions of the decomposition state of each cadaver, see Schultz (16).

In order to understand if the GPR anomalies are a function of the buried cadaver or the disturbed soil of the grave, blank control graves without cadavers were constructed and monitored with GPR. The imagery of the grave anomalies was compared over time to qualitatively assess how the anomalies changed due to compaction of the backfill and decomposition of the pig cadaver. In particular, four blank control graves (two deep and two shallow), containing only disturbed soil or backfill, were constructed at the same time as the pig cadaver graves to distinguish the response of the disturbed soil from that of the pig's decomposing cadaver and skeleton.

TABLE 1—*Detailed burial data for each pig cadaver.*

Cadaver no.	Weight (lbs./kg)	Depth	Length of Burial (months)
1	74/33.6	Deep	21
2	68/30.9	Deep	21
3	70/31.8	Deep	21
4	66/30	Shallow	21
5	68/30.9	Shallow	21
6	70/31.8	Shallow	21
7	57/25.9	Deep	13
8	71/32.3	Deep	13
9	58/26.4	Deep	13
10	63/28.6	Shallow	13.25
11	57/25.9	Shallow	13.25
12	63/28.6	Shallow	13.25

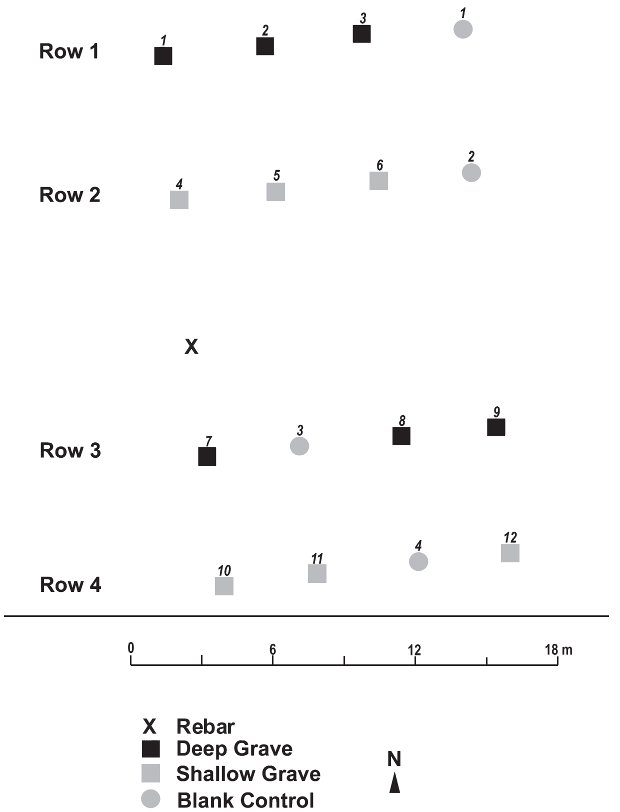

FIG. 1—*Field site map showing distribution of study graves and no trees in the study area.*

The blank control graves, with similar dimensions to the graves containing the pig cadavers, were constructed by digging the grave and then returning only the backfill to the hole. The 12 pig cadaver graves and four control graves were arranged in four rows that were oriented west to east (Fig. 1). Row one included pig cadaver graves 1, 2, and 3 followed by a blank control grave. Row two included pig cadaver graves 4, 5, and 6 followed by a blank control grave. Row three included pig cadaver grave 7, a blank control grave, and then pig cadaver graves 8 and 9. Lastly, row four included pig cadaver graves 10 and 11, followed by a blank control grave, and then grave 12. Each GPR profile that is presented (Figs. 3–9) only includes graves that were in the same row. The graves were placed in an open field away from trees, and permanent wooden markers were placed in the ground at the corners of each grave so transect lines could be replicated each time GPR data were collected.

Ground-Penetrating Radar

The GPR system used in this study was the Subsurface Interface Radar (SIR) 2000, manufactured by Geophysical Survey Systems, Inc (GSSI) with a 500-MHz center frequency antenna used in the standard position, where the dipoles are oriented perpendicular to the direction of travel. The 500-MHz frequency antenna was used for this study to make direct comparisons with Schultz et al. (13). A 500-MHz antenna frequency has been shown to provide an excellent compromise between depth of penetration and resolution of subsurface features for the soils used in this study (13,17). Depth of investigation and vertical resolution are two important considerations when choosing the appropriate antenna. In general terms, a decrease in antenna frequency (e.g., 250-MHz) will increase the depth of investigation, while decreasing the vertical resolution of the subsurface. Conversely, an increase in antenna frequency (e.g., 900-MHz) will decrease the depth of investigation, while increasing the resolution of subsurface objects. Refer to Ruffel (18) for an excellent overview of selecting antenna frequencies based on soil properties.

Ground-penetrating radar systems are used by pulling the antenna over the ground surface while continuous electromagnetic pulses of short duration are emitted downward into the ground. The velocity of the electromagnetic (EM) wave is primarily controlled by the relative dielectric permittivity (ϵ_r), a geophysical property strongly dependent on water content. Therefore, as the EM wave penetrates the subsurface, it is reflected and refracted as it encounters lithologic interfaces, such as clay, and where water content (hence ϵ_r) changes significantly. In addition, in forensic and archaeology contexts, the EM wave is reflected and refracted when it encounters areas of contrasting properties such as highly conductive objects (i.e., metal artifacts and weapons). The GPR antenna will receive the returning reflected waves and a cross-sectional picture of the subsurface is generated from the composite of the reflected waves. Please refer to the following references for detailed descriptions of GPR methodology for forensic and archaeological contexts (1,2,6,8,18,19).

Ground-penetrating radar surveys were conducted monthly from October, 2000 to June, 2002. In order to make direct comparisons with Schultz et al. (13), data collection over the length of the graves will be the focus of this study. Since graves were oriented in rows lengthwise from west to east (Fig. 1), the data collection for this study will be presented over the length of the graves in both directions (W–E and E–W). Once the appropriate dialectic permittivity and nanoseconds were determined, data collection was performed using default settings of the SIR 2000, except for gain changes. Depth was calibrated in the field each time data collection was performed by pulling the antenna over a buried piece of metal rebar (Fig. 1) that was buried at 1 m. Conyers (19) states that the most accurate velocity tests to determine depth in the field involve burying objects at known depths, such as a metal bar, so the radar travel times can be directly measured. In this study, if the depth scale needed to be adjusted slightly because of increased moisture retention in the soil from periodic rainfall, which rarely ever occurred, the depth scale was adjusted by slightly changing the dielectric constant (Fig. 2). The GPR files were then uploaded to an external computer for further analysis using RADAN for Windows NT, version 2.0.9.2, North Salem, NH, proprietary software of GSSI.

A finite impulse response (FIR) filter was used for background removal using RADAN to compare qualitatively if the resolution of the grave anomalies increased. While there are various filters and procedures that can be used to process GPR data, this study was conducted to only assess the issue of background removal with minimal postprocessing of the GPR data. The two most common types of noise in GPR data are from system ringing and scattering of the EM wave (19). Ringing, also called multiples, usually appears as horizontal or subhorizontal artificial reflections and can be the result of the EM wave bouncing off surface objects (e.g., metal fences, headstones), bad antenna contact, different antenna elevation, or, more typically, by strong near surface reflections caused by wet or clay-rich soils. In particular, antenna noise can appear as horizontal artificial reflections at the top of most GPR profiles due to ringing of some antennas and may obscure reflection data if it is not removed (20,21). The horizontal high pass filter is the preferred method for background removal of flat-lying ringing system noise (22) using RADAN for Windows NT, Version 2.0.

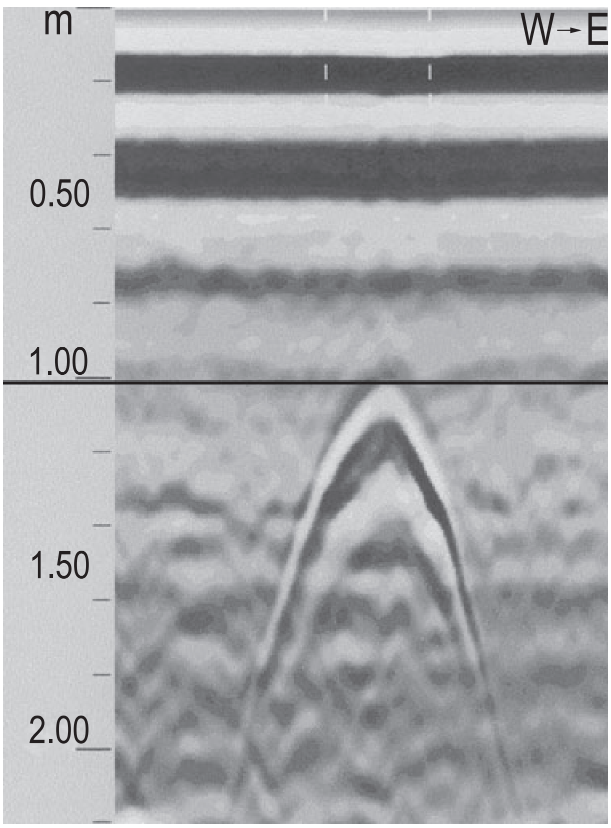

FIG. 2—*GPR profile showing depth calculated correctly for the rebar that was buried at 1 m.*

Results

In order to make direct comparisons with Schultz et al. (13), only a subset of the GPR profiles that were collected over the center of each grave will be described in detail to show the specific cadaver and soil features that were imaged on the profile and to discuss how these characteristics changed over the duration of this study. Each of the GPR profiles that are presented includes both processed and unprocessed views. A description of the general decomposition state of each cadaver at the time it was excavated and a summary of the GPR results for each cadaver is provided in Table 2. Also, detailed climatic data (rainfall and temperature) that were obtained from the NOAA (National Climate Data Center) (23) have been provided in Table 3 for each of the GPR profiles (Figs. 3–9). The climatic data are provided for researchers who wish to compare their GPR data with this study.

Shallow Cadavers in Sand

The image of a GPR profile is a 2-D picture that displays depth (top to bottom) and length (left to right). Distinctive grave

TABLE 2—*Summary information describing the general decomposition state of each cadaver at the time of excavation and an overview of the GPR imagery results for each cadaver.*

Cadaver no.	General Decomposition State	Overview of GPR Imagery Results
1	Extensive preservation of soft tissues	Decreased return exhibiting a weak hyperbolic anomaly that was poorly detected; anomaly obscured by antenna noise and was clearly discernible after postprocessing
2	Moderate preservation of soft tissues	Significantly decreased return exhibiting a weak hyperbolic anomaly that was barely detected; anomaly obscured by antenna noise and was still poorly detected after postprocessing
3	Moderate preservation of soft tissues	Significantly decreased return exhibiting a weak hyperbolic anomaly that was barely detected; anomaly obscured by antenna noise and was still poorly detected after postprocessing
4	Completely skeletonized	Decreased hyperbolic return over the last few months that was no longer detectable; no response after postprocessing
5	Completely skeletonized	Excellent detection for duration; postprocessing not required
6	Completely skeletonized	Decreased hyperbolic return over the first year that was no longer detectable over the last few months; no response after postprocessing
7	Moderate preservation of soft tissues	Excellent detection for duration; postprocessing increases resolution of hyperbolic anomaly over last month, but not needed for detection
8	Moderate preservation of soft tissues	Excellent detection for duration; postprocessing increased resolution of hyperbolic anomaly over last month, but not needed for detection
9	Moderate preservation of soft tissues	Excellent detection for duration; postprocessing increased resolution of hyperbolic anomaly over last month, but not needed for detection
10	Near complete skeletonization; minimal preservation of dessicated skin at head and thorax	Decreased hyperbolic return that was still detectable for duration; postprocessing not required for detection
11	Moderate preservation of soft tissues	Excellent detection for duration; postprocessing not required
12	Near complete skeletonization; minimal preservation of dessicated skin at torso	Decreased hyperbolic return that was still detectable for duration; postprocessing not required for detection, but increased resolution of the anomaly

TABLE 3—*Climatic data for each of the GPR profiles (Figs. 3–9) obtained from the NOAA, National Climate Data Center (23).*

Fig. no.	Daily Maximum Temp. (°F)	Daily Minimum Temp. (°F)	Daily Mean Temp. (°F)	Mean Monthly Temp. (°F)	Mean Maximum Temp. (°F)	Daily Rainfall (Inches)	Total Monthly Rainfall (Inches)
3	80	47	64	68	80.2	0.00	1.02
4	84	62	73	68.7	80.1	0.00	0.08
5	84	53	69	67.5	80.3	0.00	1.10
6	91	68	80	78.6	87.9	0.01	7.3
7	80	47	64	68.0	80.2	0.00	1.02
8	78	55	67	61.2	72.6	0.00	1.0
9	91	69	80	78.6	87.9	1.87	7.3

anomalies were initially produced for all six of the small pig cadavers that were buried at shallow depths (cadavers 4, 5, 6, 10, 11, and 12). For example, there are two distinctive features noted when viewing the unprocessed GPR profile (Fig. 3*a*) that was collected at one month and represents three buried cadavers (4, 5, and 6): the artificial reflections from ringing and the anomaly from the buried cadaver. Oriented along the top of the entire profile, the horizontal reflections are most prominent between 0.0 and 0.6 m, and the ringing does not represent any stratigraphic horizons. The thickness and depth of the ringing changed minimally during the study. Three hyperbolic shaped anomalies begin at a depth of approximately 0.50 m and appear as a vertical series of hyperbolic, or bell-shaped, curves. The cadaver is located at the apex of each anomaly and the anomaly continues inferiorly to a depth deeper than the buried cadaver. Although there is extensive ringing noted from 0.0 to 0.6 m on the GPR profile, the noise does not mask or obstruct the cadaver anomalies. Backfill above the cadavers is not detected because it is masked by the antenna noise. In addition, the blank control grave that contains only backfill barely exhibits a discernible response. It is clear from the comparison of the blank control grave with the pig graves that the anomalies are due to the pig remains and not the disturbed soil.

With the background removal (Fig. 3*b*), there is only a slight increase in the resolution of the anomalies. The hyperbolic shape of the anomalies (extensions of the hyperbola that produce the hyperbolic shape) increased because the tails are now more discernible. Also, the disturbed soil above the pig anomaly is barely detected when the noise is removed.

The small cadavers buried at the shallow depth (4, 5, 6, 10, 11, and 12) were still detected over the first year in the sandy soil of the Entisol, even though a number of cadavers would have exhibited extensive skeletonization (Table 2). For example, Fig. 4 is a GPR profile of three shallow cadavers (4, 5, and 6) collected at 12 months and 11 days. Three hyperbolic-shaped anomalies that begin at a depth of approximately 0.50 m are clearly discernible on the unprocessed profile below the ringing, although the response from cadaver 6 is reduced in comparison to the responses from cadavers 4 and 5 (Fig. 4*a*). Although there is ringing noted from 0.0 to 0.6 m on the GPR profile, the noise does not mask or obstruct the cadaver anomalies. In addition, the control grave that contains only backfill, barely exhibits a discernible response. It is clear from the comparison of the blank control grave with the pig graves that the anomalies are due to the pig remains and not the disturbed soil.

With the background removal (Fig. 4*b*), there is a slight increase in the resolution of all three of the cadaver anomalies, particularly cadaver 6. There is also a minimal response from the blank control grave that is discernible on the processed profile. However, the size and shape of the response from the control grave is clearly different

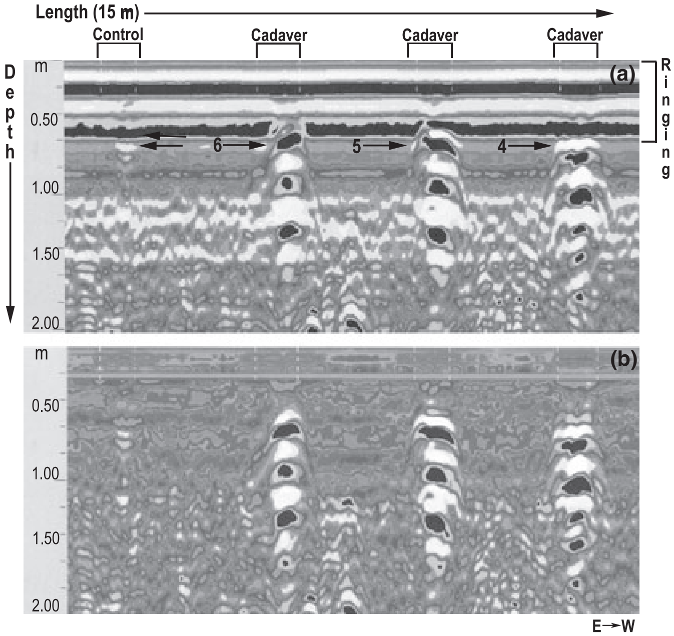

FIG. 3—*GPR profile of three shallow cadavers (4, 5, and 6) collected at 1 month that compares the unprocessed imagery (a) with the processed background removal (b). Note the distinctive horizontal ringing at the top of the profile from antenna noise (a), the three hyperbolic-shaped cadaver anomalies (a and b), the absence of a discernible response from the blank control grave (a and b), and the minimal response from the disturbed backfill above the cadaver anomalies (b). The profile is approximately 2.0 m deep and 15 m long.*

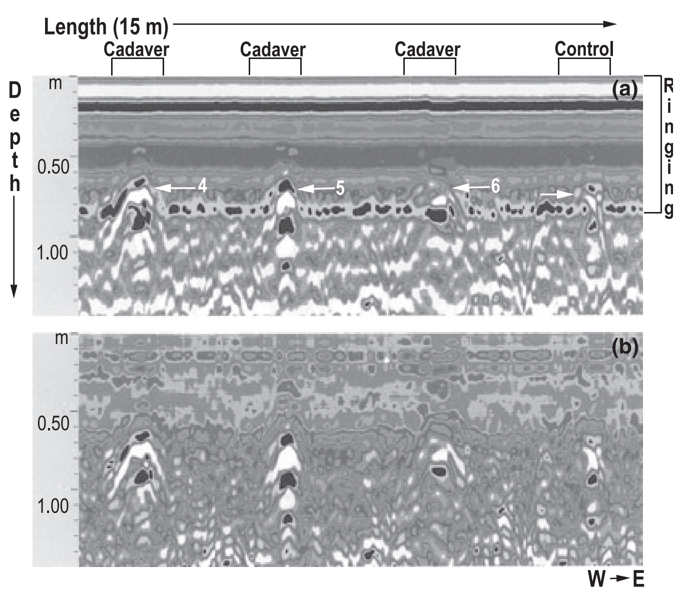

FIG. 4—*GPR profile of three shallow cadavers (4, 5, and 6) collected at 12 months and 11 days that compares the unprocessed imagery (a) with the processed background removal (b). Note the distinctive horizontal ringing at the top of the profile from antenna noise (a), the three hyperbolic-shaped cadaver anomalies (a and b), and the minimal response from the blank control grave (a and b). The profile is approximately 1.40 m deep and 15 m long.*

than the cadaver anomalies; the size of the response is smaller and does not display a hyperbolic shape.

The return from the shallow pig remains was still discernible after a year and a half. Figure 5 is a GPR profile exhibiting

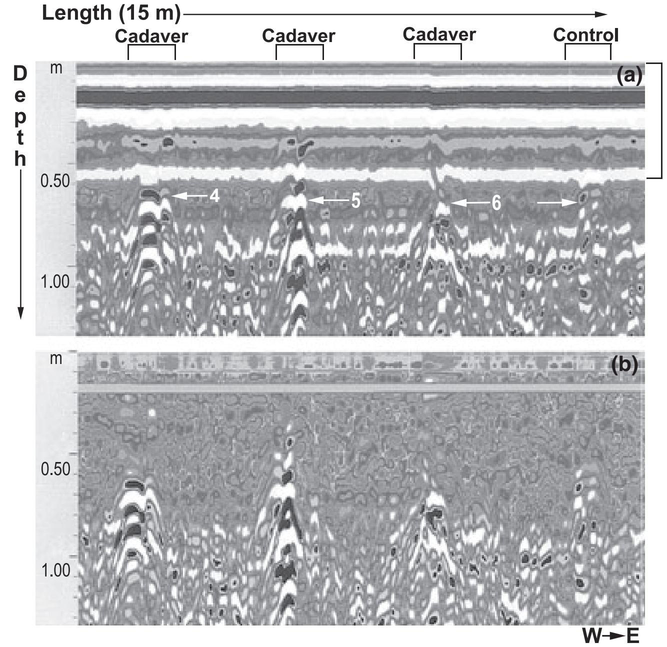

FIG. 5—*GPR profile of three shallow cadavers (4, 5, and 6) collected at 18.5 months that compares the unprocessed imagery (a) with the processed background removal (b). Note the distinctive horizontal ringing at the top of the profile from antenna noise (a), the three hyperbolic-shaped cadaver anomalies (a and b), and the absence of a discernible response from the blank control grave (a and b). The profile is approximately 1.35 m deep and 15 m long.*

hyperbolic returns from cadavers 4, 5, and 6 that was collected when the cadavers were interred for 18.5 months. The returns from the remains of the cadavers appear below the ringing on the profile that begins at the ground surface and continues to 0.60 m (Fig. 5*a*). Although the anomaly for cadavers 4 and 5 are considerably more prominent than cadaver 6, all three appear as hyperbolic anomalies that begin between 0.50 m and 0.60 m. Furthermore, the control grave with only backfill does not exhibit a discernible response. It is clear from the comparisons between the graves that the prominent grave anomalies are due to the pig remains and not the disturbed soil. Removing the antenna noise (Fig. 5*b*) slightly increased the resolution of all three cadavers, and backfill that was partially masked by the ringing is now visible directly above cadaver 5. Overall, there is no need to process the profile to detect these cadavers at 18.5 months.

The return from the small cadavers buried at a shallow depth decreased significantly over the last 2 months prior to excavation. It is important to note that all three of the cadavers (4, 5, and 6) were completely skeletonized when they were excavated at 21 months (Table 2). Figure 6 is the last profile of control grave 2 and cadavers 4, 5, and 6, and was collected when they were interred for 20 months and 9 days. The prominent ringing begins at the ground surface and continues to 70 m (Fig 6*A*). The only response that is discernible is a hyperbolic return from cadaver 5, while there is no discernible response from cadavers 4 and 6. Furthermore, the blank control grave with only backfill does not exhibit a discernible response, and it is clear that the prominent anomaly from grave 5 is due to the pig remains and not the disturbed soil.

Removing the ringing (Fig. 6*b*) did not result in discernible responses from cadavers 4 and 6, while the return from 5 increased slightly. Furthermore, while the control grave with only backfill barely exhibits a discernible response, it is clear that the prominent

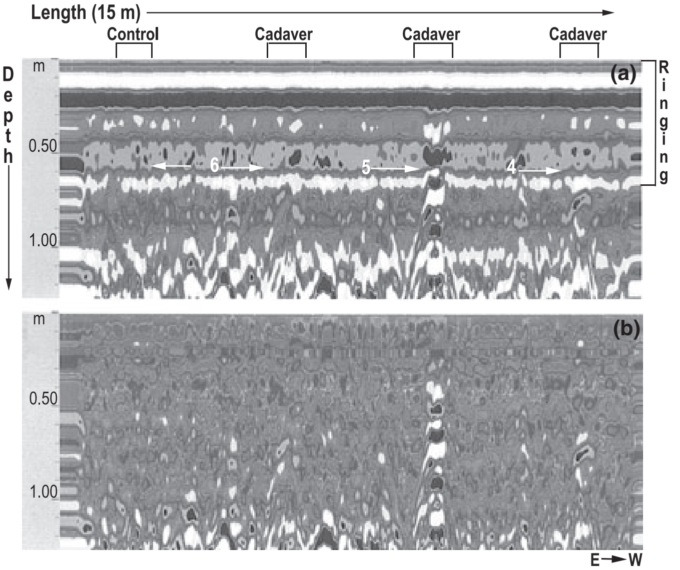

FIG. 6—*GPR profile of shallow cadavers (4, 5, and 6) collected at 20 months and 9 days that compares the unprocessed imagery (a) with the processed background removal (b). Note the distinctive horizontal ringing at the top of the profile from antenna noise (a), the absence of a discernible response from graves 4 and 6 (a and b), and the absence of a discernible response from the blank control grave (a and b). The profile is approximately 1.25 m deep and 15 m long.*

anomaly from cadaver 5 is due to the pig remains and not the disturbed soil.

Deep Cadavers in Sand

Distinctive grave anomalies were initially produced for all of the small pig cadavers that were buried at the deep depth (cadavers 1, 2, 3, 7, 8, and 9). For example, at 1 month, three hyperbolic anomalies from cadavers 1, 2, and 3 begin at approximately 0.95 m and continue inferiorly to 1.60 m (Fig. 7*a*). Prominent ringing extends from the top of the profile at 0.0 m to a depth of 0.60 m, and does not continue deep enough to mask the grave anomalies. Furthermore, the control grave with only backfill barely exhibits a discernible response, and it is clear from the comparisons between the graves that the anomaly is a result of the pig remains and not the disturbed soil. When the ringing is removed (Fig. 7*b*), there is a minimal increase in the resolution of the anomalies from the control grave and the three cadaver anomalies, and the backfill is now detected from the ground surface down to the apex of the cadaver anomalies. Overall, there is no need to process the file to remove ringing for grave detection.

While all three of the deep cadavers buried for the short-term time period (cadavers 7, 8, and 9) were detected over the 13 month monitoring period, over the first year and a half the returns from the deep graves that were buried for the long time period (cadavers 1, 2, and 3) decreased minimally.

For example, at 14 months cadavers 1, 2, and 3 exhibit distinctive hyperbolic anomalies of similar size on the unprocessed profile (Fig. 8*a*). Prominent ringing from antenna noise extends from the top of the profile at 0.0 m to a depth of 0.90 m, above the cadaver anomalies that begin at 0.90 m, and is therefore not deep enough to mask the grave anomalies. Furthermore, although the control grave with only backfill barely exhibits a discernible response, it is much smaller in size compared to the hyperbolic anomalies of the cadaver remains. Thus, it is clear from the comparisons that the

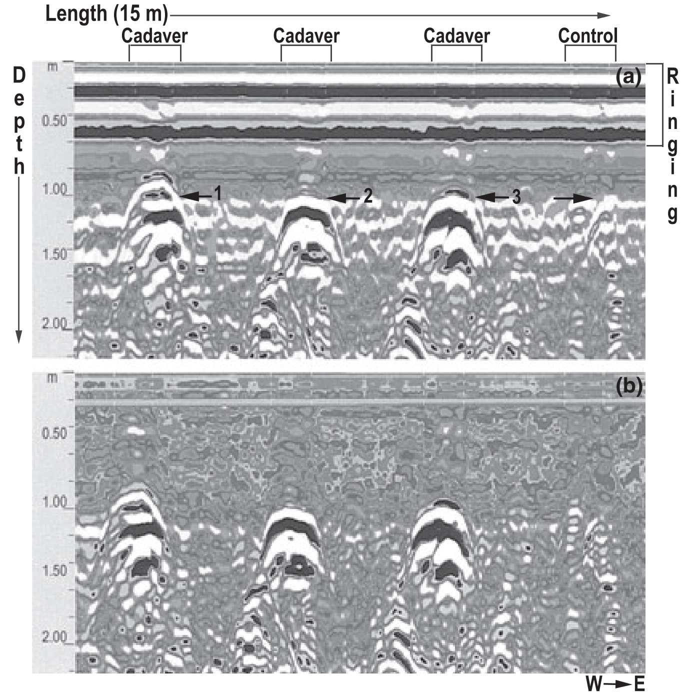

FIG. 7—*GPR profile of three deep cadavers (1, 2, and 3) collected at 1 month that compares the unprocessed imagery (a) with the processed background removal (b). Note the distinctive horizontal ringing at the top of the profile from antenna noise (a), the three hyperbolic-shaped cadaver anomalies (a and b), the absence of a discernible response from the blank control grave (a and b), and the minimal response from the disturbed backfill above the cadaver anomalies (b). The profile is approximately 2.20 m deep and 15 m long.*

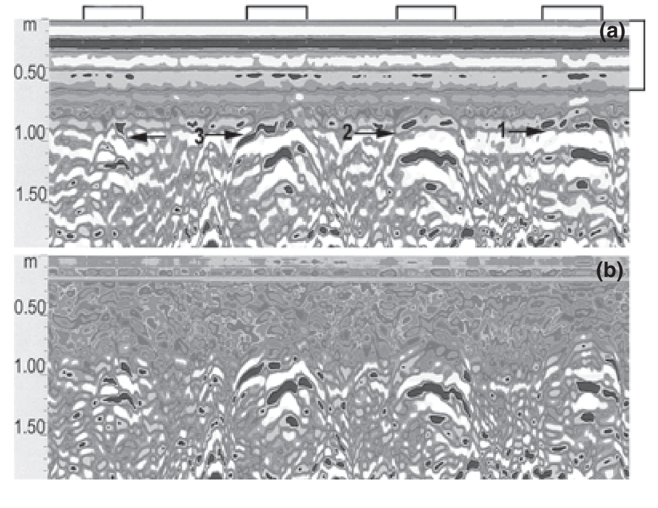

FIG. 8—*GPR profile of three deep cadavers (1, 2, and 3) collected at 14 months that compares the unprocessed imagery (a) with the processed background removal (b). Note the distinctive horizontal ringing at the top of the profile from antenna noise (a), three hyperbolic-shaped cadaver anomalies (a and b), and the minimal response from the blank control grave (a and b). The profile is approximately 1.85 m deep and 15 m long.*

response from the pig graves is the result of the cadavers and not the disturbed soil. Overall, there were no major changes to the grave anomalies when the file was processed (Fig. 8*b*), other than slightly increasing the resolution of the anomalies.

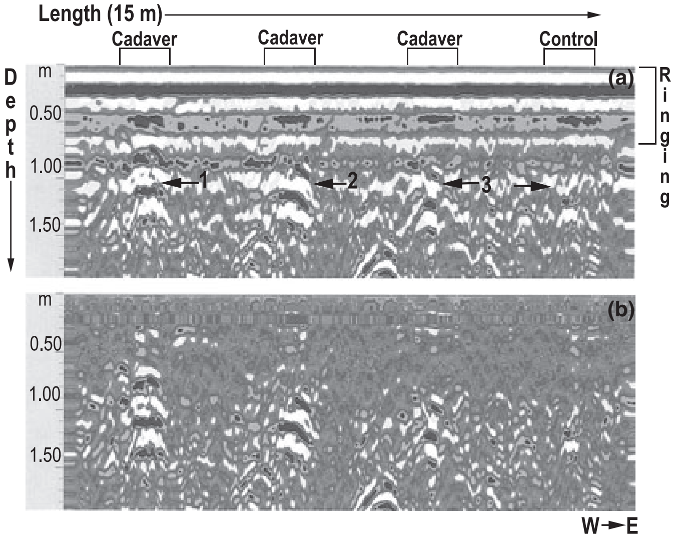

FIG. 9—*GPR profile of deep cadavers (1, 2, and 3) collected at 20 months and 9 days that compares the unprocessed imagery (a) with the processed background removal (b). Note the distinctive horizontal ringing at the top of the profile from antenna noise (a), three minimal responses of the cadaver anomalies on the unprocessed profile (a), increased response of all three cadaver anomalies on the processed profile (b), and the absence of a discernible response from the blank control grave (a and b). The profile is approximately 1.85 m deep and 15 m long.*

Figure 9 is the last profile collected for cadavers 1, 2, and 3 when they were interred for 20 months and 9 days. It is important to note that extensive soft tissue preservation was noted for cadaver 1, and moderate soft tissue preservation was noted for cadavers 2 and 3, when the graves were excavated at 21 months (Table 2). All three cadavers (1, 2, and 3) exhibit reduced hyperbolic-shaped returns beginning at approximately 0.90 m that are difficult to recognize on the unprocessed profile (Fig. 9*a*). The most prominent ringing from antenna noise extends from the top of the profile at 0.0 m to a depth of 0.70 m, above the cadaver anomalies and is therefore not deep enough to mask the grave anomalies. However, the resolution of the three grave anomalies from cadavers (1, 2, and 3) increased with the removal of the antenna noise (Fig. 9*B*). Recognizable returns are only present for cadavers 1 and 2. Of note, the largest anomaly is from cadaver 1 which still retained extensive soft tissue at excavation, while smaller anomalies were noted from cadavers 2 and 3, which retained less soft tissue (Table 2). The minimal response from cadaver 3 is still difficult to recognize on the processed file (Fig. 9*b*). Furthermore, the blank control grave consisting of only backfill does not exhibit a discernible response, and it is still clear from the comparisons between the graves that the anomalies are the result of the pig remains and not the disturbed soil.

Discussion

While GPR provides a high resolution image of subsurface features, it does not provide an actual picture of the grave, buried remains, or buried objects. Rather, a generalized image referred to as an anomaly is produced. In this study, the response from the buried remains in sand is an anomaly with a hyperbolic shape. This particular shape is due to the wide angle of the transmitted radar wave from the antenna that is radiated into the ground in the shape of an elliptical cone. The long axis of the ellipse is parallel to the direction that the antenna travels in standard position, and, as a result, it detects subsurface objects prior to arriving directly over them, when it is directly over them, and continues to detect the objects after passing them (1,9,19,24). The hyperbolic characteristics of the anomalies, including the tails (extensions of the hyperbola), are due to the increased travel time of the radar signal when the subsurface object or feature is detected by the antenna before and after passing over the object.

When remains buried in sand were detected in this study, the response was due to the remains and not the soil disturbance. The blank control graves, comprising only disturbed backfill, were very important in demonstrating that the grave response was primarily the result of the decomposing body or skeleton and not the disturbed soil, which confirms previous GPR research using larger cadavers in Florida that were buried in sand (13). At times, there may have been a minimal response from the disturbed backfill above the buried remains; however, the lack of a response from the control graves confirmed that the grave response was not from the disturbed soil. When disturbed sandy soil is detected using GPR, it is the result of an increased dielectric permittivity as a result of larger pore spaces between sand grains that retain higher levels of moisture. Over time, the backfill consisting of the disturbed soil will become compacted and somewhat homogenous with that of the surrounding undisturbed soil and may no longer be detected using GPR.

When buried remains, and not the soil disturbance, were detected with GPR in soil comprised primarily of sand, such as in this study and Schultz et al. (13), it was the result of detecting contrasting properties of the body and area surrounding the body, compared with that of the undisturbed soil surrounding the grave. The contrasting properties of the body can be due to bone, soft tissue, decomposition products, and leached minerals from the skeleton that increase the dielectric permittivity of the grave. In this study, the degree of skeletonization of buried cadavers appeared to have the greatest effect on whether a distinctive anomalous response was discernible over the duration of the monitoring period at 21 months. As a generalization, there was more difficulty detecting the smaller cadavers that were either completely skeletonized or almost skeletonized in both shallow and deep graves compared to cadavers that still retained a moderate degree of soft tissue. Conversely, Schultz et al. (13) were still able to detect larger adult-sized cadavers over the duration of the monitoring period at 21 months that were buried in sand, even when they were completely skeletonized. Therefore, the increased dielectric permittivity surrounding the body will equalize to the surrounding soil over time due to movement of the soil solution or ground water, as shown in this study. With larger bodies, this contrasting area around the body will remain for a longer period compared to smaller bodies due to a larger contrasting area that takes longer to homogenize with that of the surrounding undisturbed soil.

The other variable tested in this study was depth. Depth did seem to play a role in grave detection because bodies that are buried deeper in the ground will decompose more slowly and may be detected for a longer period of time. For example, while only one of the long-term cadavers at the shallow depth was detected at the end of the longer monitoring period, all three of the deep cadavers (two cadavers produced distinctive hyperbolic responses and the third produced a minimal response) were still detected at the end of the longer monitoring period. As a result, it may be possible to detect a deeper cadaver for a longer time period because the contrasting area around the decomposing body will remain longer.

Finally, processing the GPR files to remove background noise was generally not required for assessments that are made in the field when surveying soils comprised primarily of sand, confirming previous results by Schultz et al. (13) using larger cadavers. However, processing GPR files can be useful for interpretation of the soil stratigraphy and grave characteristics by increasing the resolution of the imagery (13,18). Unless extensive noise is noted on the profile and anomalies have very little contrast, processing of the data to remove noise is generally not needed for grave detection during the search and initial field assessment. An evaluation concerning the need for processing can initially be determined in the field by noting the resolution of shallow subsurface features and the extent of the ringing during calibration of the equipment (13). If there is a weak response from an older grave or extensive ringing that may obscure the grave response such as disturbed backfill above the remains, processing of the data should then be considered to increase the resolution of subsurface features.

Whether or not a grave will be detected using GPR depends on a number of issues. First, the type of soil and burial environment appear to be determinants on whether or not a clandestine grave may be detected. The results from this study suggest that it may not be possible to detect the remains of a body buried in a sandy soil for an extended time period, even with processing. Conversely, there have been a number of forensic cases where skeletons were located with GPR at extended postmortem intervals. For example, Nobes (7) located a body buried in a field for 12 years using a combination of EM and GPR that consisted of sand (including iron sands) with occasional pockets of silt or clay. However, the forensic case buried for the longest postmortem interval that was located using GPR was buried beneath a concrete pool deck for 28 years (5,25). In this example, soil type was described as dense clay and a grave depression was noted after the concrete was removed (25). When clandestine buried remains are detected in soils with a high clay content, or soil comprised of horizons of differing dielectric properties, it can be the result of imaging a response from disturbed soil features and not the buried remains (13). Also, soils comprised of sand and clay horizons that are disturbed will retain a mottled appearance and remain less dense than the surrounding undisturbed soil as a result of mixing stratigraphic horizons of different compositions. In this instance, a soil disturbance (backfill above the cadaver, grave walls, and gaps or disruptions of continuous stratigraphic horizons that produce localized soil changes) may be detected by GPR due to differences in dielectric permittivity between the grave and undisturbed soil (13). Also, nonbiological items included in the grave with the body may increase the chance of grave detection by contributing to the contrasting area surrounding the body. These include items added on top of the victim to help with concealment, or that are hidden with the burial such as weapons, before adding the backfill to the grave. Finally, items used to wrap the victim (e.g., tarpaulins, plastic sheathing, or rugs) and possibly clothing, may help to highlight the location of the grave by increasing the contrast of the body.

Controlled GPR research is essential for determining the utility of GPR as a search tool for buried bodies, and is essential to clarify further the usefulness of this technology in different micro-environments, soils, burial scenarios, and longer interment periods than this study. For example, another area dealing with grave detection where GPR is underutilized and could contribute significantly is in the field of human rights. Although no case studies were provided, GPR was mentioned as one of the methods that may be used for locating mass graves (26,27). When a large mass grave is located, delineation is generally performed to determine the depth of the overburden and the size using a backhoe to either clean a line across the suspected area (27) or to cross trench with a backhoe across the top of the grave until remains are located (26,28). It would appear that GPR cannot only be useful in locating mass graves, but also in delineating the size of the grave, the depth, and the extent of the overburden without any damage to the contents of the graves that may be caused by trenching.

Conclusions

Overall, there were a number of important conclusions in this study that evaluated the utility of using GPR to detect small cadavers. The blank control graves, comprising only disturbed backfill, were very important in demonstrating that the hyperbolic anomaly was primarily the result of the decomposing body or skeleton and not the disturbed soil. Next, it was shown that it may be difficult to detect small cadavers buried in sand soon after they are skeletonized because the area surrounding the body may not provide a contrasting area that will be detected by GPR compared to that of the surrounding undisturbed soil. Thus, it may be difficult to detect bodies that have been buried in sand for extended periods if a grave response is not produced from the soil features or items that may have been placed in the grave with the body. Furthermore, depth of burial also appears to influence grave detection because bodies that are buried at deeper depths may be detected for a longer period of time because of reduced decomposition rates. Finally, processing the GPR data for background removal is generally not needed for assessments that are made in the field when surveying soils comprised primarily of sand. However, removing the horizontal ringing can be helpful for grave detection because there may be an increased response from the backfill that can indicate the location of the grave when there is a weak response from the body.

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