Forensic GPR: finite-difference simulations of responses from buried human remains

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Abstract

Time domain 2.5-D finite-difference simulations of ground-penetrating radar (GPR) responses from models of buried human remains suggest the potential of GPR for detailed non-destructive forensic site investigation. Extraction of information beyond simple detection of cadavers in forensic investigations should be possible with current GPR technology. GPR responses are simulated for various body cross-sections with different depths of burial, soil types, soil moisture contents, survey frequencies and antenna separations. Biological tissues have high electrical conductivity so diagnostic features for the imaging of human bodies are restricted to the soil/skin interface and shallow tissue interfaces. A low amplitude reflection shadow zone occurs beneath a body because of high GPR attenuation within the body. Resolution of diagnostic features of a human target requires a survey frequency of 900 MHz or greater and an increment between recording stations of 10 cm or less. Depth migration focuses field GPR data into an image that reveals accurate information on the number, dimensions, locations and orientations of body elements. The main limitation on image quality is attenuation in the surrounding soil and within the body. 3-D imaging is also feasible.

Keywords: Ground-penetrating radar (GPR); Forensic; Human remains; Finite-difference modeling

1. Introduction

Davenport et al. (1988, 1990) and Killam (1990) discuss the applicability of ground-penetrating radar (GPR) and other geophysical methods to criminal investigations. The utility of GPR for the location of graves has been demonstrated by a number of authors (Bevan, 1991; Unterberger, 1992; Mellett, 1992; Miller, 1996; Nobes, 1999; Davis et al., 2000). To date, successful results have been obtained indirectly by location of non-specific radar anomalies. For example, an anomaly caused by soil disturbance found during a search in a graveyard with missing headstones has a high probability of correctly indicating the presence of a burial. The search for a buried crime victim is more ambiguous, as the search area is necessarily larger and the presence of a burial is not positively known. The detection of an anomaly leads to a time consuming excavation to investigate...
its nature; this is a costly and inefficient search method.

Misidentification of a GPR anomaly can cause problems for a criminal investigation. Mellett (1996) describes an example in which an anomaly was located beneath a concrete slab in a basement. The suspect confessed to the murder and to burying the victim in the basement. Upon excavation several years later, the detected anomaly was determined to be a geological feature (J.S. Mellett, personal communication, 1999). Thus, it is of importance to try to acquire and process GPR data in ways that allow extraction of more definitive information from GPR anomalies. This paper presents numerical results that imply that this is possible.

1.1. Previous examples

Previous work in the field of GPR grave location has concentrated in three areas: assisting in criminal investigations, forensic utility studies, and graveyard mapping. At least two murder victims have been located using GPR (Mellett, 1992; Calkin et al., 1995). GPR has also been used to map graveyards for archeological, anthropological, and historical investigations. These instances are briefly described in this section to set the context for the numerical examples in the following sections.

The first instance of locating a murder victim using GPR, as described by Mellett (1992), took place in March 1990. The victim had disappeared 8 years earlier, and was located with GPR at 0.5 m depth at a site that was identified by traditional techniques. The survey frequency was 500 MHz.

Calkin et al. (1995) describe the location of a murder victim in 1992. The GPR search was conducted 13 months after the victim was reported missing. Available evidence suggested that the victim might be buried in the basement of her house. A 500 MHz GPR survey on a grid with 0.3 m line spacing led to location of an anomaly at 0.75 m depth. Excavation produced the victim’s remains.

More recently, GPR has been used to search for suspected mass graves. Investigators used GPR to search for victims of a drug cartel in Juarez, Mexico (Eaton, 1999) and of a 1921 race riot in Tulsa, OK, USA (Nelson, 1999).

Field tests have also been conducted in controlled environments. Alongi (1973) analysed 1-D (single trace) data collected over a buried dog. Strongman (1992) conducted a 2-D survey over two goats and a bear buried at a site established to train forensic investigators. Roark et al. (1998) conducted a 2-D survey at a test site as part of a study of how clandestine burials change over time; two deer carcasses were the subjects of this study.

The location of graves in graveyards by GPR has been described in several papers. Bevan (1991) used the disturbance of soil stratigraphy to locate graves. Unterberger (1992) used soil disturbance and casket reflections to locate graves. Davis et al. (2000) describe successful location of unmarked graves with a 3-D survey in permafrost. Ivashov et al. (1998) describe the use of GPR to locate infilled excavations. These papers discuss detection of features that are secondary, and not unique, to the presence of a burial.

In a criminal burial, human remains are not likely to have been interred in a casket. Thus, investigators must rely on the presence of a soil disturbance or the detection of a buried object to mark the location of a burial. However, the presence of a soil disturbance does not necessarily indicate a site of interest. Neither does the location of a buried object necessarily denote the presence of a human body. Thus, the ability to characterize a target using only its GPR response is potentially important to a forensic investigation. For these reasons, the numerical simulation of GPR responses of human remains is a timely objective. Numerical simulations can be used to investigate the detectability of human remains under various conditions, including changing soil types and survey parameters, and also to provide test data for evaluation of data processing and imaging algorithms.

2. Modeling procedure

We used the 2.5-D finite-difference time domain approach of Xu and McMechan (1997) for simulation of full wavefield GPR responses. This algorithm solves Maxwell’s equations on a staggered grid.
superimposes 2-D responses for different (out-of-plane) horizontal wave numbers to simulate point dipole sources (Livelybrooks and Fullagar, 1994); for the examples below, we used \( K = 0, 2, 4, 6, \text{ and } 8 \text{ m}^{-1}. \) In the simulations, the long axes of the transmitting and receiving dipole antennas are oriented parallel to each other and perpendicular to the plane of the model cross-section; this is the most common field survey configuration.

The computational grid increment in all models was \( \sim 0.29 \text{ cm} \) in both vertical and horizontal directions. Source center frequencies used were 450, 900, and 1200 MHz. The source time function was a band limited (Ricker) wavelet. A trace was saved at every sixth grid point along the air/soil interface. The time step in all simulations was \( 6 \times 10^{-12} \text{ s}. \) These parameters correspond to a minimum of 10 grid points per wavelength at the dominant frequencies, and

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Fig. 1. Modeling for a skull cross-section. The CT image (a) [modified from Kieffer and Hietzman, 1979] is converted into the model image (b), which is then inserted into the geologic environment (d). Gray levels in (b) and (d) correspond to relative dielectric permittivity values at 1200 MHz, as given in the legend. Transmitters and receivers are simulated at equally spaced points along the air/soil interface. The simulated 1200 MHz monostatic radargram (c) represents a shallow burial of the skull in clay-rich sand (with 6.4% water content by volume) and is plotted with \( 2 \times \) the gain of the radargrams in Fig. 2. Labeled GPR waves in (c) are produced by the similarly labeled features in (b).
satisfy the stability and grid dispersion requirements (Petropoulos, 1994). The air/earth interface was inserted as part of the model (Fig. 1d), and Mur’s (1981) second-order absorbing boundary conditions were used on the outer grid edges.

The models were parameterized as regions with constant values of relative dielectric permittivity and electrical conductivity for each dominant frequency used (Table 1). For small values of electrical conductivity ($\sigma$) and/or high frequencies ($\omega$), the relative dielectric permittivity ($\varepsilon$) is the main determinant of the propagation velocity (v) of GPR waves:

$$v \approx \frac{c}{\varepsilon^{1/2}} \left[ \frac{2\cos \delta}{1 + \cos \delta} \right]^{1/2}$$

where $\tan \delta = \sigma/\omega\varepsilon$ and $c (=0.3 \text{ m/ns})$ is the velocity of light in vacuum (e.g., Davis and Annan, 1989; Guéguen and Palciauskas, 1994). The velocity increases as $\varepsilon$ decreases, as $\omega$ increases, and as $\sigma$ decreases. The electrical conductivity $\sigma$ is the main determinant of the attenuation of GPR waves:

$$D \sim \frac{35}{\sigma}$$

where $D$ is the depth of penetration in meters, and $\sigma$ is the conductivity at the frequency of interest in miliSiemens/meter (Sensors & Software, 1997).

Values of $\varepsilon$ and $\sigma$ for all soils and tissue/bone materials used in the models were obtained from published laboratory measurements. Gabriel et al. (1996a) surveyed an extensive body of literature and compiled dielectric properties for 13 biological tissues over a frequency range of 10 Hz to 10 GHz. Gabriel et al. (1996b) conducted continuous dielectric measurements on 20 tissue types over the frequency range of 10 Hz to 20 GHz. Curtis et al. (1995) made continuous dielectric measurements at several temperatures and moisture levels for 12 soils over the frequency range of 45 MHz to 26.5 GHz. Other sources of specific measurements used are Schwan and Li (1953), Schwan and Piersol (1954), and Pethig (1979). The values used for composite tissue regions (Table 1) are areally weighted averages of the tissues present in those model regions.

Geometries for various transverse human cross-sections were obtained from Kieffer and Hietzman (1979); computed tomography (CT) images were scanned from this text (e.g., Fig. 1a). Each scanned CT image was then converted into an electromagnetic model by assigning the corresponding properties (Table 1) to the region containing each bone and tissue type and the surrounding soil (Fig. 1b and d). This model was then input to finite-difference simulation to produce the GPR response (Fig. 1c). The

Table 1

<table>
<thead>
<tr>
<th>Material</th>
<th>450 MHz $\varepsilon$</th>
<th>900 MHz $\varepsilon$</th>
<th>1200 MHz $\varepsilon$</th>
<th>$\sigma$ (S/m)</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>0.0</td>
<td>–</td>
</tr>
<tr>
<td>Clay</td>
<td>5.1</td>
<td>4.3</td>
<td>4.1</td>
<td>0.08</td>
<td>6</td>
</tr>
<tr>
<td>Clay-rich sand (6.4%)</td>
<td>3.4</td>
<td>3.3</td>
<td>3.3</td>
<td>0.02</td>
<td>6</td>
</tr>
<tr>
<td>Clay-rich sand (25.8%)</td>
<td>11.0</td>
<td>10.6</td>
<td>10.5</td>
<td>0.13</td>
<td>6</td>
</tr>
<tr>
<td>Dry sand</td>
<td>2.4</td>
<td>2.4</td>
<td>2.4</td>
<td>0.009</td>
<td>6</td>
</tr>
<tr>
<td>Skin</td>
<td>38.0</td>
<td>35.0</td>
<td>33.0</td>
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<td>1,2</td>
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<tr>
<td>Bone</td>
<td>13.0</td>
<td>12.0</td>
<td>11.0</td>
<td>0.2</td>
<td>1–5</td>
</tr>
<tr>
<td>Brain (gray matter)</td>
<td>60.0</td>
<td>50.0</td>
<td>45.0</td>
<td>1.2</td>
<td>1–3</td>
</tr>
<tr>
<td>White matter</td>
<td>47.0</td>
<td>45.0</td>
<td>40.0</td>
<td>1.0</td>
<td>1,2</td>
</tr>
<tr>
<td>Cartilage</td>
<td>48.0</td>
<td>45.0</td>
<td>40.0</td>
<td>0.9</td>
<td>2</td>
</tr>
<tr>
<td>Muscle</td>
<td>56.0</td>
<td>54.0</td>
<td>51.0</td>
<td>1.3</td>
<td>1–4</td>
</tr>
<tr>
<td>Bone marrow</td>
<td>6.0</td>
<td>5.5</td>
<td>5.0</td>
<td>0.115</td>
<td>3</td>
</tr>
<tr>
<td>Skin with fat</td>
<td>7.0</td>
<td>6.0</td>
<td>5.0</td>
<td>0.145</td>
<td>1–5</td>
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<tr>
<td>Liver and muscle</td>
<td>52.0</td>
<td>49.0</td>
<td>47.5</td>
<td>1.15</td>
<td>1–4</td>
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<tr>
<td>Liver, lung, and muscle</td>
<td>49.0</td>
<td>46.0</td>
<td>44.0</td>
<td>0.93</td>
<td>1–4</td>
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Table 2  
The dimensions of each body section used in model generation

<table>
<thead>
<tr>
<th>Model</th>
<th>Height (cm)</th>
<th>Width (cm)</th>
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<tbody>
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<td>Skull</td>
<td>20</td>
<td>17</td>
</tr>
<tr>
<td>Upper chest</td>
<td>20</td>
<td>33</td>
</tr>
<tr>
<td>Upper arm</td>
<td>10</td>
<td>8</td>
</tr>
<tr>
<td>Lower chest</td>
<td>22</td>
<td>33</td>
</tr>
<tr>
<td>Upper pelvis</td>
<td>18</td>
<td>33</td>
</tr>
<tr>
<td>Lower pelvis</td>
<td>18</td>
<td>33</td>
</tr>
<tr>
<td>Thigh</td>
<td>11</td>
<td>17</td>
</tr>
<tr>
<td>Calf</td>
<td>13</td>
<td>10</td>
</tr>
</tbody>
</table>

other cross-sections were similarly constructed and modeled. The outer dimensions for each body section are listed in Table 2.

3. Modeling results

Modeling was performed for seven transverse body sections as a function of radar frequency, soil type and water saturation, burial depth, antenna separation, amount of decomposition, complexity of soil stratigraphy, and the increment between recording positions. In this section, the effect of each variable will be examined in turn.

Models are referred to by the body section and by the parameter that is varied; all other parameters are constant unless stated otherwise. All radargrams are monostatic and are plotted with the same constant gain unless stated otherwise. Plotting of all radargrams starts at 2.5 ns as no reflections are present at earlier times for any of the models.

Fig. 2 shows synthetic radargrams for the skull model (Fig. 1d) at two frequencies and at two burial depths in two soil types dry sand and clay. These radargrams are used to illustrate the effects of these variables.

3.1. Effect of radar frequency

For a fixed model, the primary effects of an increase in the dominant frequency of the GPR transmitter are increases in attenuation, resolution (through an increase in bandwidth), and wave velocity (via dispersion). Compare the 450 MHz responses (Fig. 2a and b) with the 1200 MHz responses (Fig. 2c and d) for the same model (Fig. 1d). The frequency-dependent parameters are given in Table 1.

Attenuation of the radar signal increases with increasing frequency (Eq. (2)), and is greater in clay than in sand [because of the increased conductivity (Table 1)]; compare Fig. 2a and b for sand, with Fig. 2e and f for clay. At this plot gain, no response is visible in the 450 MHz radargram for the deep burial in clay (Fig. 2f). Most realistic soils will produce responses between these two extremes.

The increase in GPR resolution with increasing frequency is demonstrated by comparing radargrams at 450 MHz (Fig. 2a and b) with those at 1200 MHz (Fig. 2c and d) for the same model. The 450 MHz plots show only a broad reflection, but in the 1200 MHz plots, the response is resolved into at least four distinct reflections and diffractions. These arrivals are seen more clearly in the high-gain 1200 MHz response in Fig. 1c, where they are labeled and are seen to originate at the soil/bone (T) and bone/brain (B) interfaces, and at interface irregularities (L and R).

A frequency dependent increase in wave velocity (dispersion) is indicated by two features. As frequency increases, for a given target depth and shape, the radius of curvature of the reflection hyperbola decreases and the initial arrival time of the reflected energy occurs earlier; compare Fig. 2a and c or Fig. 2b and d. Although the surrounding material (dry sand) is the same in both models, the conductivity changes with frequency (Table 1) which changes the propagation velocity, via Eq. (1).

3.2. Effect of burial depth

Fig. 2 demonstrates the effect of varying the depth of burial. In the shallow burial models (Fig. 2a, c, and e), the top of the target is 0.4 m deep. In the deep burial models (Fig. 2b, d, and f), the top of the target is 0.8 m deep. For a given target and soil type, decreasing the depth of burial increases both the travel time and the attenuation because the propagation path length increases with depth. The maximum amplitude of the reflection from the shallow target at 450 MHz (Fig. 2a) is ~ 4 times greater...
Fig. 2. Effects of varying frequency, soil type, and burial depth. All radargrams are monostatic and are for the skull model in Fig. 1d. The upper row (a, c, and e) are for shallow burials; the lower row (b, d, and f) are for deep burials. The left columns (a and b) are 450 MHz responses for burial in dry sand. The center columns (c and d) are 1200 MHz responses for burial in dry sand. The right columns (e and f) are 450 MHz responses for burial in clay-rich sand with 6.4% water content. High amplitudes are clipped.
than that for the deep target (Fig. 2b). At 1200 MHz, this amplitude factor is \( \sim 5 \) (Fig. 2c and d). In clay at 450 MHz, this factor is \( \sim 28 \) (Fig. 2e and f).

Increasing depth of burial also increases the radius of curvature of the reflections; compare Fig. 2a with b and Fig. 2c with d. For a given recording position, the reflection point moves closer to the top of a curved target as depth increases. Thus, features present in a radargram for a shallow burial will appear horizontally stretched in the radargram for a deep burial, if they are detectable at all. This apparent horizontal stretching is a purely geometrical effect.

### 3.3. Effect of soil type

Fig. 2 also demonstrates the effect of varying soil type on reflection character for the model in Fig. 1d (for shallow models). Radar velocity and attenuation are both influenced by soil type. Dry sand has very low attenuation and high velocity (Fig. 2a and b);
Fig. 4. Models and synthetic responses for (a) calf, (b) upper pelvis, and (c) lower chest sections. Gray levels in the (lower) model plots indicate relative dielectric permittivity with values indicated in Fig. 1b. Radargrams are plotted with 2× the gain in Fig. 2 and high amplitudes are clipped. Specific reflections in the (upper) synthetic GPR profiles and the model features that generated them are identified by the same letter labels.
wet, clay-rich sand has very high attenuation and low velocity (Fig. 2e and f). These represent good and poor situations, respectively, in terms of signal detection. The response amplitude in clay-rich sand at 450 MHz (Fig. 2a) is \( \approx 9 \) times smaller than that in dry sand at 450 MHz (Fig. 2e).

3.4. Effect of soil moisture content

Fig. 3 shows the effect of varying soil water content. The model used is that in Fig. 1d; the surrounding soil is clay-rich sand. Responses for 6.4% and 25.8% volumetric water content in the soil are shown in Fig. 3a and b, respectively. The increase in soil water content results in an increase in attenuation and a decrease in signal velocity. The maximum amplitude of the response of the drier (6.4% water) model is \( \approx 33 \times \) that of the wetter (25.8% water) model. The low \( \varepsilon \) values measured for these samples are a consequence of the high clay fraction; water absorbed by clay has significantly lower \( \varepsilon \) than free water (Curtis et al., 1995; Wang and Schmugge, 1980).

3.5. A selection of profiles; simulations and migrations

Fig. 4 contains models and simulated monostatic GPR profiles for calf, upper pelvis, and lower chest

![Fig. 5. Composite model (b) is for a section through the upper chest and arms. (a) is the simulated monostatic 900 MHz GPR response; (c) is (a) after depth migration. (a) is plotted using the same gain as Fig. 2; (c) is plotted with 70 \times \) lower gain. High amplitudes are clipped. Refer to Fig. 1b for the permittivity scale used to plot (b).]
body sections. All three simulations are for shallow burials in dry sand at 900 MHz. Responses were also computed (but not shown here) for a series of partial models in which layers were added one at a time. This procedure allowed identification of the origin of each of the individual reflections in the full model responses, as labeled in Fig. 4.

Figs. 5, 6, and 7 contain simulated radargrams for three models and their corresponding migrated sections. All models represent shallow burials in clay-rich sand (with 6.4% water) and all simulations are for 900 MHz. Migration was performed using a seismic frequency–wave number algorithm (Stolt, 1978) which was modified for use with GPR data.

Fig. 6. Model (b) is for a section through the lower pelvis. (a) is the simulated monostatic 900 MHz GPR response; (c) is (a) after depth migration. (a) is plotted using the same gain as Fig. 2; (c) is plotted with 70× lower gain. High amplitudes are clipped. Refer to Fig. 1b for the permitivity scale used to plot (b).
Fig. 7. Composite model (b) is for a section through the thighs. (a) is the simulated monostatic 900 MHz GPR response; (c) is (a) after depth migration. (a) is plotted using the same gain as Fig. 2; (c) is plotted with 70× lower gain. High amplitudes are clipped. Refer to Fig. 1b for the permittivity scale used to plot (b).

(Sensors & Software, 1996). Migration moves the recorded reflected and diffracted waves from the receiver locations back to where they were originally scattered in space, to form a focused image of the target. The migrated images contain more accurate information on the number, locations, dimensions and orientations of the body elements than the recorded unmigrated data do.

Fig. 8 shows a pseudo 3-D composite body image produced by placing 10 migrated 2-D body sections in their correct relative positions for perspective. The body outline and contours are visible; higher resolution could be achieved with higher frequency/bandwidth data, but Fig. 8 is a realistically obtainable representation.

3.6. Effect of antenna separation

Fig. 9 shows the effect of varying the transmitter-to-receiver antenna separation during data acquisition. The model used is that in Fig. 1d. The effect of increasing antenna separation is similar to increasing burial depth; arrival times increase as antenna separation increases because of the increase in path lengths. Apparent horizontal stretching occurs similar to that described above for increasing target depth.

GPR antennas have direction-dependent radiation patterns, which are superimposed on all recorded responses. Thus, any target is illuminated as a function of antenna separation, the target depth, and the
Fig. 8. A pseudo 3-D composite of migrated body cross-sections. The rectangle is a transparent plane parallel to the radargram sections, containing the fourth cross-section from the bottom (that labeled pelvis), as reference for the 3-D view perspective. Labels indicate the body sections imaged by the corresponding radargram.

angle of maximum antenna radiation (which is equal to the critical refraction angle at the earth’s surface). Amplitudes increase and then decrease locally as the maximum radiation angle is encountered as a survey line passes over a target. This pattern may make certain features more or less visible, depending on the angle and the target depth.

3.7. Effects of advanced decomposition

Fig. 10a shows the effect that decomposition has on the character of the skull radargram. The decomposed model was constructed by substituting soil for the skin layer and air for the brain tissue. This is assumed to simulate the decomposed state of the human skull. All other parameters, except the plotting gain, are the same as in Fig. 1c.

The radargram for the decomposed specimen contains reflections from the base of the skull, as well as internal reflection multiples. None of the fresh specimen radargrams contain visible basal reflections due to the very high GPR attenuation in body tissues. The maximum reflection amplitude from the decomposed specimen model is 60% greater than that from the equivalent fresh specimen model. The substitution of air for brain tissue results in greater dielectric permittivity and electrical conductivity ratios at the bone to skull cavity interface. The resulting higher net reflectivity causes the difference in amplitude.

3.8. Effects on responses from underlying soil stratigraphy

Fig. 10b demonstrates the effect that a buried body would have on the 900 MHz response of underlying soil stratigraphy. This model is the same lower chest section as in Fig. 4c, with the addition of a wet (25.8% water by volume), clay-rich sand layer at a depth of 0.7 m.

The main (slightly flattened) hyperbolic reflection (R) in Fig. 10b is the response from the chest. The planar reflection (S) is from the interface between the two soil types; the gap (G) in (S) is a low amplitude shadow caused by signal attenuation in the chest. Once the signal has passed through the body, it is attenuated beyond the threshold of detection. The diffraction tails (D) formed at either side are a result of the signal shadow, rather than a discontinu-
Fig. 9. Effects of varying antenna separation. The separations are (a) 20 cm, (b) 40 cm, and (c) 60 cm. See Fig. 1c for 0 cm separation. The horizontal axis gives the position of the midpoint between the two antennas. Profiles are plotted with the same gain as Fig. 2.

ous reflector. The latter explanation is clear because the diffractions are one-sided, being attenuated beneath the body; a discontinuous reflector would produce two-sided diffractions emanating from the points of truncation.

3.9. Effects of survey stepsize

Fig. 10c shows the effect of varying survey stepsize. In this 900 MHz radargram, the trace spacing is 9.25 cm; for comparison, these are the same data as in Fig. 3a, but with only every fifth trace plotted. The same general features can be recognized in both radargrams. However, the data in Fig. 10c are spatially aliased beyond the center five traces, which limits the types of processing that can be done.

Fig. 10. The effects on data for the skull model of Fig. 1d of (a) advanced decomposition, (b) the presence of soil stratigraphy, and (c) a 9.25 cm stepsize between traces. (a) and (c) are plotted with the same gain as Fig. 2. (b) is plotted at $0.5 \times$ the gain of Fig. 2. High amplitudes are clipped. In (a), T is the reflection from the skull top, B is the reflection from the skull bottom, and M is the first internal multiple reverberation within the skull. In (b), R is the reflection from the top of the chest, S is the reflection from the underlying soil interface, D is the diffraction of S at the edge of the chest, and G is the gap in S caused by high GPR attenuation in the chest.
Table 3
Estimated GPR resolution (at normal incidence) in body tissues; values listed are calculated one-quarter wavelengths

<table>
<thead>
<tr>
<th>Body tissue</th>
<th>450 MHz (cm)</th>
<th>900 MHz (cm)</th>
<th>1200 MHz (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Skin</td>
<td>2.7</td>
<td>1.4</td>
<td>1.1</td>
</tr>
<tr>
<td>Bone</td>
<td>4.6</td>
<td>2.4</td>
<td>1.9</td>
</tr>
<tr>
<td>Brain</td>
<td>2.2</td>
<td>1.2</td>
<td>0.9</td>
</tr>
<tr>
<td>Muscle</td>
<td>2.3</td>
<td>1.2</td>
<td>0.8</td>
</tr>
<tr>
<td>Skin with fat</td>
<td>6.3</td>
<td>3.4</td>
<td>2.8</td>
</tr>
<tr>
<td>Liver and muscle</td>
<td>2.3</td>
<td>1.2</td>
<td>0.9</td>
</tr>
<tr>
<td>Liver, lung, and muscle</td>
<td>2.4</td>
<td>1.3</td>
<td>0.9</td>
</tr>
</tbody>
</table>

3.10. Resolution

Table 3 lists the resolution (at normal incidence) of various radar frequencies in the major body tissues. The very high permittivity values (and hence, low velocities) of biological tissues result in higher resolution than in the surrounding soils for a given frequency; very small-scale features within the human body can produce diagnostic reflections. However, the high conductivity of tissues makes the detection of any features more than a few centimeters beneath the upper surface of the body unlikely (Eq. 2).

4. Discussion and conclusions

GPR has been used to locate buried human remains under a variety of circumstances. To date, this work has relied primarily on the location of non-specific and non-diagnostic GPR anomalies. This paper demonstrates the potential ability of GPR to resolve diagnostic features of the human body. It also shows the limitations of GPR for this application.

GPR frequencies must be 900 MHz or greater to resolve details within the human body. At these frequencies, resolution is better in biological tissue than in soils. However, signal attenuation also becomes a serious problem at these frequencies. GPR performs best in drier, sandier soils. Lower frequencies may be required to detect burials in wetter, or more clay-rich soils. High resolution may only be possible at shallow depths. Fortunately, criminal burials are typically shallow (~ 0.5 m). The problems listed above can be partially alleviated by increasing the number of traces that are stacked at each survey point during acquisition, to improve the signal-to-noise ratio.

Only the upper layers of the human body produce detectable GPR reflections because of the extremely high electrical conductivity of biological tissues. The resulting high attenuation produces a signal shadow and associated diffraction tails beneath the body. The GPR profiles for most body cross-sections are expected to contain responses mainly from the upper soil/tissue interface. Deeper burials will produce responses that are horizontally stretched with respect to shallow responses.

The radargrams presented above should be considered only as a general guide for interpretation and as a demonstration of application potential. The human body varies significantly in morphology along its longitudinal axis; our 2-D modeling ignored these variations. For instance, a radargram imaging a human skull would normally also contain off-line reflections from the shoulders; thus, real data would be more complicated than the synthetic data presented here. However, the main conclusions will also hold true for real data.

During modeling, the organs of the chest and abdominal cavity were treated as a single homogeneous mass. The permittivity and conductivity assigned to each abdominal or chest section was an areally weighted average of the values of the organs present in that profile. This was done to keep the complexity of the models within reasonable limits. These organs, for the most part, have similar dielectric behavior. However, reflections from the abdomen of a real body would be more complex than those shown here.

The modeled radargrams will also only be consistent with real data for some time after death and burial. A significant change in radargram character will take place with the collapse of the abdominal cavity. Depending on depth of burial and other parameters, this occurs ~ 6–12 months after death (Rodriguez and Bass, 1985; Galloway, 1997; Rodriguez, 1987). Decomposition proceeds more rapidly in shallow burials. The collapse of the abdominal cavity will result in a concave reflecting surface in
the abdomen and proximal sections. Eventually, the body will become completely skeletonized. When this occurs, the ribs collapse and the pelvis flattens. By this time, very little of the data presented above would be pertinent. However, the numerical simulation technique used here is equally applicable to all such situations. Such modeling would also be useful for archeological, anthropological, and historical applications and is a topic for future research.

Data acquisition in the past was characterized by the use of relatively low frequencies in continuous survey profiles. A stepped survey (recording at a series of discrete points) provides more accurate and diagnostic data than a continuous survey because of less lateral smearing and the ability to stack traces at each survey point to increase the signal-to-noise ratio. Determination of diagnostic features for an imaged human target requires a survey frequency of 900 MHz or greater and a survey stepsize of 10 cm or less. Such a small stepsize would result in a time-consuming survey and thus, is not well suited to a broad reconnaissance survey, but is ideal for detailed investigation of candidate sites identified by other more traditional means.

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