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A Controllably Anisotropic Conductivity or Diffusion Phantom Constructed from Isotropic Layers

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Abstract

Phantoms with controllable and well-defined anisotropy are needed to test methods for imaging electrical anisotropy. We developed and tested a phantom that had properties similar to a homogeneous anisotropic conductive medium. The phantom was constructed with alternate slices of isotropic gel having different conductivities. The degree of anisotropy in the phantom could be varied easily by changing the relative conductivity of the two gels. We tested the stability of several phantoms and found their properties were maintained for approximately 8 h following construction. The phantom has application to electrical impedance tomography, magnetic resonance electrical impedance tomography, EEG and ECG source imaging and diffusion tensor imaging.

Keywords

Anisotropy; Phantom; EIT; DTI; MREIT; Inverse EEG; Inverse ECG

INTRODUCTION

Methods have recently been proposed to reconstruct conductivity distributions in electrically anisotropic materials.^{4,21,22,24} Many methods also exist for estimation of strength and position of current dipoles in the heart and brain,^{1,18,19} and these must take into account the effects of anisotropy in adjacent tissues such as white matter and cardiac muscle.^{12,20,28} Standardized anisotropic phantoms must be developed in order for the accuracy of these methods to be evaluated and compared with other candidate reconstruction methods. The challenges of this situation include creating a stable and reproducible composition and being easily able to vary the degree of anisotropy.¹³ It is also important to ensure that the phantom is indeed anisotropic at the measurement scale.

Diffusion tensor imaging (DTI) is analogous to low frequency electrical imaging in several ways. In particular, anisotropic water diffusion and electrical conductivity tensors in tissue such as white matter and muscle may be related to each other via scaling constants.²⁵ Many anisotropic phantoms have been constructed for use in diffusion tensor imaging and fiber tracking.^{2,5,8,9,11–13,15,17} These have generally been constructed by placing a fixed structure of synthetic or biological material having a directional dependence in a homogeneous background. Methods of construction vary from the simple¹ to the highly complex.¹³ In many of these phantoms, different types of closely packed fibers were placed in a uniform background. Different anisotropies could be selected using fibers with different diffusion characteristics when immersed in the background. In one phantom¹⁵ anisotropy was

manipulated by changing the spatial density of fibers. This may cause problems if the structure is not sufficiently dense to appear homogeneously anisotropic to the measurement system.

In a previous study evaluating the adequacy of a single homogeneous anisotropic compartment to model the skull,¹⁷ we found that the field patterns developed in a three-layered model consisting of alternating low and high conductivity isotropic materials (possibly similar to skull composition) were quite different from those formed in homogeneous anisotropic tissue. However, where layers were arranged at a spatial frequency greater than about 10 times the measurement scale the electrical behavior of the layered structure approached that of a homogeneously anisotropic conductivity element. Thus, we identified a criterion for construction of a physical phantom that approximated anisotropic behavior. Further, since the degree of anisotropy—the ratio of longitudinal to transverse conductivity—in such a structure can be controlled continuously by changing the relative conductivities of the layers, the phantom can be used to quantitatively test results of anisotropic imaging methods. In this paper we illustrate these earlier results and demonstrate the validity of the design using a real phantom composed of layered isotropic materials.

Isotropic and Homogeneously Anisotropic Structures

In all materials, observed *resistances* depend strongly upon measurement configuration. In anisotropic materials, observed *conductivities* depend upon measurement configuration. When measurements are made on isotropic materials, correct isotropic conductivities can be determined directly by first measuring a cell constant κ for the electrode configuration using a known (isotropic) conductivity standard. This constant can then be combined with a resistance measured on an unknown substance to obtain a conductivity value. In anisotropic tissue, the conductivity obtained will also depend upon the anisotropic conductivity tensor of the material and there will be a complex relation between effective isotropic and actual anisotropic conductivities. We therefore term a value obtained by multiplying a cell factor by an observed resistance an *apparent* conductivity. Values for anisotropic conductivity tensor components may straightforwardly be obtained in cases where homogeneous fields are applied to the object; for example by using large plate electrodes applied to the faces of a rectangular block of tissue whose axes are coincident with the anisotropic axes. However, homogeneous fields are not easily applied to real tissue, or *in vivo*, where pairs of small electrodes placed on the object's surface are typically used to apply currents and measure voltages. In the sections below we review observations of conductivity in anisotropic structures subject to homogeneous fields and also consider three inhomogeneous field patterns that can be used to assess tissue anisotropy.

Anisotropy in Layered Structures: Homogeneous Fields

An anisotropic structure can be constructed using layered isotropic elements. We define the anisotropy or anisotropy ratio, k , as the ratio of longitudinal (along anisotropic axis, σ_l) to transverse (across anisotropic axis, σ_t) conductivities observed using uniform electric fields.

$$k = \frac{\sigma_l}{\sigma_t} \quad (1)$$

In a structure composed of slices, the longitudinal direction is parallel to slice planes and transverse directions orthogonal to them, as shown in Fig. 1 (top right). This factor can easily be computed for the case of an n -layered structure consisting of materials having two different isotropic conductivities. In uniform fields, the k -value observed does not depend on the number of layers of the two different materials or their arrangement, only on the total thickness of each material.

Consider the anisotropy formed by alternating layers of two different isotropic conductivities, σ_1 and σ_2 . The maximum value of k , $k_{\max}$, occurs when the total thicknesses of the two types of layers are the same, i.e. at a relative layer thickness $\alpha_t = t_2/t_1 = 1$, and depends only on the two conductivities. The maximum value of k in this case is

$$k_{\max} = \frac{(\sigma_2 + \sigma_1)^2}{4\sigma_2\sigma_1} \quad (2)$$

Details of the derivation may be found in Sadleir and Argibay.²¹ For thickness ratios other than $\alpha_t = 1$, the anisotropy of the layered structure may be significantly less.

Diagonal, Orthogonal, and Parallel Current Patterns

We illustrate the effect of measuring anisotropic impedances with non-uniform fields by demonstrating results that can be obtained with one electrode layout. Four electrodes labeled *A*, *B*, *C* and *D*, are shown placed on facing surfaces of a domain in Fig. 1 (top left). If four-electrode measurement strategies are employed, the electrical properties of the domain can be assessed in three different ways. The domain has an overall width d and height h , and the distance between electrodes (width ed) on either face of the domain is a , as shown in Fig. 1 (top right). The assignment of electrodes to either current application or voltage observation for each strategy is shown in Fig. 1 (bottom). ‘Diagonal’ measurements involve current flowing obliquely from top to bottom of the sample via electrodes *A* and *D*, and the voltage difference measured between electrodes *B* and *C*. In orthogonal measurements, current is passed between *A* to *C* and voltage differences are measured between *B* and *D*. In ‘parallel’ measurements current is passed between electrodes positioned on one face of the sample (e.g., *A* to *B*) and voltage differences are measured between electrodes on the opposite face (*C* to *D*). Voltage measurements can be converted to resistance by dividing by applied current, and then further processed to conductivity equivalents by multiplying by a cell factor κ that takes account of the measurement geometry, with the factor h/a being the main determinant of this factor for each geometry. The cell factor also depends on electrode size and overall tissue diameter.¹⁰ Further, the apparent resistivity or conductivity depends critically upon the ratio of longitudinal to transverse conductivity (σ_l/σ_t). If the domain is not homogeneously anisotropic and is instead composed of layered isotropic samples, the measurements should converge to that of a homogeneously anisotropic domain as the number of layers increases.

The work presented here demonstrates a layered phantom that can be used to investigate the performance of methods for reconstructing anisotropic conductivities or measuring diffusion characteristics. The design of the phantom is flexible enough to allow testing of imaging algorithms over a range of truly anisotropic characteristics, as opposed to being constrained to using a phantom with the parameter controlled by fiber type, fiber density (which may lead to non-anisotropic distributions), or to use of a tissue phantom with inconsistent characteristics. We present both an analysis of the design and demonstration of phantom construction. We also assess our construction’s practicality and longevity, the possibility of constructing a phantom with the same structure from different material, and the extension of the design to different scales and imaging methods.

METHODS

In this section we detail strategies used to verify properties of layered structures. These include measurement of bulk conductivity and cell factors, values for apparent conductivity or resistivity and finite element simulations of measurements on slice models.

Dependence of Diagonal, Orthogonal, and Parallel Measurements on Anisotropy and Geometric Factors

In order to verify the apparent conductivities we measured from our phantoms, we needed to compare these values to reference models. We devised finely meshed 3D finite element models of block-shaped objects (Comsol, Burlington, MA, USA) that incorporated finite sized electrodes of the same size as those used in the measurement cell. Each model typically contained around 500,000 quadratic elements. On these we computed apparent resistivities for three-dimensional models as numbers of isotropic layers increased from 4 to 10, keeping h/a fixed at 1. The layered models were constructed by dividing the model into n layers, each with thickness h/n . Alternate layers had conductivities σ_1 or σ_2 , with $\sigma_1 \leq \sigma_2$. In the case of odd-layered models, $(n + 1)/2$ layers were chosen to have conductivity σ_1 and the remainder σ_2 , with low conductivity layers next to electrodes. A 'one layered' model was used to calculate expected values of cell constants in diagonal and orthogonal configurations and to verify bulk conductivity measurement data. These models were used to compute approximate cell factors and apparent conductivities for comparison with experimental findings. We also varied the overall dimension d of models while keeping h and a fixed in order to calculate the dependence of cell constant on size.

Phantom Construction

TX-151 (The Oil Research Centre, Lafayette, LA, USA) is a gelling compound consisting mostly of polysaccharides.¹⁴ After being mixed with water and agar and being heated, it solidifies into a material with the consistency of rubber.²⁶⁻³¹ It can be formed into various shapes using molds. Further, its conductivity and permittivity can be adjusted using different concentrations of sodium chloride and sucrose. Once formed, different TX-151 sample materials can be placed next to each other for extended periods without diffusion or mixing of adjacent phases.²⁹ TX-151-based samples can be sliced and formed into in a layered structure without the need for intervening contact material. We used two recipes to make low and high conductivity gels respectively. Both gels had a substrate of TX-151, agar and sugar. The high conductivity gel (gel A) had 3 g of NaCl added per 492 mL of water (0.6% W/V), and the low conductivity gel (gel B) had no NaCl added. Precise details of the phantom formulation are given in the Appendix. Gels were set into molds with approximate dimension 65×59 mm.

We constructed structures with 3, 5, and 10 layers by alternating layers of gels A and B. All had the same initial dimensions ($65 \times 59 \times 23$ mm). The samples were sliced transversely into thin slices (Professional Series PS77711) with minimum thickness 2 mm, before being assembled into alternating layers. A photograph of one phantom during construction is shown in Fig. 2. Where odd numbered layers were used, we chose to site the lower conductivity slices (gel B) on the outside of the phantom structure. Individual slice thicknesses were not directly measured, but care was taken to ensure that the total height of each phantom was the same as the distance between electrode centers (22.5 mm), thus forming an assembly having $h/a = 1$.

Measurements of Apparent Conductivity

Solid blocks of gels A and B were used to calculate bulk conductivities and were used to make diagonal and orthogonal measurements in order to calculate cell factors κ relating measured resistance and apparent conductivities in slice phantoms. These cell factors were then used to calculate apparent conductivities in 3-, 5-, and 10-layer slice phantoms.

Cell factors were calculated from experimental data as

$$\kappa_{\text{meas}}^{(d,o)} = \sigma_{\text{meas}}^{\text{uniform}} R_{\text{meas}}^{(d,o)} \quad (3)$$

Apparent conductivities of unknown samples were then calculated from measured diagonal or orthogonal resistances as

$$\sigma_{\text{app}}^{(d,o)} = \frac{\kappa_{\text{meas}}^{(d,o)}}{R_{\text{meas}}^{(d,o)}} \quad (4)$$

Finite element models were created with the same dimensions, slice thicknesses and conductivities and electrode sizes as the slice phantoms. The factor by which the measured resistance of a slice sample at the measured contrast σ_2/σ_1 differed from an isotropic sample was calculated and designated the slice factor S . This factor was divided into the measured isotropic low conductivity value to obtain the predicted apparent conductivity for the phantom, as shown in Eq. (5)

$$\sigma_{\text{app,predicted}}^{(d,o)} = \frac{\sigma_{\text{meas}}^{\text{uniform}}}{S_{\sigma_2/\sigma_1}^{(d,o)}} \quad (5)$$

Conductivity Measurement Methods and Apparatus

Sample resistances were measured over a range of frequencies between 10 Hz and 100 kHz using a bio-impedance spectroscopy system (BIS) provided by the Impedance Imaging Research Center at Kyung Hee University, Korea. This system is based on the KHU Mark 1 system.¹⁶

Measurements in Homogeneous Fields—Uniform conductivity measurements on block isotropic samples were performed by attaching two large copper plates to cover sample ends, and measuring the voltage difference between two electrode pins pushed into the gel close to the plates. In these cases, resistance measurements were converted to conductivities using the dimensions of the sample. Resistances were measured through each of the three pairs of faces of each sample and values were compared for consistency. For the case of layered constructions, conductivities were estimated for both transverse (through layer) and longitudinal (along layer) directions using homogeneous fields and the same procedure as above.

Diagonal and Orthogonal Measurements—Diagonal and orthogonal conductivity measurements were performed by securing small electrodes (diameter 6.3 mm) to two plastic plates. Two electrodes, centers separated by 22.5 mm, were attached to the top plate, immediately over two electrodes in the same relation in a plate underneath the sample. Hydrogel pads (HUREV Co. Ltd., Korea; <http://www.hurev.com/>) with a thickness of 5 mm were placed between electrodes and sample to avoid damaging the sample and to ensure that a uniform field distribution was obtained near the electrodes. Diagonal and orthogonal resistances were first measured on block isotropic samples and these measurements were used with their previously determined homogeneous field conductivity to determine experimental cell constants for each configuration. Apparent resistivity or conductivities of layered phantoms were then calculated from these experimental cell constants. In order to confirm that measurements were consistent for each sample, multiple resistance measurements were made at each frequency. In the case of diagonal and orthogonal measurements, two measurements were made for each configuration: one in ‘normal’ mode (e.g. for a diagonal measurement, using electrode pair AD for current injection, and BC for voltage measurement) and the other in ‘reciprocal’ mode (BC for current injection and AD for voltage measurement).

Measurements of Frequency Dependence and Longevity—Apparent conductivities were measured for 3-, 5-, and 10-layer phantoms. We also determined the frequency dependence of isotropic and apparent conductivities.

We used 3- and 10-layer phantoms to test the longevity and stability of samples. Apparent conductivities of phantoms were tracked for hourly for a period of 8 h in the case of a first 10-slice sample, and daily for 10 days in the case of the 3 and 10 slice phantoms. The 10-slice phantom tracked over an 8-h period was assembled and monitored hourly while in place within the measurement cell on a laboratory bench. The two phantoms monitored over 10 days were wrapped in plastic .lm and placed in a refrigerator (maintained at a temperature of 4 °C) after each measurement, and were removed from the refrigerator and allowed to warm to room temperature for a period of about 30 min before each measurement was made.

Error Analysis

Error in conductivity estimations is related to uncertainties in measurements of sample dimensions, in resistance measurements and deviations in fields formed by test electrodes from those assumed in models.

We calculated relative uncertainties in measured quantities as follows: for uniform field measurements of isotropic conductivities we have that

$$\varepsilon(\sigma_{\text{meas}}^{\text{uniform}}) = \varepsilon_l + \varepsilon_w + \varepsilon_b + \varepsilon_R \quad (6)$$

where l, w, b and R subscripts denote relative errors in measurements of sample length, width breadth and resistance, respectively. We measured l, w and b to within 0.1 mm, with maximum errors in these values typically around 4%. Errors in R were at most about 0.15%.

For cell constant determination, relative error was obtained from

$$\varepsilon(\kappa) = \varepsilon(\sigma_{\text{meas}}^{\text{uniform}}) + \varepsilon_R \quad (7)$$

and for diagonal and orthogonal measurements, we used the expression

$$\varepsilon(\sigma_{\text{app}}^{(d,o)}) = \varepsilon(\kappa) + \varepsilon_R \quad (8)$$

Finally, for predicted diagonal and orthogonal measurements, the error was calculated from

$$\varepsilon(\sigma_{\text{app,predicted}}^{(d,o)}) \approx 3\varepsilon(\sigma_{\text{meas}}^{\text{uniform}}). \quad (9)$$

The expression in (9) is used because Eq. (5) involves both errors in measured uniform conductivity and the ratio between measured uniform high and low conductivities. There is some error in estimation of the conversion constant S as it depends on exact sample dimensions, but this was neglected in error estimations. We found that S varied only a small amount with sample width as long as h/a remained constant and this sensitivity was neglected in error calculations.

RESULTS

Finite Element Calculations

Diagonal and parallel measurements both increased with increasing electrode spacing, with diagonal measurements being more variable. Orthogonal measurements decreased with increasing electrode spacing, with a similar absolute slope to diagonal measurements.

Simulation results from 3D anisotropic and layered models are shown in Figs. 3a, 3c, and 3e, for diagonal, orthogonal, and parallel configurations, respectively. Comparisons of apparent resistivities rather than apparent conductivities are shown here in order to better display data near the diagonal conductivity minima. Curves correspond to apparent resistivities relative to transverse resistivity, i.e. values have been divided by resistivities observed using a homogeneous transverse field. The abscissae in Figs. 3b, 3d, and 3f have been scaled to be in terms of model anisotropy, that is, values for layered models are plotted as σ_t/σ_l against normalized resistivity, with the ordinate axes scaled to be relative to the sample transverse resistivity. Results for layered isotropic models converged to homogeneous anisotropic models as the number of layers increased, best shown after the scaling applied in Figs. 3b, 3d, and 3f.

In all cases, diagonal resistances and apparent resistivities decreased resistivity as conductivity contrast σ_2/σ_1 for isotropic, layered models, or longitudinal conductivity (for anisotropic models) increased. At a particular k value between 2 and 3 the apparent resistivity became infinite. This corresponded to an isopotential surface passing through the two measurement electrodes. Above this point, the voltage polarity on the measurement electrodes is switched and apparent resistivity increases as the surface progressively flattens. More details of this behavior may be found in Sadleir and Argibay.²¹ The position of the resistivity minimum varied with the number of layers, but the position of the minimum for layered models shown in Fig. 3a occurred at a larger contrast value than k value for anisotropic models. When data were scaled as in Fig. 3b, these minima all approximately coincided. In the case of orthogonal calculations measured resistances decreased with increasing conductivity contrast σ_2/σ_1 whereas measured orthogonal resistances of anisotropic media increased with k (Fig. 3c). When layered data results were scaled to be in terms of k instead of σ_2/σ_1 data were appropriately reconciled (Fig 3d). Parallel results all showed a monotonous decrease in apparent resistivity with k , with large (even) layered isotropic models approaching anisotropic behavior (Fig. 3e). Again, rescaling to show data as a function of k (Fig. 3f) showed an increasingly anisotropic approximation with increasing n . Results from all configurations clearly showed that when ten or more alternate conductivity layers were used, the behavior of the model layer composite approached that of a purely anisotropic structure.

Conductivity Measurements

Copper plate measurements of gels A and B yielded conductivity measurements of around 0.17 S/m $\pm$ 5.6% and 0.70 S/m $\pm$ 5.6% respectively at a frequency of 1 kHz. Most variability in measurements arose from uncertainties in measurement of sample sizes, which accounts for the similar error levels. Conductivity values measured through different faces agreed within about 3% in all cases. Measured conductivities for the different sample cases at 1 kHz are shown in Table 1. We averaged conductivities measured over each frequency for use in further calculations.

Frequency Dependence

We found that in all cases measured resistances on layered constructions were not significantly affected by frequency. A plot of the frequency dependence of measured diagonal and orthogonal apparent conductivities in a 10-layered sample is shown in Fig. 4. The results show

that quite consistent values were obtained until conductivities started to increase at around 50 kHz. Accordingly, we chose to tabulate longevity data at a single frequency of 1 kHz.

Measurements of Cell Constants on Isotropic Samples

Cell constants were calculated from experimental data and then used to calculate apparent orthogonal and diagonal conductivities. These values were compared with cell constants found for finite element models with similar dimensions. The measured cell constants and error estimates are shown at 1 kHz in Table 2, and agreed well with values calculated from models of 1.77 and 10.76 for orthogonal and diagonal measurements respectively. The calculated cell constants were very different in magnitude. Orthogonal measurements with $h/a = 1$ had a much smaller cell constant than corresponding diagonal measurements. This difference mostly illustrates the peculiar dependence of diagonal measurements. In orthogonal measurements, the sign of the voltage measured on a measurement electrode never changes and there will always be a horizontal isopotential surface halfway through the sample. In this case measured resistances vary monotonically with conductivity ratio. In diagonal measurements the voltages are measured at 'crossed' points on upper and lower sample surfaces close to where an isopotential plane emerges (this behavior is most clearly illustrated in Fig. 5a of Sadleir and Argibay²¹). The point at which the isopotential plane cuts the surface was fairly close to measurement electrodes for isotropic samples, thus accounting for the large cell constant. As conductivity contrast or k increases, the plane changes position, which produces the dependences observable in Figs. 3a and 3b.

Measurements of Longevity

Results measured at 1 kHz are shown in Fig. 5 and Fig 6. We measured resistances immediately after preparation (hour 0) and then subsequently hourly for 8 h (for a 10-slice phantom) and daily (for a 3-slice and a second 10-slice phantom) over 10 days.

The time course of measured apparent conductivities showed that phantom compositions were stable over about 8 h after first construction. Measured resistances were generally within calculated errors of those predicted from finite element models. Where this was not the case, we believe this was due to irregularities in sample composition caused by air inclusions or because of another irregularity in the phantom construction such as drying, unequal slice thicknesses or uneven mixing of gel components. For example, we noted that in the case of the 10-slice phantom measured over 8 h (Fig. 5), initial diagonal and orthogonal measurements were higher and lower, respectively, than their eventual values, possibly reflecting an adjustment of the layers after initial construction into a more stable state and showing the effect of elimination of air from the structure.

DISCUSSION

While we used a contrast of around four in this study, different anisotropy factors can be chosen by using different amounts of salt in gels A and B. Although the ten-layer phantom appeared stable over a period of 8 h—which would seem adequate to support many experimental protocols—phantom life will be ultimately limited by diffusion characteristics. Our experiences, and those of other workers,¹⁶ are that TX-151 anomalies have good conductivity stability even when gels of very different conductivities have been placed side-by-side. We have evidence that similar structures, such as the gelatin phantom demonstrated by Hamamura *et al.*⁷ have useful lifetimes of around four hours, and the lifetime of our phantom may be somewhat longer than a gelatin based phantom because of its higher viscosity and therefore lower diffusion. However, we would expect that the lifetime of our phantoms would be shorter the more layers are used.

The results shown in Sadleir and Argibay²¹ established that as long as the characteristic scale of the measurement is such that there are more than 10 layers within the characteristic scale of the measurement (a or h in this case), there should be approximately anisotropic behavior in the structure. This principle can be extended to contexts such as diffusion tensor imaging (DTI). Therefore, if there are more than approximately 10 layers or fibers inside one DTI voxel, there should also be satisfactorily anisotropic behavior, that is, the behavior should be similar to those observed when much finer layered structures such as white matter are present. Other phantoms^{17,23,27} that depend upon the relative absorption properties of absorbent materials such as cottons, polyester yarns and glass have the ability to test at different levels of anisotropy fraction, but these values depend upon the properties of available materials in fiber form.

Another work¹⁵ described assembly of an anisotropic phantom for use in magnetic resonance electrical impedance tomography (MREIT) involving silk fibers suspended in saline. The anisotropy was adjusted by varying the cross-sectional density of the fibers, although at low densities the fit of the phantom data to homogeneous anisotropic behavior would likely be poor. The approach described here may therefore be of particular use when simulating anisotropy values similar to those measured in skeletal muscle⁶ or in extracellular measurements of cardiac tissue.³ In MREIT applications, this phantom can have application where at least 10 layers per pixel size are present.

This phantom has application to use in inverse EEG and ECG, as well as in EIT and MREIT. Many papers exist discussing the error in source location due to anisotropy in tissue such as white matter, skull and cardiac muscle. Phantoms have already been constructed in order to test the ground truth of inverse ECG reconstruction algorithms,¹² and it is hoped that the modeling guidelines shown here will guide future construction of similar phantoms.

The design shown in this phantom demonstrates the use of thin slices in phantom construction rather than threads of material similar to those used in other phantoms. The basic principles of design outlined here will also be obeyed with an array constructed of alternating low and high conductivity extended rectangular blocks rather than slices. We found that on translating our model calculations from 2D (as in our earlier work²¹) to 3D here that there were scaling changes in apparent resistivity solutions. These differences are most evident in the decrease of the resistivity minimum shown in Fig 2b from a k -value over 3 to 2.6 (representing a change by a factor of $1/\sqrt{2}$). Similarly, on translating the physical representation from slices to a thread array there will be a difference in the scaling frequency required to attain homogeneous anisotropy. Work to exactly estimate this factor in this modified geometry is underway.

CONCLUSION

We have shown that it is possible to construct a controllably anisotropic conductive structure using a minimum number of alternating layers of isotropic conductive samples. The lifetime of the phantom is sufficient to support most experimental protocols. The method has the advantage of avoiding the difficulties and uncertainties associated with measurements on real anisotropic tissue (such as skeletal muscle or white matter), and allows continuous variation of anisotropy ratio k by altering the relative ratio of alternate conductivity layers. The phantom could be used to test performance of anisotropic reconstruction algorithms for EIT, MREIT; and in source location reconstruction in inverse EEG and ECG. Because conductivity and diffusion are linked transport phenomena, this phantom could also find application in DTI.

APPENDIX: PROCEDURE FOR MAKING TX-151 GELS

TX-151 gels suitable for use in these phantoms can be produced using the procedure below. The components are the same as those used in Mazzara *et al.*¹⁴ and Oh *et al.*¹⁶ but quantities

were adjusted to form a thicker gel. The original version of this formulation appears in Zhang.
³⁰ We measured the conductivity

TABLE A

Composition of TX-151 gels.

Ingredient	Purpose	Mass (g)
Deionized water	Principal ingredient	492
Sucrose	Sets electric permittivity	84
Agar	Solidifier	15
TX-151	Thickener	15
Sodium chloride	Sets electric conductivity	x

with $x = 0$ and 3 g and found the conductivities reported in Table 1 at 1 kHz.

1. Assemble ingredients in Table A.
2. Combine ingredients in a glass beaker and stir thoroughly using a glass stirrer (a handful of glass stirrers may be useful as the solution thickens).
3. Cover the solution using plastic film. Make some holes in the film to allow ventilation.
4. Microwave for 9 min (may vary with microwave). The solution is overheated if it begins bubbling or boiling. If so, allow to cool one minute before proceeding.
5. Carefully pour the hot mixture into the mold. Avoid mixing in air.
6. Cover the mold with plastic film and refrigerate for 4 h. The product is ready once it has solidified.
7. Wrap unused product with plastic wrap and keep refrigerated.

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FIGURE 1. (Top left) Three-dimensional positions of electrodes on sample, (top right) cross-section through sample showing interelectrode distance (a), sample diameter (d), sample thickness (h) and electrode diameter (ed). Dotted lines indicate slice planes and direction of highest conductivity; also indicated are conductivities σ_l and σ_t measured using homogeneous fields applied along and through planes respectively. (Bottom) Electrode assignments for diagonal, orthogonal and parallel measurement configurations.

FIGURE 2.

Assembled slice phantom consisting of many alternating layers of TX-151 gel, prior to placement inside measurement cell.

FIGURE 3.

Comparison of calculations using (a, b) diagonal, (c, d) orthogonal and (e, f) parallel configurations, with $h/a = 1$, for homogeneous anisotropic (+) and isotropic even layered models consisting of 4–10 alternating sheets. In (b, d, f) Resistivities were normalized with respect to the model transverse resistivity (obtained from measurement of block bulk samples), and the abscissae for isotropic, layered models were rescaled to be the anisotropy ratio k . Layer thicknesses were equal to h/n in each case.

FIGURE 4.

Apparent diagonal and orthogonal conductivities of 10-slice phantom as a function of frequency. Error bars in orthogonal conductivities were of similar scale to markers.

FIGURE 5. Predicted and apparent orthogonal and diagonal conductivities measured as a function of time for a 10 slice phantom over an 8-h period. Error margins for predicted values are indicated with shading.

FIGURE 6.

Predicted and apparent (left) orthogonal and (right) diagonal conductivities measured as a function of time for 3 and 10 slice phantoms over 6 days. Error margins for predicted values are indicated with shading.

TABLE 1

Measurements of high and low gel conductivities at 1 kHz in S/m.

Batch	Gel A (low conductivity)	Error	Gel B (high conductivity)	Error
3 slice	0.1734	0.0097	0.699	0.039
5 slice	0.1790	0.0100	0.712	0.040
10 slice	0.1734	0.0097	0.700	0.039

Batches are denoted 3, 5, and 10 slice, as bulk sample conductivities were measured at the time of construction of each phantom

TABLE 2

Orthogonal and diagonal κ values at 1 kHz.

Phantom	κ -Orthogonal	Error	κ -Diagonal	Error
3 slice	1.775	0.040	10.72	0.04
5 slice	1.889	0.040	10.69	0.04
10 slice	1.743	0.040	10.75	0.04
Model	1.77	–	10.76	–

Each value was calculated from block sample dimensions and measured resistances. Model k values were obtained from finite element model.