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## **Finite Difference Transmission Line model for the design of safe multi-sections cables in MRI.**

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**Purpose:** To show the relevance of a simple finite difference transmission line model for help in the design of safe cables in 1.5 T MRI's using the multi-section cable approach.

**Methods:** A two section wire will be studied as a function of the length of the two different sections. The result concerning the heating of the electrodes for a constant electrical field excitation along the wire as well as the estimation of the correction phase factor will be compared to full-wave simulation results. Such information allows estimation of the worst case heating of the cable in MRI taking into account the phase effects.

**Results:** The transmission line predicts correctly the full-wave simulation results. The optimum length of the second section reduces by 37% the worst case heating at the electrode compared to the best case unique section wire.

**Conclusion:** The multi-section cable design can reduce the heating of cables in MRI taking into account the phase effects. The finite difference transmission line model presented is a simple valuable tool to estimate the worst case heating of multi-section cables thus helping to optimize the design of such cables.

Keywords: radiofrequency, transfer function, cables, MRI safety, phase effects, pacemaker

## INTRODUCTION

MRI has become an essential imaging modality for soft tissue. At the same time, patients implanted with devices such as pacemakers, defibrillators or neurostimulators are more and more common as the population in developed country ages. These implanted medical devices use a lead to transfer the energy from the implanted active case to the desired organ in the body such as the heart or the brain. Currents are induced on the conducting leads by the MRI radiofrequency field and can result in consequent heating of the tissue at the interface with the implanted stimulation electrode and to induced voltages at the input impedance of the active case. These input voltages can lead to dysfunction of the implanted device presenting further risk for the patient. Serano et al.(1) proposed to use the "resistive tapered stripline" (RTS) technology introduced by Bonmassar (2) for electroencephalogram (EEG) cables for deep brain stimulators leads. This technology introduces discontinuities in the conductivity of the line such that the radiofrequency energy is reflected at the interfaces therefore modifying the response of the lead compared to a continuous conductivity line. To model a two section wire, Serano et al. (1) considers that the implanted wire acts as an antenna and a transmission line. The analytical model they use was introduced for a discontinuous transmission line with multiple reflections (3) but with a feeding port at the end of the line. This model was adapted to an EEG cable submitted to a distributed excitation field by an external antenna such as a radiofrequency MRI coil by Bonmassar (2). This model considers that the signal delivered to the electrode is a term corresponding to the total signal received by both monopoles corresponding to the two sections that constitute the cable minus the different components of the signal reflected back to the opposite end to the electrode. In (2), Bonmassar says that the expression of the signal received by the two monopoles is valid for the short monopole approximation. The model was

established for EEG cables for which the surrounding medium is air. Therefore the wavelength of the radiofrequency field which is about 4.7m for a 1.5T MRI is indeed large in front of the length of the EEG cables. Nevertheless, it seems contradictory to consider that the wavelength is short enough to use the transmission line model to model the possible reflections at the discontinuities and to apply at the same time the short monopole approximation. Moreover, for implanted cables in a tissue imitating material the wavelength is divided by approximately 10 compared to air. Therefore as, for example, the length of deep brain stimulator leads is at least tens of cm, the short monopole approximation is no longer valid.

In (1), Serano et al. present this analytical model but finally analyze the possibilities offered by the RTS model with full-wave numerical simulations. And they do not confront the potential results of this analytical model with the full-wave simulation results. In (4) I presented a modified transmission line model for a cable embedded in tissue imitating gel at 64 MHz. It was inspired by previous work by Acikel et al. (5) but with a simple passive model for the electrode in contrast with the Thevenin equivalent model presented in (6) by the same group. It models the excitation from the MRI radiofrequency antenna as a distributed excitation all along the cable. It was shown that there is an equivalence between our transmission line model and the function transfer model introduced by Yeung *et al.* (7), its full potential for complex cables later brought to light by Park et al.(8). This transfer function model allows to take into account the effect of the phase distribution of the incident field on the potential heating at the lead electrode (7). Indeed Serano et al. (1) show that their two section design can reduce the heating at the electrode compared to conventional leads but for a given configuration in the American Society for Testing Materials (ASTM) phantom (9). This configuration corresponds approximately to a constant phase and constant amplitude incident field. The incident field in the human body varies significantly and phase effects need to be taken into account to ensure patient safety. If one follows Park *et al.* (8) formalism, the worst case heating at the electrode of a cable taking into account the phase effects can be estimated by the following information. First the heating at the electrode for a constant amplitude and constant phase incident field and second by the amplitude and phase distribution of the normalized transfer function. Such information allows the estimation of the heating at the electrode for a given constant amplitude of the incident field that can be considered to be the maximum possible electrical field in the human body and the worst phase distribution that is given by the transfer function distribution (7,8).

The transmission line model presented in (4) was built for insulated wires of simple cylindrical geometry, the conductor being a full cylinder in contrast to the fine layers of metal deposited on a substrate of the RTS technology. For this simple cylindrical insulated wire, analytical expressions of the transmission line parameters exist (10). The RTS technology uses conductivity discontinuities of the layers of the different sections to create the reflections of the wave. In this work the discontinuities were created by changes in the insulation thickness and relative permittivity  $\epsilon_r$ . The transmission line model is solved by the finite difference method with the incident field along the cable as an input. The result is the current and voltage distribution along the cable. The active power at the load impedance gives an evaluation of the heating at the electrode. It can be solved with varying parameters along the cable with no further effort compared to a uniform cable. The finite difference model also allows to get the transfer function model.

Therefore, it allows to study multi-section cables heating taking into account the phase effects in a very straight forward way.

This work aims at demonstrating that this finite difference transmission line model is indeed a reliable tool to study the possible heating of a simple two-section cable taking into account the phase effects. Results will be compared to full-wave simulation results of the losses at the electrodes of the cable under a constant phase and constant amplitude incident field and of the transfer functions that allows to get the correction phase factor to estimate the worst case heating. The commercial software CST MICROWAVE STUDIO® (CST® MWS®, Darmstadt, Germany) was used for the full-wave simulations.

## THEORY

### Evaluation of the worst case heating taking into account the phase effects.

Park et al. (8) uses the following formalism for the estimation of the scattered electrical field at the electrode as a function of the incident field.

$$E_{scattered}(P) = E1(P) \int_0^L TF_N(z) E_{inc}(z) dz$$

where **E1(P)** is defined as the scattered field at the electrode for a constant amplitude and phase incident field of 1V/m.  $TF_N(z)$  is defined as the normalized transfer function such as  $\left| \int_0^L TF_N(z) dz \right| = 1$  which results directly from the definition of **E1(P)**. The heating at the electrode is proportional to the square of the scattered electrical field. The worst case heating appears when all the terms under the integral  $TF_N(z)E_{inc}(z)$  are in phase meaning that the phase of the incident field is minus the phase of the transfer function to a constant close. If one fixes the amplitude of the incident field to be constant and equal to the maximum along the path in the human body  $E_{inc\_max}$ , the worst case heating can be estimated by the following equation.

$$\Delta T_{max}(P) = \left| E1(P) E_{inc\_max} \int_0^L |TF_N(z)| dz \right|^2$$

Therefore knowing **E1(P)** and the value of  $\int_0^L |TF_N(z)| dz$  that is the correction phase factor, one can estimate the worst case heating of the two section cable for different lengths of the different sections.

### Finite difference transmission line model.

In the finite difference transmission line model, the cable is described by two vectors **Z** and **Y** that represent the impedance per unit length  $Z(z)$  and admittance per unit length  $Y(z)$  at each of the N nodes of the one dimension model. It is also described by two load impedances  $Z_{LOAD1}$  and  $Z_{LOAD2}$  that represent the termination conditions. The input to the model is the complex incident field  $E_{inc}(z)$  at each node. The finite difference model takes the following matrix form:

$$\begin{bmatrix} \mathbf{Dz1} & \mathbf{MZ} \\ \mathbf{MY} & \mathbf{Dz2} \end{bmatrix} \begin{bmatrix} \mathbf{V} \\ \mathbf{I} \end{bmatrix} = \begin{bmatrix} \mathbf{E}_{inc} \\ \mathbf{0} \end{bmatrix}$$

where  $\mathbf{V}$  and  $\mathbf{I}$  are the voltage and current distribution along the cable.  $\mathbf{Dz1}$  and  $\mathbf{Dz2}$  are  $N \times N$  matrixes that operate a first order derivation and  $\mathbf{MZ}$  and  $\mathbf{MY}$  are  $N \times N$  diagonal matrixes containing the parameters vectors  $\mathbf{Z}$  and  $\mathbf{Y}$ . The boundary conditions are implemented at the  $N^{\text{th}}$  and last line of the whole matrix.

The heating is actually proportional to the square of the current or voltage at the load. The calibration factor can be determined from a temperature measurement for a known incident field.  $\mathbf{E1(P)}$  is proportional to the current or voltage at the load for a incident field  $E_{\text{inc}}$  constant in amplitude and phase. In this study there is no need to evaluate the calibration factor as the aim is to compare  $\mathbf{E1(P)}$  between the different multi-section cables.

As mentioned in (4) the transfer function and therefore the correction phase factor can be determined simply from the finite difference model. Inversing the square matrix expresses the current and voltage distribution as a function of the incident field and more particularly the current and voltage at the loads as a function of the incident field. The formalism is then exactly the one of the transfer function. The transfer function for the left load is the  $N-1$  first values of the first line of the inverse matrix. For the right load it is the  $N-1$  first values of the  $N^{\text{th}}$  line of the inverse matrix. Normalizing this transfer function allows to estimate the correction phase factor.

The square of the product of  $\mathbf{E1(P)}$  times the correction phase factor estimation of the worst case heating of the two-section cables and compare them to study the added value of this multi-section design compared to a one section design taking into account the phase effects.

## **METHODS**

### **Transmission line model of the two-section cable.**

The cable studied was a 53 cm long insulated cable with 1 cm of insulation removed at both ends. It had a 0.75 mm radius. The first section of the cable of length  $L2$  was insulated by a 0.25 mm thick insulation with a relative permittivity of 3. The second section of the cable of length  $L1$  will be insulated by a 1.1 mm thick insulation with a relative permittivity of 1.6. It was considered to be embedded in tissue imitating gel with a relative permittivity of 80 and a conductivity of 0.47 S/m at 64 MHz. The transmission line parameters  $Z$  and  $Y$  are calculated from the analytical expressions given in (10). The value of the load impedance is estimated from solving the inverse problem on the simulated transfer function in (4). Nyenhuis *et al.*(11) raised the issue that the measured transfer function depends on the boundaries of the phantom. We realized that the simulated transfer function using the reciprocity approach is also sensitive to the phantom boundaries. The transmission line model of the finite difference model was determined by solving the inverse problem on the full-wave simulation of the transfer function with the cable placed in an ASTM phantom such as represented in Figure 1. The inverse problem was solved by fixing  $Z$  and  $Y$  to the analytical values given in (10) so the only variable parameters are the end load impedances. As the simulated transfer function depends on the phantom boundaries, the extracted load impedances for the finite difference transmission line model also depend on the boundaries of the phantom.

All the transmission line parameters at 64 MHz for this placement in the ASTM phantom are summarized up in Table 1.

	Z (ohm/m)	Y(S/m)	Z <sub>LOAD</sub>
L2	85.1+j 361.7	0.0319+j0.1875	66.1-j39.9
L1	85.1+j 361.7	0.0010+j 0.0384	66.1-j39.9

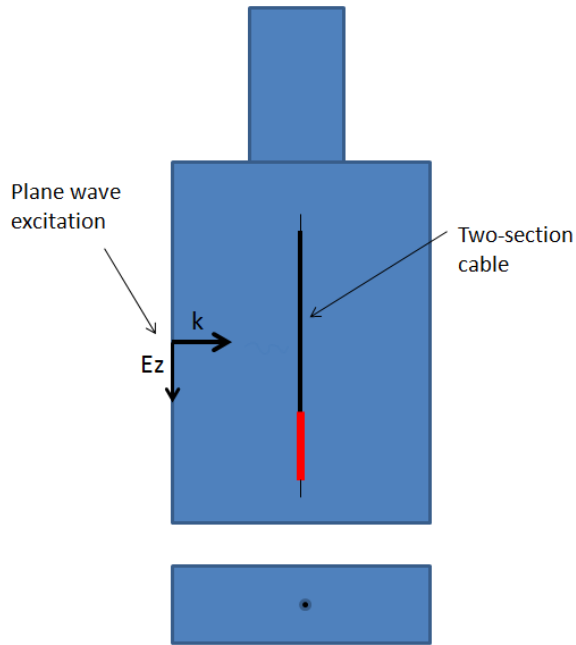
**Table 1 Transmission line model parameters for the two section cable.**

The length L1 will be varied from 0 cm to 53 cm every cm the extreme cases corresponding to a one section cable or insulation material 2 and insulation material 1. L1 and L2 take into account the 1 cm length of the bare electrodes at both ends.

### **Validation of the estimation of E1(P) by the Finite Difference Transmission Line model**

We placed the model of the 53 cm long two-section cable along the length of an ASTM phantom as represented in Figure 1. We excited with a plane wave excitation with a propagation direction x and a linear polarization of the electrical field along z as in Figure 1. Because of the boundaries of the ASTM phantom, the incident field at the position of the cable was not exactly constant in amplitude and phase. For each value of L1, the mean losses on a 2 mm side cube at both electrodes were calculated. As the cable is dissymmetric due to the two different sections, the losses at the left and right end will not be the same. Both were studied and the behavior of the predicted losses at the electrodes as a function of L1 from the transmission line model were compared to the full-wave results. An arbitrary scaling factor has to be applied between both sets of data.

The entry to the transmission line model was the incident field that was extracted from the full-wave CST simulation of the empty phantom excited by the plane-wave excitation. In the full-wave simulation, it was not possible to have simultaneously a constant amplitude and phase incident field and take into account the boundaries of the ASTM phantom. But if the transmission line model predicts correctly the losses at both electrodes as a function of L1 for a given approximately constant incident field it is likely it will predict correctly the losses for a constant amplitude and phase incident field **E1(P)**.



**Fig. 1 Full-wave simulation setup for the plane-wave simulations and the transfer function simulations.**

### **Validation of the estimation of transfer function by the Finite Difference Transmission Line model**

The full-wave simulation of the transfer function is made following the reciprocity approach proposed in (12). The electrode studied is excited locally by a short monopole and the current density along the cable is then the transfer function that can be normalized. The position of the cable in the ASTM phantom for these simulations is the same as the one presented in Figure 1 for the plane wave simulations.

To evaluate if the correction phase factor is correctly estimated by the transmission line model, we compared the transmission line transfer function to the full-wave simulated transfer function for the two section cable described above with  $L_2=10$  cm for both electrodes. Indeed as the cable is asymmetric the transfer function of electrode 1 is different from the transfer function of electrode 2. If the amplitude and phase of the normalized transfer functions are accurately estimated, the correction phase factor is correctly estimated too. The comparison was also made for a three section cable of the same length and geometry with a first section of length 20 cm with insulation material 2, a second section of 21 cm with insulation material 1 and a third section of 12 cm with insulation material 2. This assesses the ability of the finite difference transmission line model for even more complex cables for which the determination of an analytical model becomes even more complex.

### **Worst case heating as a function of length of section 1**

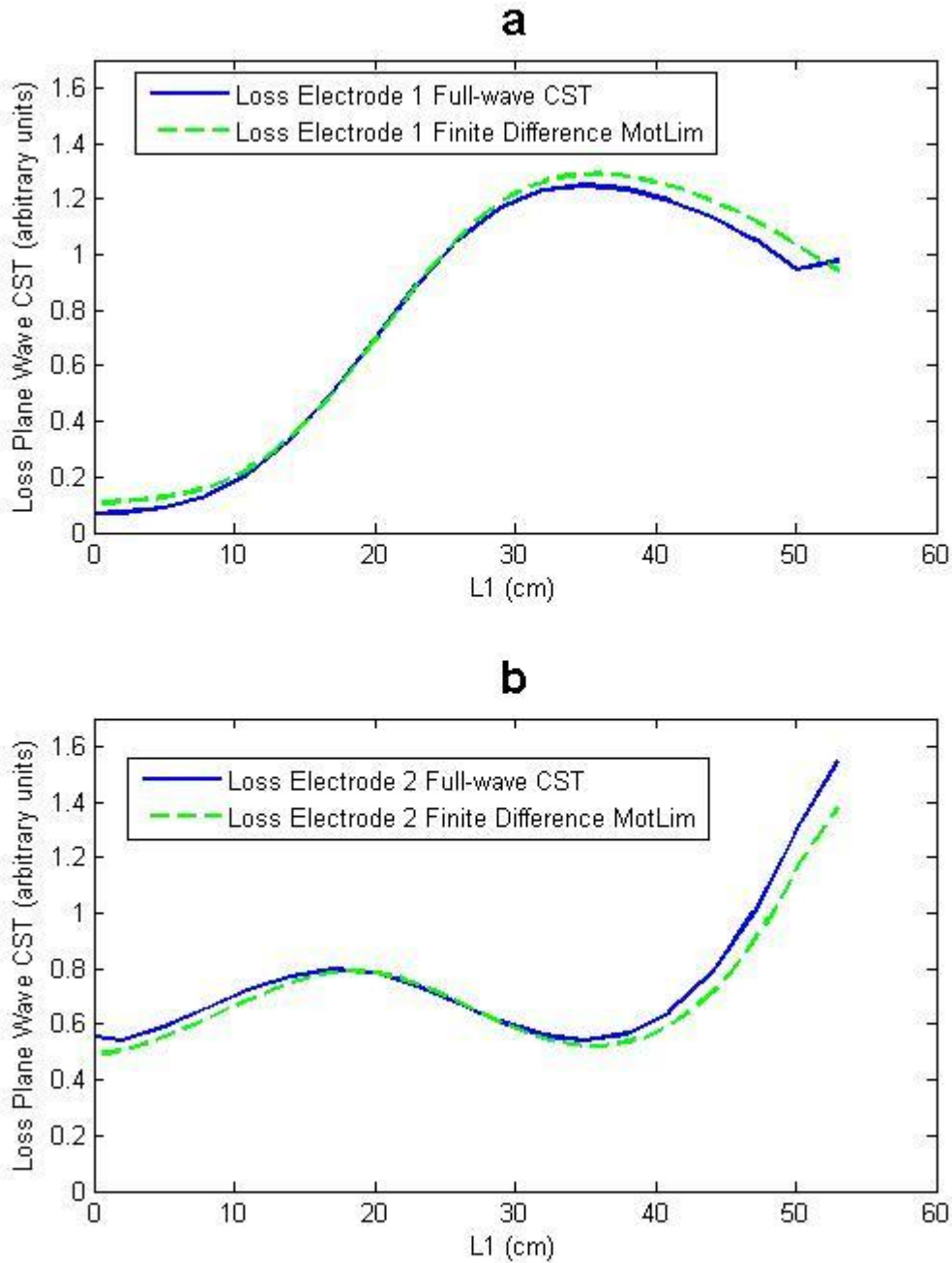
The transmission line model was used to predict the worst case heating variations at the two electrodes of the two-section cable as a function of  $L_1$ . This was estimated from the square of  $\mathbf{E1(P)}$  times the correction phase factor for each value of  $L_1$ . The potential benefit of the two section cable was compared to the one section cable with the insulation material which gives the least worst case heating.



## RESULTS

### Validation of the estimation of $E_1(P)$ by the Finite Difference Transmission Line model

Figure 2 shows the results of the losses at both electrodes of the two section cable as a function of the length of the cable insulated by insulation material 1  $L_1$ . The results given by the Finite Difference Transmission Line model coincide very well with the full-wave simulation results. There is abrupt change for electrode 1 which is on the side of insulation material 1 when the cable is entirely insulated by material 1 for the full-wave simulations. The same phenomenon is observed for electrode 2 when the cable is entirely insulated by material 2. No explanation was found. Nevertheless, on the whole, although the incident field was not exactly constant in amplitude and phase, we can conclude that the Finite Difference Transmission Line model is a good tool to evaluate the relative heating of a two section cable under a constant phase and constant amplitude incident field  $E_1(P)$ .

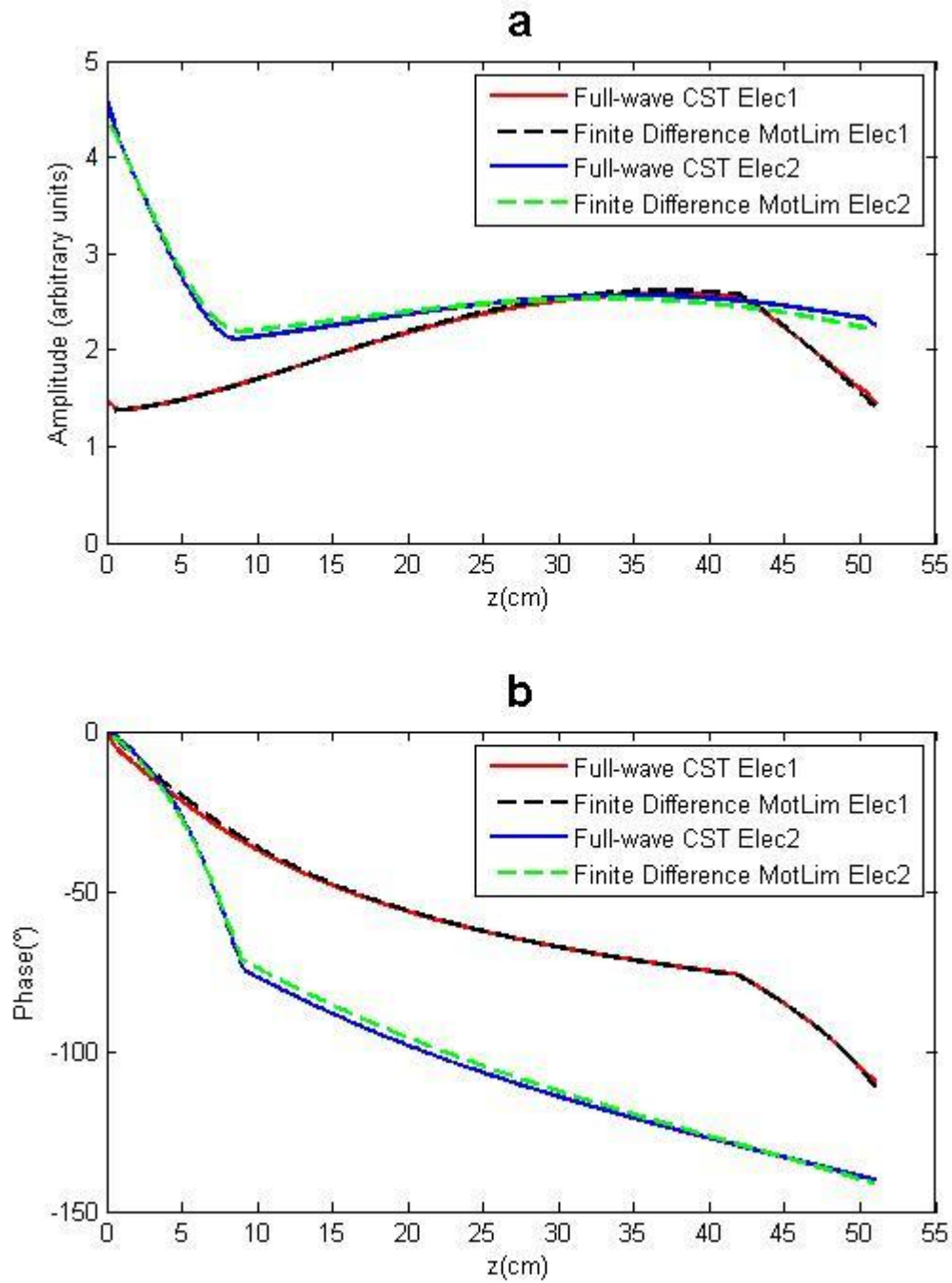


**Fig. 2 Comparison of the losses at the electrodes of a two section cable predicted by a full-wave plane wave simulation and the Finite Difference Transmission Line model as a function of the length of the section insulated by material 1 L1. a) Electrode 1 on insulation material 1 side. b) Electrode 2 on insulation material 2 side.**

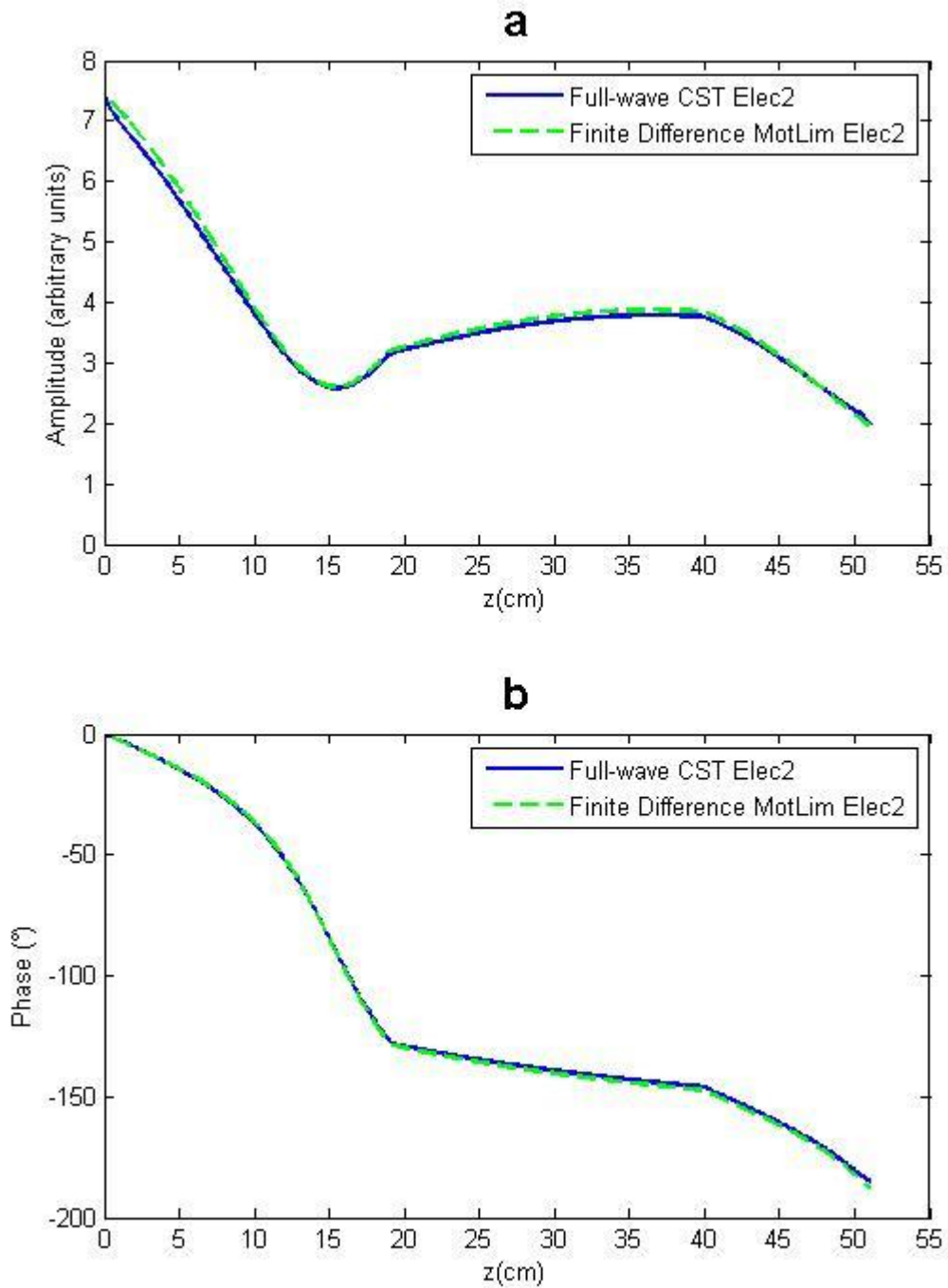
### **Validation of the estimation of transfer function by the Finite Difference Transmission Line model**

Figure 3 shows the amplitude and phase of the normalized transfer functions of the two electrodes of a two section cable. The origin of z-axis is at the electrode meaning that the direction along the cable is different depending on which electrode we look at. There is a very good agreement between the predicted transfer functions by the full-wave simulations and the Finite Difference Transmission Line model. One can notice that the transfer functions are different as the cable is indeed asymmetric. A discontinuity in the first derivative is observed at the junction of the two different materials for the amplitude and for the phase.

Figure 4 shows the results of the comparison for an even more complex three section cable for which the determination of an analytical solution becomes too cumbersome. The results are in very good agreement showing the potential of the Finite Difference Transmission Line model to be a good design tool.



**Fig. 3 Comparison of the transfer function predicted by full-wave simulations based on the reciprocity approach and the Finite Difference Transmission Line for a two section cable with  $L_2=10$  cm and  $L_1=43$  cm. a) Transfer functions amplitude. b) Transfer functions phase.**



**Fig. 4 Comparison of the transfer function predicted by full-wave simulations based on the reciprocity approach and the Finite Difference Transmission Line for a three section cable with a first 20 cm section of insulation material 2, a second 21 cm section of insulation material 1 and a third 12 cm section of material 2. 2 a) Transfer functions amplitude. b) Transfer functions phase.**

### Worst case heating as a function of length of section 1

The finite difference model having been validated against full-wave simulations, it is used to predict  $E1(P)$  and the correction phase factor of the two section cable as a function of the length of the cable insulated by material 1  $L1$ . Figure 5 presents the relative worst case heating of the two section cable as a function of  $L1$  for both electrodes deduced from  $E1(P)$  and the correction phase factor as explained in the theory section. It happens that the worst case heating curves as a function of  $L1$  for both electrodes are exactly the same although  $E1(P)$  and the transfer functions were not the same. A theoretical explanation can probably be found. The best case for the one section cable is the cable entirely insulated by material 1. The results are therefore normalized to this case to evaluate the benefit of the two section design. For  $L1=41$  cm (taking into account the bare electrode this means 40 cm of cable really insulated by material 1) and  $L2=12$  cm (11 cm of cable insulated by material 2), there is a reduction of 37% of the worst case potential heating compared to the one section case.

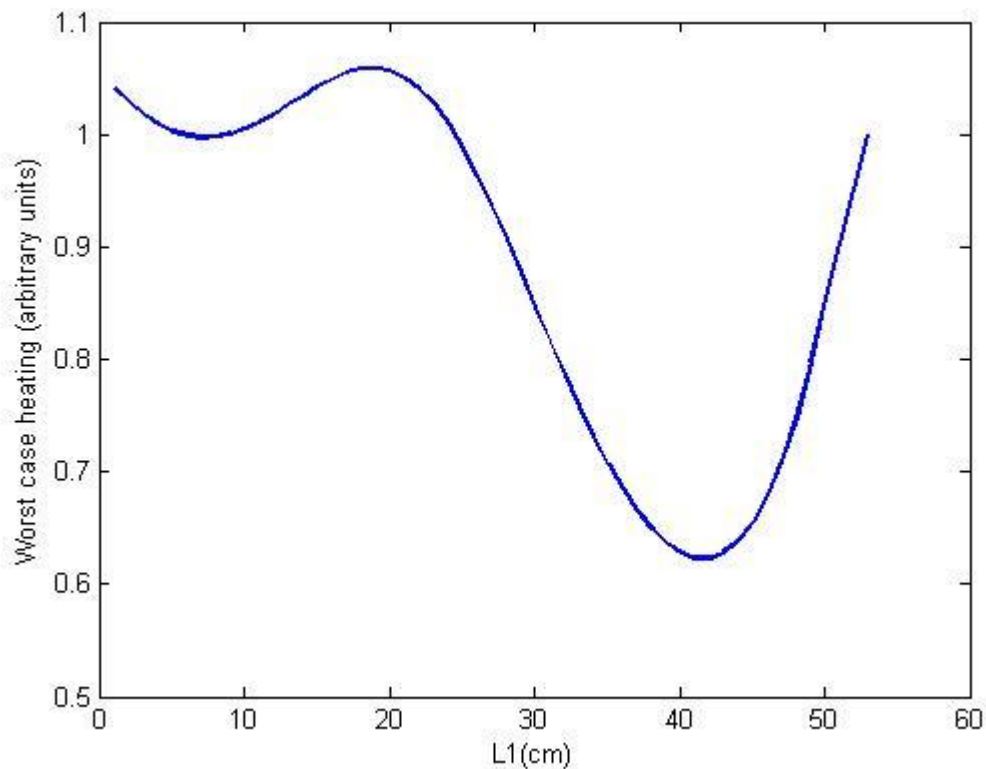


Fig. 5 Worst case heating of a two section cable as a function of  $L1$  normalized to the one section case of the cable entirely insulated by material 1.

## DISCUSSION AND CONCLUSIONS

The aim was to show the relevance of a Finite Difference Transmission Line model to help in the design of safe multi-section cables in MRI. The reliability of the model was shown by comparison to full-wave simulation results. The agreement was very good. The Finite Difference Transmission Line model can therefore be used to estimate the worst case heating taking into account the phase effects therefore helping in the design of cables that are really MRI compatible.

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