Specialty Area:	RF Engineering: Coils
Speaker Name:	Steven M. Wright smwright@tamu.edu
Talk Title:	Basics of Transmission Lines and Wave Guidance
Target Audience:	Researchers interested in understanding the interconnection of the subsystems in an MRI system, building and connecting radiofrequency coils, or developing novel high frequency coils.
Outcome/Objectives:	This talk will introduce the listener to:

The different modes of RF signal guidance used in MRI systems.
The major types of TEM transmission lines.
Factors in selecting TEM transmission lines.
Different applications for transmission lines in an MRI system.
Using the Smith Chart transmission line calculator.
Emerging applications of wave guidance in MRI systems.

Introduction: MRI systems are complex collections of interconnected subsystems. In many cases, the connection between these subsystems are taken for granted- we simply plug in transmission lines to connect one box to another. However, improper use of transmission lines can severely degrade the performance of the scanner in a variety of ways. For example, even with the best transmission lines, approximately 50% of the power exiting the RF transmitter in an MRI system is dissipated in the transmission lines and connectors before reaching the RF coil. While a long transmission line to the preamplifier from a receive coil similarly dissipates the received signal and can severely degrade signal-to-noise ratio. This talk will introduce the listener to the basic forms of transmission lines and their properties, discuss the specifications to look for in purchasing transmission lines, and discuss applications of transmission lines beyond simply transferring signals from input to output. Finally, the talk will discuss some emerging applications of wave guidance in MRI.

Guided Waves: Transmission lines are only one form of wave guidance that is used in MRI. Transmission lines are two conductor devices that permit propagation of the TEM mode (transverse-electric-magnetic), which has no low frequency limit, or 'cutoff frequency'. Other forms of wave guidance, such as the common rectangular or circular metal waveguide, fiberoptic cables, and other dielectric waveguides, are now emerging in the MRI field. While these behave differently, they both carry TE or TM waves (transverse electric or transverse magnetic) and do not operate below some 'cutoff' frequency' which is usually much higher than the Larmor frequency. There are a number of excellent undergrad or graduate level electromagnetic textbooks that provide excellent overviews of waveguides and transmission lines [1-3]. A full analysis of these different wave guidance methods proceeds from the boundary conditions in each structure. But, as a rule-of-thumb, transmission lines can have dimensions that are very small in comparison to the wavelength, as is generally the case in MRI, while true waveguides have dimensions on the order of the wavelength in the guide. Until recently, this 'rule-of-thumb' has meant that we use transmission lines in MRI, while waveguides were used in microwave/millimeter/optical regimes. However, the boundaries between transmission lines and waveguides are blurring in the MRI community due to the emergence of high field MRI as well as the introduction of high-dielectric constant materials [4] and metamaterials [5]. Thus, while conventional TEM lines are used for the majority of applications in

MRI, it is important to have an understanding of these different modes of propagation. We will also discuss dielectric resonators [6], another form of wave guidance, characterized by TE and TM modes, but with more complex boundary conditions than either transmission lines or standard waveguides.

Types of Conventional Transmission Lines: The most commonly used transmission lines in MRI are the coaxial and microstrip lines. Both are characterized by the spacing between the two conductors, the dimensions of one or both conductors, and the dielectric material surrounding the conductors. Both carry energy in the TEM mode. There are many other forms of two wire transmission lines, but these are not commonly used in MRI.

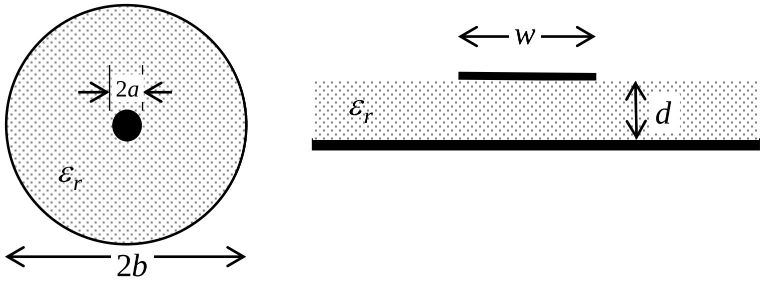

Figure 1. (left) End view of a coaxial transmission line, with inner conductor of radius a, and outer shield of radius b, with a dielectric relative permittivity ε_r. (right) End view of a microstrip line, often made from a strip of width w etched on a double sided PC board or other substrate with thickness w and relative permittivity ε_r.

Formulas for the impedance of these transmission lines are readily available. Coaxial and microstrip lines are not only used as transmission lines in MRI subsystems, but are themselves used as elements in RF coils and coil arrays [7-11].

"Off-Label" uses of Transmission Lines in MRI: Of course, transmission lines are used most commonly to transfer power, or at least signals, from point A to point B. But, there are many more applications of transmission lines. Perhaps the most common is simply to use a transmission line as a phase shifter. In the earliest days of MRI, switching different lengths of transmission lines in series with the transmitter was the simplest means of creating phase shifts for phase cycling experiments. More recently, transmission lines of different lengths can be used to generate phase shifts for multiple channel transmit arrays [12]. Simple transmission line networks can also be used to split or combine power equally between two or more (matched) ports, using a Wilkinson divider [13]. These can even be extended to match over dual bands [14], or to provide unequal power splits. Of course, perhaps the most useful and general application of transmission lines is their ability to generate, or transform, impedances. Ignoring loss in the line, we can obtain any reactive value from a shorted transmission line. This is also true of the open-circuited line, but that is not as commonly used. The most general form for this impedance transformation property (for a lossless line) gives the input impedance of a transmission line of characteristic impedance Z_o, length l meters, terminated with an impedance Z_l as:

$$Z(l) = Z_o \frac{Z_l + jZ_o \tan(\beta l)}{Z_o + jZ_L \tan(\beta l)}$$

where $\beta = 2\pi f \sqrt{\mu_o \varepsilon_o \varepsilon_r}$ is the propagation constant for the transmission line. For a microstrip line the effective relative permittivity would be used instead of ε_r of the dielectric substrate. Formulas for the effective relative permittivity for different microstrip lines are widely available, and depend on the ratio of the height to the width of the stripline, and other factors for more complex microstrip geometries. Note that l is the physical distance from the load, not the electrical distance, or distance in wavelengths. An important aspect of transmission lines is the velocity factor, which accounts for the slower-than-free-space propagation in the line. For most coaxial transmission lines, the velocity factor, v_f , is 0.66, meaning that the effective wavelength in a transmission line is 0.66 times the physical length of the transmission line. In the above equations this is taken into account through the propagation constant β . If the line is short-circuited at the end, this simplifies to:

$$Z(l) = jZ_o \tan(\beta l)$$

This behavior has been used for a variety of applications since the earliest days of NMR, ranging from transmission line tuned dual frequency coils [15] to diplexers for inserting or separating dual frequencies from a single transmission line [16] to the construction of matching networks for RF amplifiers [17]. Another use of the Wilkinson power divider structure is to generate “forced current” feed structures, in which each port is forced to have equal current (but potentially unequal power) despite variations in the load impedance. This has been used to create array coils that are insensitive to element coupling and sample loading [18]. Another important application that will be discussed is the use of transmission lines themselves to prevent current on the outside of transmission lines. Commonly called “baluns”, in this application the name ‘wave trap’ or ‘cable trap’ may be more appropriate [19, 20] An important tool for understanding and analyzing the impedance transformation properties of transmission lines is the Smith chart [21]. This is a graphical tool that forms the basis of the display of most vector network analyzers, the basic tool of coil designers and RF engineering. A variety of programs are available that provide PC and smartphone based implementations of the Smith chart. These programs are very useful for impedance matching and transformation applications in particular.

Transmission line specifications: One tends to purchase coaxial cables and manufacturer microstrip lines. When purchasing or specifying transmission lines there are a number of critical specifications that are readily available on line. Note that transmission lines that appear to be the same- RG-58 for example, come in many flavors, with different specifications. The manufacturers have excellent websites which explain both basics and details. One should be careful to know exactly what is being used. Perhaps most important is the attenuation per 100 ft. This can vary over a tremendous range, and is highly frequency dependent. A second is the power and/or voltage handling capability. A cable that may be fine for a receive coil, and may handle the average power applied during an NMR sequence, may not be able to handle the applied peak voltage. As an example, consider two Belden cables, both of type RG58A/U. Belden part number 8219 lists a maximum operating voltage of 300 V RMS, while their part number 8840 lists a maximum operating voltage of 1400 V RMS [22]. Note that the voltage on a transmission line can vary significantly due to mismatch. This is not only due to standing waves on the line, but because the transmit power may need to be increased significantly to account for the mismatch! Other factors include the percentage of shielding, as well as the material. What is ostensibly the same transmission line can come with anywhere from 100% shielding, or even double shielding, down to relatively poor braided shields with 40% coverage that can radiate significantly. A great concern when running multiple channels through a cable bundle, for example. This is one of the reasons that manufacturers are moving towards fiberoptic, or even wireless connections of array elements out of the bore [23-26]. Additionally, not all cables are non-magnetic. The quality of the dielectric can impact the lifetime of the transmission line.

Moisture, cracking due to bending, and other factors can significantly change the performance of a transmission line over time.

A few emerging applications: With a few notable exceptions, the RF coil was the last stop for the transmission lines in the MRI system. The transmission line delivered power, generated a current on the coil, which then created a field pattern, largely and relatively effectively modeled by quasistatics at 1.5 Tesla and below. The magnet bore behaved as a cutoff waveguide and propagation more or less was considered to be stopped once power hit the coil. Today, particularly at 7T, the RF coils and the bore, as well as the patient himself/herself play an important role in determining the final RF field distributions. The ability of the body to guide fields by behaving as a dielectric resonator (though perhaps not resonant and very lossy) was quickly recognized as high-field MRI became available [27]. Some researchers began to recognize the potential to use dielectric materials to manipulate the fields inside the bore to optimize performance of RF coils (shimming) as well as how to use dielectric materials instead of copper as the RF coils themselves [4, 28, 29]. As mentioned above, at 7T the bore can actually act as a propagating waveguide (TE_{11} mode), enabling a variety of new and exciting potential approaches to MRI RF coils [30-33]. We might even see reconfigurable MRI antennas using wave guidance technology [34].

Finally, the emergence of metamaterials may open up dramatically new capabilities based on the ability to control and create negative relative permittivity (and permeability) [35-37]. Metamaterials are already finding application in MRI acting as transmission media to focus or carry RF fields to/from coils and as lenses for focusing RF fields [5, 38], for example. Additionally metamaterials may overcome some of the narrowband properties of some transmission line devices, such as Wilkinson power dividers and baluns [39].

Conclusion: Guidance of RF signals is fundamental to MRI, in everything from simply interconnecting two subsystems to designing matching networks to tailoring RF fields inside the patient. In this talk an overview of conventional transmission lines, waveguides and resonators is provided, focusing on applications of conventional transmission lines in properly transferring signals to the RF coil and back. The growth of high-field MRI and metamaterials promises a challenging and exciting next decade for RF engineers.

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