

Design of a MR Phantom for the Simulation of Lumbar Intervertebral Disks



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Abstract

A phantom was designed for use in an MR imager to assess the accuracy of the scanner using T_2 relaxation values. The phantom can also be used to determine how certain variables such as distance from coil and loading affect the scanner's accuracy. The phantom holds Gadolinium (Gd) doped water samples and artificial intervertebral disk samples to assess accuracy and research the relationship between disk composition and resulting MR T_2 data. The final design for the phantom consists of an acrylic container with tubes running through to hold glass vials. The glass vials contain the Gd and disk mimicking samples. This design allows variation in sample placement throughout the phantom and encompasses adequate loading for the MR scans.

Executive Summary

A phantom was designed for use in an MR imager to assess the accuracy of the scanner using T_2 relaxation values. The phantom can also be used to determine how certain variables such as distance from coil and loading affect the scanner's accuracy. The phantom holds Gadolinium (Gd) doped water samples and artificial intervertebral disk samples to assess accuracy and research the relationship between disk composition and resulting MR T_2 data. The final design for the phantom consists of an acrylic container with tubes running through to suspend glass vials. The glass vials hold the Gd and disk mimicking samples. This design allows variation in sample placement throughout the phantom and encompasses adequate loading for the MR scans.

Validation of the design in the relaxometer and MR imager is currently in progress. From the data taken on the relaxometer, a correlation between Gd concentration and T_2 values was determined. This information was used in determining theoretical T_2 values of Gd samples tested on the MR scanner. Values measured on the scanner were compared to the theoretical values and varied by approximately +/- 5 ms. Future work will help improve the accuracy.

Disk samples were also prepared by using hydrogels as a matrix to suspend the intervertebral disk components. Thus far, gelatin has been chosen as the most appropriate hydrogel for this task and experiments have been performed to include another disk component, glycoaminoglycans (GAGs), in the hydrogels as well. Future work with the disk samples includes MR testing with GAGs and later with collagen added as well.

The phantom has not yet been tested as a single entity. The current prototype constructed is non-functional and the design team is working to have the design fabricated by an outside company. Once this step is completed, all elements of the design (disk samples, Gd water samples, and phantom container) can be combined and tested as one. This final validation will be completed by May 2006.

1 Introduction

Magnetic resonance (MR) imaging uses magnetic fields with the strength up to 7 Tesla, which is 140,000 times stronger than the earth's magnetic field, for diagnosing and researching diseases and is a growing modality in medical imaging. During the spring semester of the 2004-2005 school year, a team in the Biomedical Engineering program at UW-Madison started working on a design project that incorporates this imaging

modality. Work has been done on designing, testing, and constructing a phantom to calibrate a MR scanner and hold samples that mimic the intervertebral disks in the spine.

1.1 Problem Statement

The phantom is needed to assess the accuracy of an MR scanner by comparing known T_2 values to that which the MR scanner measures. Measurements made with the phantom will help assess which variables affect the accuracy of the MR scanner, such as the distance between the spinal coil and the patient's spine, the size of the patient, and the sensitivity of the MR scanner to very similar solutions. The phantom will also hold artificial samples which have a composition of water, collagen, and proteoglycans and a T_2 value comparable to that of lumbar intervertebral disk tissue. Research will be done using the phantom examining the relationship between disk water content, T_2 value, collagen, and proteoglycan content in order to better assess the integrity of intervertebral disk tissue using MR technology.

1.2 Medical Background

To better understand the problem general background research was completed on intervertebral disks, MR technology, phantoms, and the project's client, Dr. Haughton, a professor of Neuroradiology from the UW Hospital.

1.2.1 Intervertebral Disks

Millions of people suffer from back pain due to degeneration of the intervertebral disks in their spine. The spine consists of many vertebra and cushioning disks between to act as shock absorbers. As people grow older the stress on their back begins to add up, resulting in deterioration of the intervertebral disks. This deterioration can cause vertebrae to shift, leading to possible pinched nerves and muscle spasms [13]. Researchers know that intervertebral disks degenerate as a result of diminished blood supply and water content, part of the aging process. Because of its high level of accuracy, MR is the top choice for imaging intervertebral disks. Often, only MR is able to observe changes necessary to diagnose degenerative disks. Researchers would like to better assess the degree of damage or disk integrity using disk water content and MR.

1.2.2 MR Scanner

The MR scanner consists of a horizontal tube, known as the bore, running through a large electromagnet from front to back. The portion of the patient to be imaged is moved into the bore to the exact isocenter of the magnet. The scanner maps the tissue by using radio waves to determine the tissue type. Most MR scanners use superconducting magnets consisting of wires and coils that electricity flows through to generate a magnetic field. The system is continuously cooled to almost absolute zero by a vacuum of liquid helium to set the resistance in the wires to nearly zero and avoid heating the bore of the magnet. The magnetic field is constantly maintained with this system.

In the scanning process, the hydrogen atoms in a patient's body align with the main magnetic field of the magnet upon entering the bore of the magnet (see Figure 1).

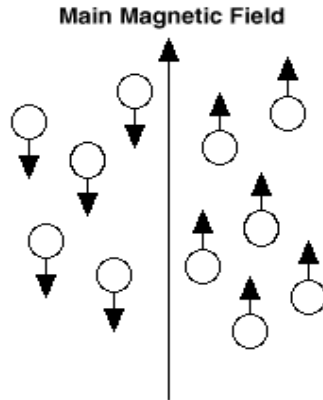


Figure 1: The alignment of protons with the main magnetic field

The alignment of the hydrogen atoms with the magnetic field is referred to as longitudinal alignment. Also, there is no net magnetization in the transverse plane, the plane that involves spinning of the protons. During imaging, the MR scanner applies radio frequency (RF) pulses to the area being imaged that targets the protons in that area. To concentrate on specific areas of the body, different coils can be used to send and receive signals locally. The RF pulse causes the protons to absorb energy and spin (see Figure 2).

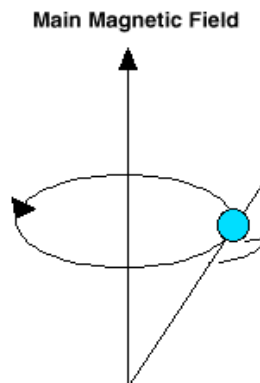


Figure 2: The spin of the protons following RF pulse

The tissue type dictates the frequency, direction, and duration of the spin. As the protons return to their original alignment, they release the energy that they absorbed. The scanner reads this information and uses a Fourier Transform to reconstruct an image. The specific measurement that the project's client asked the team to focus on is T_2 relaxation time, a measurement that involves the rate at which the spin-spin interactions decay after the RF pulse is applied.

1.2.3 Phantoms

Phantoms are widely used in conjunction with MR scanners. Phantoms simulate one or more body tissues by using materials that interact with the ionizing radiation administered by the MR imager. Phantoms are widely used to test the performance of medical equipment, calibrate equipment, teach new operators, and aid in medical

research. Phantoms measure, “system resolution, focal spot size, contrast, exposure controls, image artifacts, etc [19].”

1.3 Client Information and Motivation

Our client, Dr. Victor Haughton, is a neuroradiologist at the UW-Hospital with research interests in dynamic spine MR imaging. Dr. Haughton frequently uses MR imaging to practice medicine as well as conduct research at the hospital. His interests include functional MR and spectroscopy [4]. He is also studying cerebrospinal fluid through the foramen magnum in patients and cysts in the spinal cord and degenerative intervertebral disks [3]. Our client wishes to use an MR measurement, T₂ time, to assess the health of intervertebral disks. To do this, he first needs to establish a relationship between the two quantities. Our phantom helps establish this relationship by holding disk-mimicking hydrogels holding varying amounts of water (which correspond to differing degrees of disk health). Our client also wishes to assess the accuracy of the MR scanner in calibration. This can be done by placing solutions of known T₂ time in the scanner and comparing this known value to the T₂ measurement made by the MR scanner. Our phantom holds solutions of known T₂ time made by doping water with Gadolinium and testing in a NMR relaxometer. By knowing the accuracy of the scanner, our client will know the validity of tests performed and measurements made on the scanner. By knowing the relationship between T₂ value and intervertebral disk health, it would be possible to perform a MR scan and accurately assess a patient’s disk health with no invasive procedure.

1.4 Client and Design Requirements

The client would like a MR phantom that will ultimately aid in testing the accuracy of the scanner. One of the top priorities of the design is that it should contain Gadolinium (Gd) doped water samples with known T₂ values. The T₂ values should have a range of 50 to 100 ms in order to test the sensitivity of the scanner to T₂ values close in value. Another top priority of the phantom is that it should accommodate changes in two variables, the distance from the intervertebral disk to the coil and the volume of the patient. By making the phantom able to vary these two elements, the client will be able to examine just how these variables affect the measurements made by the MR scanner.

Another requirement, of equal priority to the aforementioned, is that the phantom will hold artificial disk samples comparable to that of lumbar intervertebral disks. The client stressed that the solutions must contain the same three components as the human body (water, collagen, and proteoglycans) but the percentage of the components can be varied. In addition, when preparing these artificial disks, at least one component must be kept constant so that the results can be compared to one another (experimental control). For example, a set of solutions can have different percentage of water but contain the same amount of collagen.

Two important safety concerns must be taken into consideration during the design of the phantom. First of all, no metallic materials will be allowed in the construction of phantom due to their interference with the strong magnetic field created by the MR scanner. Another concern is related to some substances commonly used in phantoms. Chemical compounds often used as the bulk solution within the phantom such as nickel chloride hexahydrate are considered hazardous waste products. To prevent any leakage to

the environment, these substances must be well enclosed. In addition, the phantom should include a safety-warning label for users.

This phantom will be used less than once per week to calibrate the MR scanner for lab experiments. It will be loaded onto the spine coil that is placed on the MR table. Therefore, it must sit securely onto a nearly flat surface.

2 Current Practices

Phantoms are used daily with MR scanners. Generally a commercially available phantom is sufficient to calibrate the machine for patient imaging. When conducting specific research projects, special phantom characteristics are generally needed. When a phantom with those characteristics isn't available, one can be designed to meet the needs of the researcher.

2.1 Commercial Phantoms

Several MR phantoms are currently available. Phantoms provided by the scanner manufacturer are generally used in the system set-up and accreditation programs to characterize performance [19]. Most phantoms hold water doped solutions that use ions to alter relaxation rates. Some major companies producing phantoms include GE, Supertech, and CIRS. These phantoms range in price from \$2000 to \$5000 [22,25].

During a visit to the Department of Radiology at the University of Wisconsin Hospital, the project's client, Dr. Victor Haughton, showed the team an example of a MR phantom [5]. A picture of this phantom, designed by Dielectric Corporation, Model #2131027-2, DQA Phantom, is shown in Figure 3.



Figure 3: A phantom commercially available for use with an MR imager [photo taken by the authors]

This design consists of a plastic chamber held together with plastic screws. The liquid component is water doped with nickel chloride hexahydrate ($\text{NiCl}_2 \cdot \text{H}_2\text{O}$) to adjust the relaxation time of the solution to correspond to the biological relaxation times in vivo. Since nickel chloride hexahydrate is a hazardous waste material, the phantom has been clearly labeled and securely sealed. This particular phantom is designed to fit into the

grooves of the table, because it is used without a pad or coil placed underneath it. The overall weight is 11 lbs; therefore, it can be easily lifted and placed by the scanner operator.

2.2 Phantoms for Research Purposes

Most phantoms designed and developed solely for research studies differ considerably from the commercially available phantoms. Several of these phantoms use tissue-mimicking (TM) materials rather than doped water solutions. These phantoms are designed to yield very accurate and stable measurements.

TM materials are commonly used in MR phantoms to accurately represent soft tissues and provide T_1 , T_2 , and T_1/T_2 values that are stable over time [21]. Soft tissues typically have T_2 values ranging from 40-200 ms, T_1 values from 200-1200 ms, and T_1/T_2 values from 4-10. T_1 and T_2 values are also depend on temperature. If the MR scanner and phantom temperature are known, these values can be determined accurately and TM materials can be made to represent tissue with various T_1 , T_2 and T_1/T_2 values.

3 Design from Spring 2005

Based on the background research, three initial design ideas were brainstormed in the spring of 2005. Within the design alternatives, the method of creating the doped water samples was kept constant. Doped water samples, enclosed in small vials and having T_2 values ranging between 50 and 100 ms are needed for Dr. Haughton’s research. There will be a very small T_2 difference (e.g. 50 and 52 ms) between some samples in order to test the sensitivity of the scanner to this slight variation.

A branched pathway approach was utilized when evaluating the design alternatives. Two design constructions (or physical devices) were developed and then within each of these constructions, two different approaches for disks or TM materials were developed (see Figure 4).

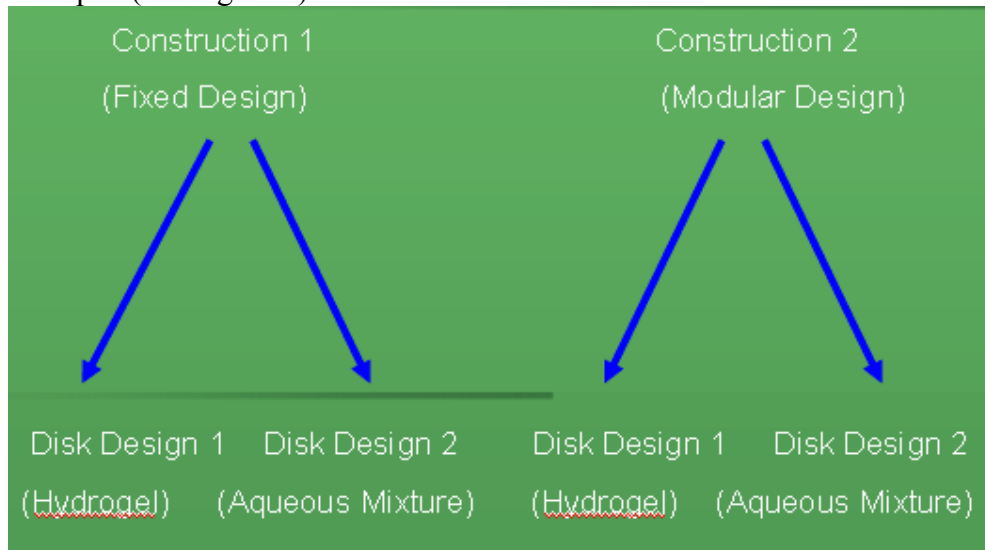


Figure 4: The four different design combinations possible combining physical construction and artificial disks [diagram developed by the authors]

3.1 Fixed vs Modular Construction

Construction design 1 is a fixed design for an MR phantom. This design alternative consists of a 4 liter beaker with stationary disk samples set within it at different levels. This design was developed because it would reduce excessive plastic, air, and water interfaces that can create artifacts in the image. Constructing this design would be fairly simple and would involve filling the beaker full with agar/gel solution and having glass spheres filled with the artificial disks or doped water samples randomly arranged in the beaker such that they are in a single plane (see Figure 5). There are some disadvantages to this construction including the fixed size of the phantom which limits experimental variation and physical size of the phantom being too large.

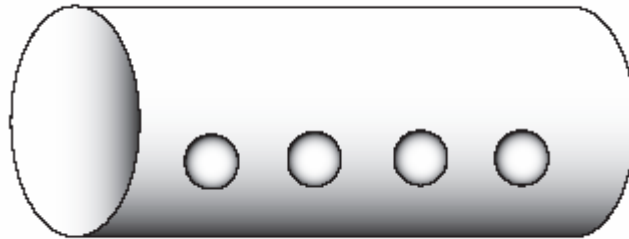


Figure 5: Fixed construction design [image developed by the authors]

Construction design 2 is a modular design for an MR phantom. The modular design allows for the phantom to have individual samples, whether they are doped water or artificial disks, be removable and interchangeable. The importance of this design being modular is that it allows for more variation of the samples. With this option, the phantom can physically be smaller in size and allow for more variety in experimentation (see Figure 6). There are a variety of drawbacks to this construction alternative including complex construction and additional material interfaces.

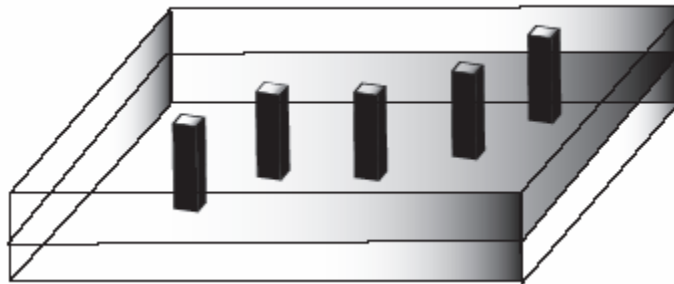


Figure 6: Modular construction design [image developed by the authors]

3.2 Hydrogels vs Aqueous disk samples

The first alternative for creating a TM substance was to use hydrogels. Hydrogels are water-swollen polymeric networks comprised of chemical or physical cross-links (Figure 7). The physical cross-links may be crystallites, entanglements, or weak associations (e.g. hydrogen bonds or van der Waals interactions). In the late 1950's, hydrogels were found to have an importance in biomedical applications with the development of poly(2-hydroxyethyl methacrylate) (PHEMA) gels as a soft contact lens

material. Today, hydrogels are used in numerous biomedical applications including ophthalmological devices, biosensors, biomembranes, and others [17].

The hydrogels that would be involved in this design as TM substances would be composed of poly(ethylene glycol) or PEG. The hydrogels would be polymerized in a container that would be sealed off from the phantom with a range of water, proteoglycans, and collagen to mimic an intervertebral disk. The benefits of utilizing hydrogels include a known composition of water and other components and few motion artifacts due to the high viscosity of hydrogels. The disadvantages include time consuming hydrogel development and the possibly complex interaction between the polymer and T2 value.



Figure 7: Example of a hydrogel [photo taken by authors]

Another possible disk design is an aqueous mixture of substances found in human intervertebral disks, water, collagen, and proteoglycans. The artificial disks will be carefully prepared with varying percentages of the three components listed above. Making the aqueous mixture disks will be simple and inexpensive since it is just a combination of three ingredients into a vial or cuvet. However, since the mixture is aqueous, some substances will be able to move freely which might cause artifacts to be present on the MR images due to liquid movement. Another possible consequence of the disks being aqueous is that the mixture may separate and no longer mimic the disk well.

3.3 Decision Matrices

The construction design matrix (see Table 1) elements were scored on a scale of one to five, with a rating of five being the best and one being the worst. All elements were weighted equally. As is seen in the construction design matrix, the fixed construction had the higher score, making it a more reasonable design choice.

Table 1: Construction design alternatives [by the authors]

	Construction 1: Fixed	Construction 2: Modular
Accuracy	5	3
Variety of Measurements	3	5
Construction	4	2
Cost	5	3
Total	17	13

The disk design alternatives (see Table 2) were also rated on the same scale of one to five with five being the best. Again, all elements were weighted equally. The hydrogel disk design scored higher making it the more reasonable disk design alternative.

Table 2: Disk design alternatives [by the authors]

	Disk Design 1: Hydrogels	Disk Design 2: Aqueous
Cost	3	4
TM Capability	4	3
Stability	5	3
Construction	4	4
Total	16	14

3.4 Spring 2005 Final Design

The combination of a fixed construction and the aqueous disk samples was chosen as the design we developed during the spring of 2006. This construction design was chosen mainly because of the ease of construction and the increased accuracy. The disk design was chosen due to the time constraints of the semester; use of hydrogels involved extensive testing which time did not permit.

Putting together these two elements led to the development of a working prototype. The final design was a four-tier stair structure with 6 holes drilled on each tier. Each of the 24 holes could hold a vial containing Gd-doped water or disk mimicking solutions. With this design, the samples could be placed at varying distances to the MR coil. In addition, up to 24 samples could be tested at once during an MR scan providing much experimental variability.

Since the phantom is used in an MR scanner, no ferrous metals were used in the construction of the prototype. The stairs were made with rectangular pieces of HDPE, which is durable and easy to cut. After holes were drilled on each level, the HDPE pieces were combined together using dowels and epoxy to make the structure. The structure is constructed to be supported within the phantom. The phantom lid is lined with rubber in order to obtain a better seal. Figure 8 shows a diagram of the stair structure and Figure 9 provides a picture of the finished prototype.

Figure 8: Stair Structure [image developed by the authors]



Figure 9: Photo of first prototype [photo taken by the authors]



4 Testing Results from Spring 2005

Two sets of testing were done on the MR scanner: once to test which tubes would provide the most accuracy by eliminating artifacts and an additional time to determine the accuracy of the prototype. The results from testing showed which areas of the design needed additional improvement.

4.1 Testing of Gadolinium Samples

The Gd-doped water preparation was initially based on the equation:

$$1/T_2(\text{sample}) = 1/T_2(\text{water}) + R_2 * [Gd]$$

This became troublesome because the decay rate of Gd, R_2 , is unknown. Consequently, the samples were prepared and tested with an NMR relaxometer. Based on the results of two testing sessions on the relaxometer, data was fit to a graph and an equation was found (see Figure 10). From this equation, concentrations of Gd that corresponded to the desired T_2 values for the phantom were calculated.

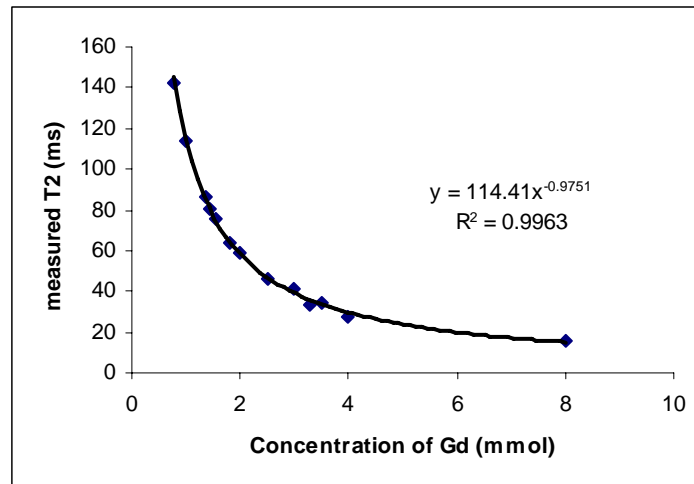


Figure 10: Graph of Relaxometer Data and Equation Relating Gd Concentration and T_2 Values [by the authors]

4.2 Disk Sample Testing

Aqueous solutions of collagen and proteoglycans were made with different composition to mimic intervertebral disks. The goal was to change one of the three

variables while keeping the other two constant. Based on a paper by Wiedenbaum that discusses the composition of healthy and degenerative disks, reasonable disk compositions were determined [25]. These combinations can be seen in Table 3.

Table 3: Compositions for Aqueous Disk Samples [by the authors]

	Keeping % Water Content Constant			Keeping % Collagen Content Constant			Keeping % Proteoglycans Content Constant		
	Percent Composition*								
Water	65	65	65	60	65	70	60	65	70
Collagen	65	70	75	70	70	70	65	70	75
Proteoglycans	10	15	20	10	15	20	15	15	15

* Percent composition of listed as a percentage of total sample for water and percentage of dry weight for collagen and the proteoglycans.

Due to cost limitations, the collagen and proteoglycans used were from pill supplements that were found at local drugstores. Due to the impure composition of these pills, it was impossible to make samples with the desired compositions.

Once the samples were made, the collagen and proteoglycans repeatedly precipitated out of solution despite extensive mixing and heating of the samples to aid the substances in dissolving. This problem showed that the aqueous disk samples were not correctly mimicking intervertebral disks. In intervertebral disks the binding of collagen and proteoglycans to water keep the substance uniform. The binding occurring in the aqueous samples was different than the binding in the intervertebral disks. Due to this setback, the data that was collected from testing the disks in the MR scanner during the prototype testing was determined to be inaccurate, and therefore, insignificant.

4.3 Testing Results of Tubes and Prototype

A standard testing and analysis procedure was established to obtain meaningful data. Two scans were run on the MR scanner during the testing procedure: a localizer, to verify that the phantom was correctly placed in the field of view, and QID, a fast spin echo sequence that is modified to make T_2 measurements. Data processing was completed with a Matlab program developed by John Perry that was used to obtain an average T_2 value and a standard deviation for each sample [10].

Some preliminary testing was done on three types of tubes in order to conclude which tube would provide the most accurate results. The three tubes that were tested are 2 ml conical tubes, 5 ml Nalgene plastic tubes, and 8 ml glass vials. During tube testing, three Gd-doped water samples with known T_2 values were placed in three different tube types. The results from the tube testing and the actual T_2 values measured by the NMR relaxometer can be seen in Tables 4 and 5 respectively. Based on the data collected, it was determined that the glass vials provided the most accurate results.

Table 4: Tube Testing Results [by the authors]

Results from MR Data Collection											
Concentration											
1 mmol						3 mmol					
2ml		Glass		Nalgene		2ml		Glass		Nalgene	
Ave. T_2 (ms)	Std. Dev.	Ave. T_2 (ms)	Std. Dev.	Ave. T_2 (ms)	Std. Dev.	Ave. T_2 (ms)	Std. Dev.	Ave. T_2 (ms)	Std. Dev.	Ave. T_2 (ms)	Std. Dev.
205.55	19.81	191	21.85	216.01	22.41	71.98	7.03	67.13	4.09	82.15	8.13

Table 5: Actual T₂ values from Relaxometer Testing [by the authors]

Actual Values from Relaxometer Testing	
Concentration	T2 value (ms)
1 mmol	113.62
3 mmol	41.66

When testing the prototype setup, six Gd-doped water samples with known T₂ values (50, 75, 80, 81, 83, and 85 milliseconds) and three disk samples (all consisting of 15% dry weight proteoglycans, 70% dry weight collagen, varying amounts of 60, 65, 70% water) were placed in the phantom. Two QID scans were run, one with the samples far away from the coil (on the top tier of the stair structure) and another with the samples close to the coil (on the bottom tier of the stair structure). The results showed variations between the calculated and measured T₂ values as well as differences in measured T₂ as the distance to the coil varied. Table 6 shows results from the prototype testing.

Table 6: Results from the Prototype Testing [by the authors]

Prototype Testing Data Summary - Gadolinium Samples						
Scan 1: Vials Far Away from the Coil						
Theoretical T2 (ms)	50	75	80	81	83	85
Average T2 (ms)	57.3	68.9	71.3	74.5	73	91.6
Difference (Theoretical - Measured)	-7.3	6.1	8.7	6.5	10	-6.6
Scan 2: Vials Close to the Coil						
Theoretical T2 (ms)	50	75	80	81	83	85
Average T2 (ms)	58.3	80.2	83.8	86	78	94.2
Difference (Theoretical - Measured)	-8.3	-5.2	-3.8	-5	5	-9.2
Overall Difference (Scan 1 - Scan 2)	-1	-11.3	-12.5	-11.5	-5	-2.6

The theoretical and measured values are expected to differ by 7% due to the difference in frequency of 60 and 64 MHz between the relaxometer and the 1.5T MR scanner, respectively [24]. Some of the variation in the prototype results is due to the varying distance of the samples from the center of the magnet. The magnetic field strength decreases as the distance from the center of the magnet increases. Additional variation may be due to non-uniform mixing of samples, artifacts caused by the water-glass interface, or inaccuracies in the theoretical values.

5 Client Feedback

Based on the testing of the Spring 2005 design, many elements were in need of improvement including the material it is constructed of, a redesign of the phantom container, creating replacing the aqueous disk samples, and additional testing in the MR scanner.

5.1 Improvements, Enhancements, and Changes

After examining the prototype from the spring semester, our client provided important feedback on improvements for the fall semester. First, the client commented that the quality the MR scans might have been influenced by the material the phantom was constructed of (HDPE). The client also commented that the physical arrangement of the disk samples within the ladder structure was too far apart. For this semester, a different material should be used to minimize interference with the signals during MR scan and the samples should be placed closer together such that they experience the same magnetic field. The disk samples also need great improvement. Once the samples were made, the collagen and proteoglycans repeatedly precipitated out of solution despite extensive mixing and heating of the samples to aid the substances in dissolving. Because of this, the design team looked towards hydrogels to more accurately maintain a homogeneous mixture. Lastly, once these components are improved upon the phantom needs extensive testing in the MR scanner.

6 Design for Fall 2005

Based on the Spring 2005 phantom testing and improvements necessary, we divided the Fall 2005 phantom into three main components: the phantom container, a set of gadolinium solutions, and a set of artificial disk samples. The phantom container provides the placement and loading for the gadolinium and/or artificial disk samples. The phantom will be made of a nonferrous material and hold water for loading effect. As discussed in the project motivation, the phantom's contents will be used to conduct research and assess MR scanner accuracy. During an experiment, the phantom will hold its gadolinium and/or disk samples (of varying degrees of health) will be scanned in an MR imager such that the design specifications discussed earlier are met. The MR scans on the gadolinium or disk samples can then be analyzed using a MatLab program to obtain T2 values. Prior to being placed in the phantom, the gadolinium samples will be tested in a relaxometer to obtain a correlation between the concentration of gadolinium and T2 values.

6.1 Gadolinium samples

Similar to the Spring 2005 semester, gadolinium was used to create doped water samples with specific known T2 values. These samples are held in the glass vials and are used to assess the accuracy of the MR scanner. Using the relationship found during Spring 2005, additional gadolinium samples were made and the relationship between gadolinium concentration and T2 value was improved upon during further testing (see section 7.1). Table 7 shows the gadolinium samples made. The solutions can then be placed within the phantom when testing tissue mimicking samples for sample comparison and verification of the accuracy of the T2 measurements.

Table 7: Gadolinium samples made. T2 is expected theoretical T2 value [created by authors]

[Gd]	2.315408	1.539579	1.442756	1.42483	1.390278	1.357358	1.152547
T2 (ms)	50	75	80	81	83	85	100

6.2 Hydrogel disk samples

Due to the fact the aqueous artificial disk samples separated out of a homogeneous mixture, the design team re-investigated the feasibility of using hydrogels. Although hydrogels still would not completely represent intervertebral disks accurately, they would provide a stable matrix to hold the components in place and in a homogeneous state; they would also allow some binding properties of proteoglycans and collagen.

During Fall 2005, five different types of hydrogels were researched to determine which would be the best to use according to client specifications. The five types of gels were as follows: poly-ethylene glycol (PEG), acrylamide, agarose, alginate, and gelatin. PEG turned out to be too time consuming and expensive to create in a bulk manner. Agarose gels were difficult to create greater than 2 weight percent. A reliable and reproducible procedure for creating alginate gels consistent with client specifications could not be found. After further research, only acrylamide and gelatin gels were created. Both showed promising results, but the gelatin was easier to manipulate weight percents. The gelatin gels were created by mixing gelatin and distilled water, heating it until it dissolves, and then cooling in the refrigerator. Acrylamide gels were created using a stock solution of 30% acrylamide and by using the following formula (and scaling it) (Table 8):

Table 8: Formula for Creating Acrylamide Gels [by the authors]

Ingredients	Amount for 100mL	Scaled down to 10ml (20%)
Acrylamide (stock)	$3.3(x\%) = A\text{mL}$	6mL
1.5 Tris-HCl (pH 8.8) ¹	25mL	2.5mL
10% SDS ^{2,3}	1.0mL	1.0mL
Distilled DI H ₂ O	$(73.5 - A)\text{mL}$	1.39mL
TEMED ²	50 μ L	50 μ L
10% APS ²	500 μ L	500 μ L

¹TBS 1x may be used as a substitute. ²Compound does not scale down. ³SDS does not need to be used unless working of electrophoresis projects.

Gelatin gels were made a 10, 15, 20, 25, and 30 weight percent (g/100mL). Due to the acrylamide stock solution concentration of 30%, only samples of 10, 15, 20, 22.2% were created.

6.3 Phantom Construction

In designing our phantom, first considered was the optimal arrangement and orientation of the samples. In order to have the magnetic field within each sample be as consistent as possible, the samples were aligned with the direction of the bore. By placing them all parallel to each other, scan analysis is easier, requiring only one axial slice from the scan to be analyzed.

The samples are arranged close enough together to minimize the difference in magnetic field between samples; but hopefully far enough for sample T2 values to not be

affected by artifact of material interfaces. The configuration of samples is also symmetric to easily observe the effect of the differences in magnetic field and distance from the coil on T2 values. This can be done by rotating the phantom 90-180 degrees.

We initially hoped to create our phantom out of a solid plastic material that mimicked the T2 and image properties of water in MRI scans. In attempts to find a material like this, we contacted Standard Imaging, Inc. which develops these types of plastic materials for CT machines in hopes that some characteristics would be similar to these techniques. But these samples produced no MR signal as all solid plastics. Therefore, we reverted to a hollow design that we could fill with water to create the necessary image loading around our samples.

With this established we attempted to compact the design for storage and ease of use while still having at least a 2 liter of water storage capacity for sufficient water loading. We set the dimensions of our design to hold approximately 2.5 liters. For durability and water tightness, we decided polymer molding our phantom would be the optimal. In order to make our phantom translucent, we choose to use acrylic, a clear form of ABS or polycarbonate. Figure 11 depicts the computer modeling of the phantom.

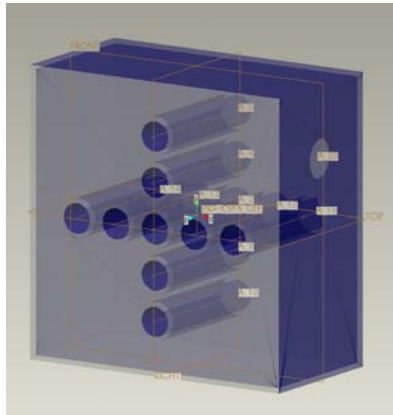


Figure 11: Computer aided modeling of the phantom container [created by authors]

7 Progress and Testing in Fall 2005

In order to assess the validity of our phantom design, each of the three elements discussed above must be tested separately prior to their combination. The gadolinium sample testing is much like that of Spring 2005 while the artificial disk testing is very different. Testing of the efficacy of the phantom's physical design and the phantom as a completed unit will be conducted once the fabrication is completed.

7.1 Gadolinium sample testing

To create Gadolinium samples to be used in the phantom as a calibration tool, we created several Gd solutions of varying concentration and measured their T2 value using a relaxometer in the lab of Prof. Ernie Madsen. Using this data we obtained a very strong relationship of Gd concentration to measured T2 value (see Figure 12). We then used this relationship to create several solutions that produced T2 values within the expected range of human intervertebral discs. The solutions can then be placed within the phantom when testing tissue mimicking samples for sample comparison and verification of the accuracy of the T2 measurements.

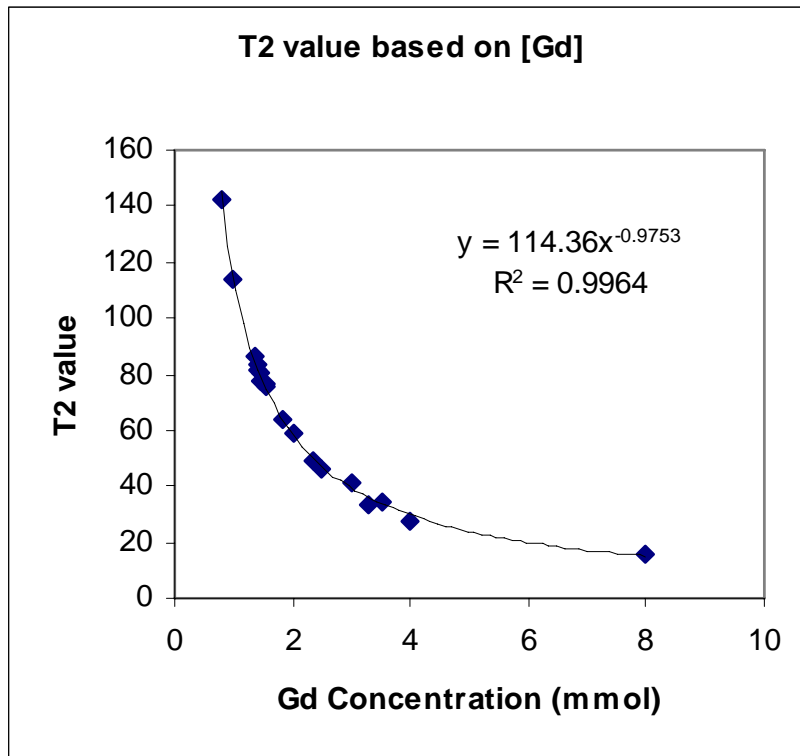


Figure 12: Relationship between gadolinium concentration and T2 value after another testing iteration [created by the authors]

7.2 Hydrogel Sample Testing

To determine which gel produced T_2 values closer to the desired values of intervertebral disks (50-100ms) as well as which gel would be used when adding in proteoclygans and collagen, the gelatin and acrylamide gels were scanned in the MR machine. The same testing procedure discussed in section 4.3 was used in the testing of the hydrogel samples. The first scan that was run produced unreliable results and the image appeared all white, correlating to a T_2 value of zero. This was most likely due to an insufficient amount of water surrounding the samples during the scan. The scan was repeated and fortunately produced useful results (see Figure 13).

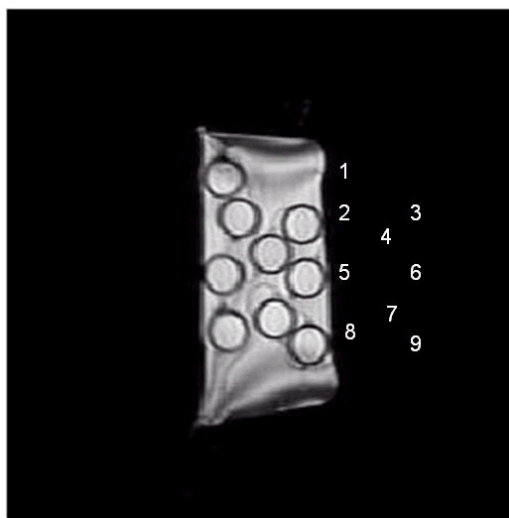


Figure 13: MR Scan Image of Hydrogel samples. See Table 9 for identification of each numbered hydrogel [created by authors]

The results from the scan were then analyzed and it was concluded that the samples produced T_2 values in the range of 150ms to 300ms which is close to the desired T_2 values. The data gathered from the MR scan is compiled in Table 9.

Table 9: MR Data for hydrogel samples [created by authors]

Type of Gel	Number	Gel Concentration (%)	T2 value	SD
Gelatin	7	10	262.3	6
	9	15	209	24.4
	6	20	207.2	6.3
	3	25	182.2	5.2
	4	30	169	3.7
Acrylamide	8	22.5	241.6	24.9
	5	20	276.8	8.1
	2	15	334.7	26.4
	1	10	256.2	43.7

Unfortunately, any samples with a standard deviation above ± 10 should be discounted due to the large artifacts in the image corrupting the results. Even with this artifact, it was determined that the gelatin samples had a closer T_2 value to the desired value and hence should be used for further work. These gelatin gels will be scanned again to determine a more precise T_2 value. In the meantime, two gelatin/proteoglycan (or GAG) samples were prepared by adding chondroitin sulfate to 20 and 25 weight percent gels. The maximum solubility of chondroitin sulfate is 100mg/ml or 10%. The concentration used for the two samples created was 5%. Biologically safe temperatures (a concern for proteoglycans) fall below 37 degrees Celsius. When creating gelatin, it must be heated a considerable amount. Chondroitin sulfate was then directly added to the gel once the temperature cooled below 37 degrees. The gels were then stored in the refrigerator.

Although time was not permitting, the previous gelatin samples and the new gelatin/GAG samples will be tested in the MR scanner and analyzed to correlate T_2 values. Once this value is determined and tested to be accurate and reliable, collagen can be added to the gels. In the end, the disk mimicking sample should be fairly representative of an intervertebral disk and its T_2 value. Once this sample is completed it can be tested against human intervertebral disks removed from cadavers to test the efficacy of the design.

7.3 Phantom Construction

We pursued the construction of our prototype with several commercial plastic molding companies and the UW Mechanical Engineering Lab. We initially hoped this could be done with a rapid prototyping machine but because of its hollow structure and necessity to be water tight, this is not possible. Currently, we are working with and placing an order with Todd Kile and the UW Mechanical Engineering Lab to have our phantom made by milling out the cavity of our phantom from a solid piece of plastic and then gluing on a sixth side to complete the container. Having our phantom made by more an experienced hand than ourselves will better ensure the quality of the water tight seals and phantom durability.

8 Future Work/Potential Problems

The design group will continue working on this project for an additional semester. The goal of continuing this project would be to have a fully functioning and accurate phantom and components constructed by May of 2006.

8.1 Phantom Construction

To ensure the accuracy and usefulness of the phantom, the fabrication is going to be done by an outside source. Currently, the process of contacting a company and discussing the design with a company that is able to fabricate it, is both challenging and time consuming. Also, the cost for such a phantom must be in a range approved by the client which limits the companies and resources for use. The design of the phantom is difficult to create and therefore by utilizing an outside source, it will eliminate more potential errors.

8.2 Additional Testing

More testing is needed for the hydrogel samples. As mentioned earlier, testing is needed for the gelatin samples and the gelatin/GAG samples. Once this is completed and analyzed collagen may be added to the gels and then tested to correlate T_2 values to data. Also, the possibility of using intervertebral disks from cadavers to test the efficacy of the design could occur. However, a consistent problem is artifact in the scans. This phenomenon must be minimized in order to produce useful data. This brings up another concern of scheduling scan time within an already busy hospital schedule.

Further, testing must be done on the completed phantom, with and without samples. This would ensure that the phantom is behaving accurately and that there is no considerable artifact in the images.

8.3 Other Future Work/Potential Problems

Once these components are secured, the possibility of applying for a patent lays ahead. The necessary procedures involved in such a task await the completion of the design. Also, the importance of a name for the design is a concern for the client who is applying this design in other studies.

8.4 Future Work Summarized

Additional work can be done on almost every aspect of the design. Additional work is necessary on the hydrogel samples to ensure accurate results. Fabrication of the phantom is needed. Further testing on the MR scanner will aid monitoring progress, identifying problems, and validating the accuracy of the design.

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