UNIVERSITY OF WISCONSIN-MADISON
DEPARTMENT OF BIOMEDICAL ENGINEERING
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Open Source Rat Phantom

Mid-Semester Report

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Abstract

Once a medical scanning device is developed it becomes necessary to test the device to ensure proper function and workability. This is where phantoms come in. Phantoms can be placed in the scanner to calibrate the machine and check whether the imaging equipment is producing the scans with the correct accuracy and reliability. These phantoms can also be reconfigured to test for radiation distribution as well as contain simulated tumor inserts. Our client is producing an open source combined radiation therapy (RT), positron emission tomography (PET), and computed tomography (CT) scanner. Our device will be used to calibrate the machine and test its imaging ability. Our final design contains a combination of cuts, being one vertical and one horizontal, allowing for testing in all of the necessary areas of the device.

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Problem Statement

The client for the Rat Phantom project is currently developing an imaging and therapy system for small animals that integrates micro CT, micro PET, and micro RT scanning systems into one device. His project is open source, making all designs and specifications readily accessible on the internet so it can easily be replicated at low cost. The CT/PET/RT system will be used to treat and image rats, and thus requires a rat phantom for testing and calibration of the system. Specifically, the rat phantom will be used for the characterization of the micro collimator of the scanning device. The phantom will be based on the full CT scan of an actual rat, and is required to contain different density materials for various tissue types. Additionally, the rat phantom will contain inserts for radiation detectors and tumors to simulate the actual tests that will be performed on real rat specimens.

Background

Phantoms are used in the medical industry with the main purpose of testing imaging equipment such as CT scanners and MRI machines. They are also used in an educational setting to teach interventional imaging guided procedures to students and doctors. Finally, phantoms are frequently used by maintenance crews for servicing scanning equipment.

In the testing of an imaging device, a phantom must scan similarly to how the real specimen would. Thus, phantoms are constructed of materials that contain different densities to mimic various bodily tissues such as the muscle tissue, lungs, and organs. It is crucial that phantoms behave similarly to their real-life specimen, and therefore they are designed with careful attention to their anatomical correctness.[1]

There are many different types of phantoms to simulate proper scanning for animals and humans. While these phantoms are designed to be anatomically equivalent to their corresponding specimens, they often do not look anatomically similar to the animal or human they simulate. In fact, many phantoms are just objects that contain places for testing inserts that are utilized during the scanning process. Although they may not look like their designated specimen, they scan with extreme precision to mirror the animal or human they are portraying.[2]

Motivation

The open source rat phantom project is part of Thomas Mackie's larger venture of designing and producing a combined PET/RT/CT scanner for the imagining and treatment of small animals. Thomas Mackie is the chairman, co-founder, and co-inventor of TomoTherapy Inc. as well as a UW-Madison professor in medical physics. His focus is the construction of medical devices that can be used from research labs to clinical use, with the goal of improving current technologies.[3] Consequently, the scanner requires a rat phantom that can test, calibrate, and service the system so that it can be as successful as possible. Currently, one can purchase rat or mouse phantoms, like those shown in figure 1 from JRT Associates, for a significant amount of money. These types of phantoms, while durable and accurate, cannot be used in a scanner such as that being developed by Thomas Mackie because they do not contain slots for thermoluminescent dosimeters (TLD), organ, and tumor inserts. Other companies produce sphere-shaped and block phantoms that contain such

Figure 1

inserts, but don't look like a rat. Thus, there is not presently another product on the market that both contains the necessary inserts and anatomically looks like a rat as this rat phantom will.

Since the rat phantom is to be designed as an open source project, it must be completed with minimal expenses so that it can be easily replicated for a reasonable price. This means that materials for the different tissue densities and the TLD inserts must be low-cost and easily obtainable for other locations so that the rat phantom can be produced worldwide.

Design Constraints

Our project was created with a specific goal of creating a product that could be used with a custom CT/RT/PET scanner that is currently being developed as an open source project. The scanner itself is not near completion and this caused some complications in creating design constraints. It's a little trickier to design a product for use in a product whose design isn't finalized. However, our contact Surendra Prajapati, did a good job providing us with our needed specifications. The scanner itself will have a 12 cm diameter chamber; this obviously would be our size limiting factor, certainly large enough to fit the mold of a rat. The maximum weight of the phantom was set at 2 kilograms. We were instructed that the phantom must be anatomically correct when scanned using CT or PET imaging, meaning that it must have an accurate skeletal structure as well as correct tissue densities corresponding to the muscle, organs, etc.

Inside the phantom, the client needed to place several TLD sensors. These sensors would be used to measure radiation levels and the effectiveness and accuracy of the radiation therapy. It is important that the radioactivity in these sensors does not contaminate the rest of the body of the phantom. The phantom must also allow for placements of organs. The client would like the option of switching between standard organs and those with a tumor.

It is very important that the phantom has a long shelf life. The device will be used many times while testing and calibrating the scanner and must be able to withstand this use. At the same time it is also very important that the phantom produces predictable results which do not change over time. Like all projects, the cost of material and design also needs to be considered.

Design Alternatives

Design 1. Solid Design

Our initial thoughts for a design were centered on the principal of a solid phantom body, as shown in figure 2. This body would be cast modeled around an actual rat skeletal structure which we purchased online. We would create the mold using a 3D printer allowing for an accurate representation of a rat exterior. The actual skeleton allows us to achieve correct density, size, and placement of all the necessary bones. Gammex brand material would be used for the internal organs, allowing us to control their densities and shapes. Muscle tissue could be created from an epoxy mix, allowing us to vary the density in accordance to what was required.

After the entire phantom was molded, slots for the TLD detectors would have to be added. We would cut these slots out from the exterior allowing TLD sensors to be dropped into the phantom if needed. The solid design does not allow for interchangeable organs unless slots could be cut deep into the interior of the phantom. However, the

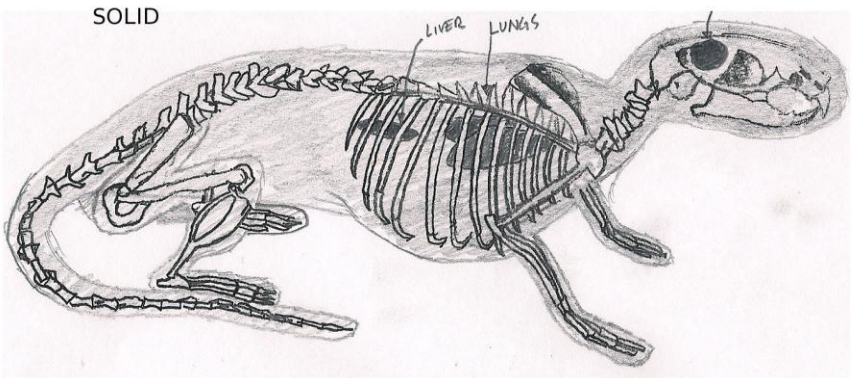


Figure 2

scanning benefits of not having any internal cuts are worth considering.

This design would be completely solid considering the one piece design and should have no problem withstanding large amounts of use. The TLD sensors would be wrapped in a plastic that would prevent radiation from contaminating the rest of the phantom. The material used to make this phantom would all dry as solids, so loss of definition or warping should not occur over time. The cost of this model would also be within our budget as it would have minimal different materials and fewer chances for erosion of the materials making up the phantom body.

Design 2. Vertical Cut

Our next design was centered on the idea of easily removable TLD sensors and organs. This would allow for regular organs to be swapped for tumor laden organs, which was a design request of our client. To accomplish this ease of removal we would create a phantom that consisted of two parts, as shown in figure 3 on the following page. The phantom would separate vertically in the middle allowing for internal organs and TLDs to be accessed. These organs and TLDs would be housed within a softer material than the outer skin. Again the TLDs would be wrapped in a plastic that would prevent the exposure of radiation to the surrounding phantom body.

Like the previous design we would use a mold to cast the exterior around an actual rat skeleton. After this had been completed we would vertically cut the rat phantom in half directly behind the rib cage. This would be the best location for this cut as it would only cross through one bone structure, the spine, and would allow access to both the lower and upper chest cavities. After the cut had been performed these cavities would be hollowed out. Muscle tissue could then

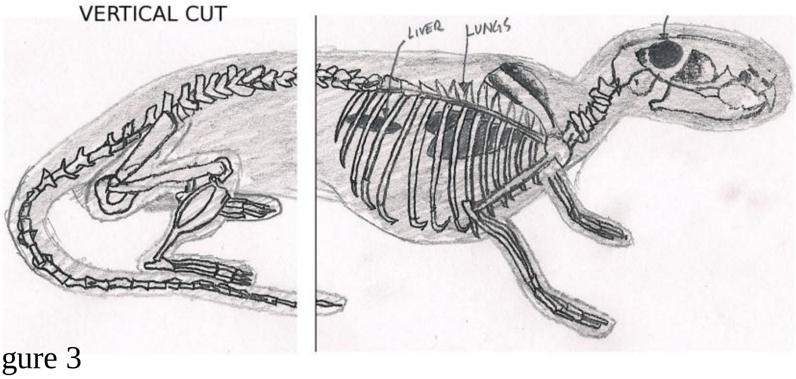


Figure 3

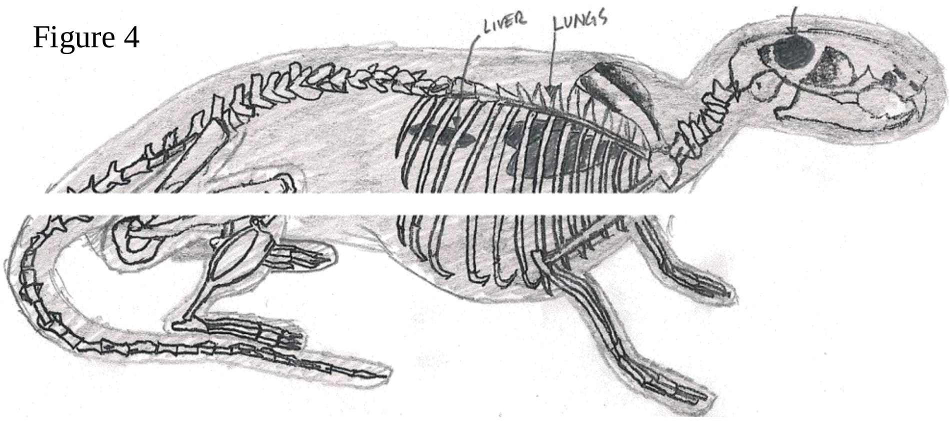
be molded with ballistics gel. The use of ballistics gel would create a more consistent and accurate representation of the muscle tissue than the previous use of mixed epoxy. We would than create pockets within this ballistics gel to mount TLDs and organs in their anatomically correct locations.

This design would not be as solid physically as the first design. However, it would still have a hard external shell which would protect the phantom from warping shape or having its interior weaker materials being disturbed. The vertical cut creates some problems with imaging as any air in the gap between the two pieces of the phantom creates imaging anomalies. To solve this problem we would have to create some sort of locking mechanism that holds the pieces together. The ballistic gel would be slightly more expensive than the epoxy used in the past design, but the increased accuracy would be worth the cost. Our current budget would have no problems with this design.

Design 3. Horizontal Cut

The third design of a horizontal cut, shown in figure 4, is somewhat of a solution to the inaccessibility of organs in the solid phantom. Once we get our skeleton, we would find a real rat of similar size, and scan it in the MicroCT scanner at the Wisconsin Institute for

Figure 4



Medical Research (WIMR) at UW-Hospital. Then, we would scale the scanned rat up to the size of our rat skeleton and leave some extra room for muscle tissue, fat, and skin. We would use this image and manipulate it with a computer program at the WID to create a drop cast for it. This drop cast would be sent to the rapid prototype machine to create a mold for our rat skeleton. The rat skeleton would be placed in the drop cast along with the selected organs: lung, liver, and brain. Instead using an epoxy mix, we would use ballistics gel to mimic the muscle tissue. Ballistics gel has similar density to that of animal muscle tissue, which makes the phantom more anatomically accurate. After the ballistics gel hardens and the phantom is a solid, we would make a horizontal cut longitudinally along the length of the body. This allows us to access the lungs and liver more easily than the solid design or vertical cut designs. Also, since the cut is horizontal, gravity acts on the two halves of the phantom, and there would be minimal air gaps in the phantom, increasing the image accuracy.

Design 4. Combination Cuts

The combo cut design, shown in figure 5, uses elements from both the horizontal cut and the vertical cut designs. The phantom will still be made out of ballistics gel, but will now contain a vertical cut behind the ribs about halfway down the rat in addition to a horizontal cut from the anterior part of the phantom to the middle where the two cuts meet. These cuts out the anterior-superior part of the phantom allow greatest organ accessibility to put the TLD’s, organs, and tumors. Additionally, there will be minimal air gaps in this design because this sections fit together with the other part of the phantom via gravity for the head portion that is horizontally cut, and via a puzzle piece fitting for the posterior section due to the vertical cut. The ballistics gel has a high friction coefficients and will stick together to form minimal air gaps.

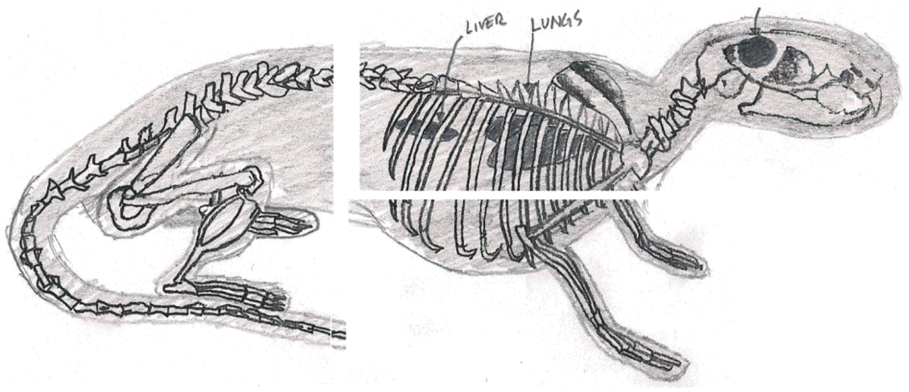


Figure 5

Design Matrix

In order to pick a specific design to continue our project with, a design matrix was created. The design matrix was split into 5 different categories: cost, anatomical accuracy, shelf-life, organ accessibility, and image accuracy. Figure 6 illustrates the relative weighting of points for each of the individual categories. Figure 7, on the other hand, shows the specific breakdown of points for each category and each design, allowing us to determine which design would be most effective to continue our project with.

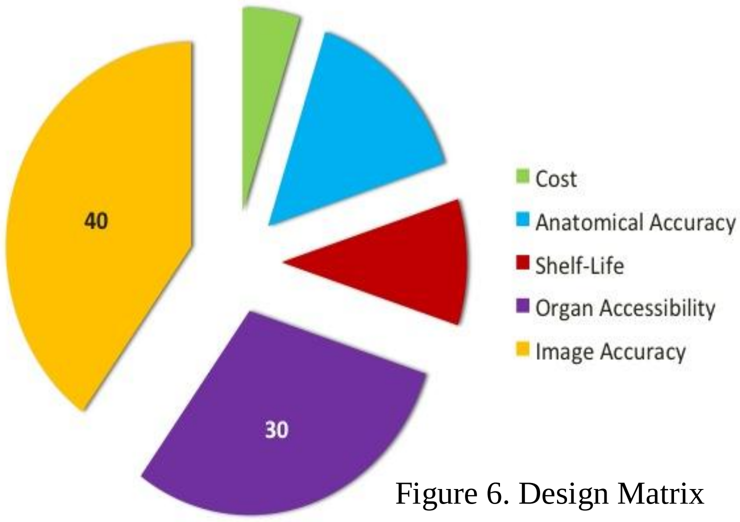


Figure 6. Design Matrix

Category	**Total Points**	**Design 1: Solid**	**Design 2: Vertical Cut**	**Design 3: Horizontal Cut**	**Design 4: Combo Cuts**
Cost	5	2	4	4	4
Anatomical Accuracy	15	12	12	12	12
Shelf-Life	10	10	6	6	6
Organ Accessibility	30	7	21	23	30
Image Accuracy	40	40	24	33	30
	100	71	67	78	**82**

Figure 7

Cost, the first category, received minimal weighted points with only 5% of the total. Cost is a necessary part of the design matrix as we were to keep the project budget to a minimum. However, all of the designs will be very similar in cost and therefore not a major deciding factor in the design choice. The solid design received the lowest ranking for cost, 2, as the materials necessary to make the solid device will be slightly more expensive than the gels and other materials used to produce the other three devices. The horizontal, vertical and combination cut designs will all use exactly the same materials and vary only in the method of separating the pieces of the design. Therefore, the rest of the designs received a ranking of 4.

Anatomical accuracy was the next variable we reviewed with a total of 15% of the total points. Anatomical accuracy of the design is a necessary component for the design matrix as it is directly tied to the quality and usefulness of the final design. If the design is not anatomically correct the images and testing of the device will not be as helpful in assessing the ability of the scanner. All of the designs will be using the same internal organs and bone structures so all received the same award of 12 points. The designs incorporate major tissues such as bone, lung, liver, and muscle. These tissues will give an adequate look at the ability of the scanner to differentiate between different tissue densities and placements.

Next the shelf life of each of the designs was analyzed. The shelf life is a part of the design matrix as it is necessary for the design to be used repetitively for testing and radiation dosage distribution. This led to the shelf life variable being assigned 10% of the total points towards the design. The solid design received the highest ranking of 10 points as once the design is produced it will be very durable and there are no cuts in the design that might degrade and pull apart over time. The ballistics gel used in the other designs is softer and more pliable than the solid design. Also the cuts made in the designs must hold their form to prevent the pieces from slipping and negatively affecting the image quality. All of the ballistic gel designs received an award of 6 points. Also coming into play with the shelf life of the designs is the use of TLD's to test for radiation distribution. However, all of the designs simply use saran wrap around the radiation to prevent the radiation from coming into direct physical contact with the device. This is a very necessary part of the design as once the design is contaminated the half-life of the radiation used is 40 days. This would be an excessive amount of time to wait in between testing trials.

The organ accessibility for each of the devices was the next variable examined. This received a ranking of 30% of the total points, as it is very necessary to be able to change out the organs for testing when tumor progression is to be modeled. Also incorporated into this category was the ease of TLD placement and removed for radiation distribution testing. The solid design has no cuts and the organ accessibility is therefore nonexistent. However, the TLD slots could easily be incorporated into the design and earned this design an award of 7 points. The vertical cut is the next design examined and received an award of 20 points. The vertical cut will be right behind the rib cage and will allow for much easier access to the organs that sit in the rear of the rib cage. However, the organs in the front of the rib cage will still be relatively difficult to access. The horizontal cut received 24 points as it greatly increases the access to the organs throughout the rib cage in the plane of the cut and also allows the TLD in the hind leg to easily be placed and removed. Lastly, the combination cut received the highest point reward of 27 as the horizontal cut allows for access to the organs throughout the plane in the rib cage while the vertical cut allows for the organs that are not in the plane of the other cut to be placed and removed as well.

Finally the image accuracy of each of the designs was examined. As the image accuracy is ultimately the final goal of the design it received the highest ranking of 40 points. Once again the solid cut received the highest ranking with 40 points. The solid design has no cuts or slots for air bubbles to get into the design and affect its image accuracy. Once the solid design is cast it should be a very reliable testing device. Next, the vertical cut received the lowest ranking of 25 points. The vertical cut in the design will cause gravity to try and pull the sides apart, allowing air to get in-between the two pieces and lower image accuracy. An interlocking method, similar to that of a puzzle piece, was incorporated into the design to help hold the pieces together and counter the effects of gravity but we did not believe this would be enough to fully resolve the problem. The horizontal cut received a rank of 33 points as even though there is a cut in this design gravity will help to pull the two pieces together and eliminate air gaps. Lastly the combination cut received an award of 30 points, right between the vertical and horizontal cut award. Even though it has a vertical cut in the design the cut does not go all the way through the design and gravity will therefor have less of an effect on the air gaps between the pieces. Also the horizontal cut will help the top and bottom pieces to mesh together and further eliminate any air gaps that are present.

Final Design

After the design matrix was completed, the totals each design had accrued were added up. The combination cut emerged as the winner in a relatively close process. Although each design addressed certain variables better than other the combination cuts consistently scored among the top of every test. We believe the combination cut design adequately addresses all of the client's needs as all of the organs and TLD locations are easily accessible, its cost is low, the shelf life of the design should be adequate to properly test the scanner and run radiation dosage distribution experiments, and its high anatomical accuracy leads to high image accuracy. We believe this design will be much more useful in testing the design than other standard calibration devices on the market today.

Future Work

Now that the final design has been determined we must take the necessary steps to ensure we will have a device to give the client by the end of the semester. Once we have obtained the CT scan of a rat from the WIMR lab we will be able to take the file and upload it into the computers at WID that have the software to run their 3D printers. This file can then be scaled up or down so its dimensions match that of the rat skeleton that we have purchased for the project. The exterior of the rat scan can then be used to create a mold for the ballistics gel that will imitate the muscle tissue in the device. Once the rat skeleton and organs are placed inside the mold in their appropriate positions the ballistics gel can be used to fill the rest of the design. Once the gel hardens the vertical and horizontal cuts can be made and the TLD slots will be cut into the design. Finally, adequate testing using the CT scanner at WIMR will be completed to ensure our design works properly. Any issues that arise will be addressed in the proper manner.

References

1. The Phantom Laboratory. http://www.phantomlab.com/documents.php

2. Sigma-K Corporation. 2011. http://www.omniphantom.com/Home_Page.php

3. Morgridge Institute for Research, Wisconsin Institutes for Discovery. 2011. http://discovery.wisc.edu/home/morgridge/about-morgridge/leadership/thomas-mackie/

Appendix

Project Design Statement

Problem Statement: This project is for the design and development of a mouse phantom that will be used to characterize and test the micro collimator of an open source small animal imaging and therapy system. This machine includes micro CT, micro PET, and micro RT tests, and thus the mouse phantom must be compatible with all three systems. Ultimately, the system will be used to treat and image mice, rats and other small animals. The phantom will be designed for effective calibration and testing of the device while also researching the effects of radioactive materials placed inside the device to track radiation dosage distribution.

Client Requirements:

- Appear anatomically similar to a rat
- Fit the 12cm diameter bore of the scanner
- Physically scan similar to a rat
- Be able to detect radiation via inserts
- Contain radiation inserts without contamination to the rest of the phantom
- Contain 3 different tissue types of accurate densities: bone, muscle, lung
- Contain inserts for vital organs such as the heart, kidneys, lungs, and liver
- Separable in different pieces with minimal air gaps

Design Requirements:

1. Physical and Operational Characteristics

a. Performance requirements: The phantom should be able to fit inside the 12 cm diametertube of the scanner while attached to the loading table. The phantom may be submittedto repetitive use depending on the needs of the researchers.

b. Safety: The device will not be used on human subjects so there are little safety concerns involved. When radiation is used in conjunction with the device safety precautions will have to be taken to avoid human contact with any harmful elements.

c. Accuracy and Reliability: A high level of accuracy is required in the design, as it will be used to calibrate the scanner being built. The phantom will need to mimic the anatomical features of the rat, including the bones, lung, and muscle tissue.

d. Life in Service: The phantom should be able to withstand repetitive use. Also radioactive materials will be used that must not be allowed to contaminate the device.

e. Shelf Life: The shelf life of the phantom should be an indefinite amount of time. The device should maintain working order until the machine is built and testing has been completed.

f. Operating Environment: The phantom will be exposed to radioactive material and must be able to withstand the radiation while remaining un-contaminated. It will be used at standard room temperature and exposed to the elements of the RT, PET, and CT scanners.

g. Ergonomics: The device should experience little human contact besides the placement on the scanning platform and the removal of the device for storage.

h. Size: The phantom needs to be able to fit inside the 12 cm diameter scanner tube. Also the phantom is to come apart into two or three pieces. This will allow for removal of the bones and possible radioactive material placement.

i. Weight: The device should not exceed 2 Kg.

j. Materials: Material restrictions are limited to densities that mimic the real rat tissue while also being capable of placement in all three scanners

k. Aesthetics, Appearance, and Finish: The physical shape and form of the phantom shouldresemble the anatomical properties of a rat, as the goal of the project is to make sure the device scans like a rat.

2. Production Characteristics

a. Quantity: One phantom is initially to be designed. Depending on the final design decidedon a mold might be produced that will allow for multiple phantoms to be produced.

b. Target Product Cost: Product cost should not exceed a few hundred dollars.

3. Miscellaneous

a. Standards and Specifications: FDA approval is not required.

b. Customer: Customer is willing to try a variety of tactics to reach the final goal as long as the phantom accomplishes the desired functionality.

c. Patient-related concerns: The main concern for the cleanliness and storage of the device if only one is produced is that the radioactive materials used in the test trials not contaminate the device.

d. Competition: There are similar items that exist on the market today but they cost large sums of money. The goal of this project is to create an inexpensive, yet effective, alternative to these devices, which also accomplishes the necessary calibration and research.