C-HOLO

Enabling the ability to “see” radiation oncology therapy with a new perspective.

PROGRESS REPORT #2

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PROBLEM & OBJECTIVE

Problem

There is a need for a more efficient way for radiation therapists to optimize the patient setup process in the radiation oncology clinic. Currently, there is no streamlined way to verify patient identity, accessory usage, and patient positioning during external beam radiation treatment. Setup and treatment must be completed within back-to-back 15 minute appointments. As of now, patient identification is only checked at discrete time points. When last minute schedule changes occur, accidentally administering the wrong treatment plan to the wrong patient would result in inaccurate dosing and hazardous excess radiation exposure to the patient. Additionally, there is currently no way to document the use of immobilization devices. Each patient setup requires about 2-5 unique devices, and therapists are responsible for quickly switching these devices in and out between treatments. Therapists currently must rely on their memory and shorthand notes on the patient's file, leaving room for human error especially in this tight 15 minute window.

Most importantly, patient positioning and motion management is one of the most crucial aspects of radiotherapy. Misalignment will result in radiating the incorrect target site and damaging healthy tissue. Because patients come in for treatment everyday for 2-5 weeks, it is essential for them to be positioned correctly each time. There are two phases of positioning each day: Initial Positioning and Final Positioning. For Initial Positioning, therapists currently align patients to roughly the correct position using a laser alignment system; however, these lasers are often difficult to see and objects can get in the way of the laser projections. For Final Positioning, X-Rays are used to fine-tune patient positioning; however, these images expose the patient to excess radiation. Some clinics currently use surface alignment systems to help fine-tune positioning; however, the current existing devices are cumbersome to use since the therapist must constantly look back and forth between the computer monitor and the patient. Current devices also have resolution issues, and their cameras often have difficulties determining the distance between themselves and the patient surface in situations where the patient's skin has slight discoloration due to radiation treatments.

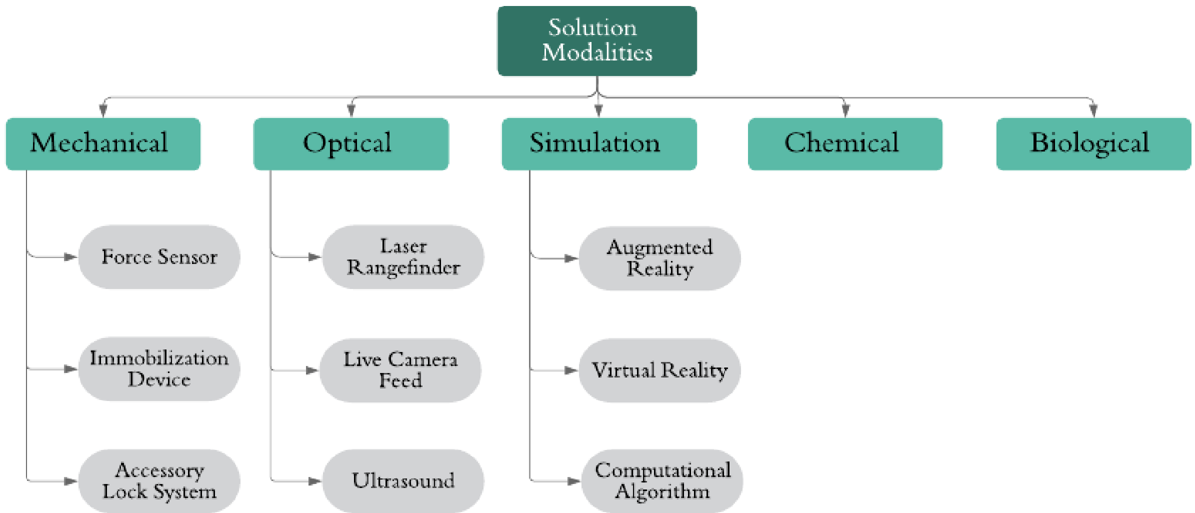
Objective

Our long-term objective is to develop a device that will verify patient identity, accessory/equipment usage, and increase patient positioning accuracy during the Final Positioning phase of the patient setup process. The device will allow radiation oncology therapists to safely treat cancer patients more quickly and to position them within smaller margins.

For the purpose of completing this project within the span of Senior Design, we have decided to narrow the scope of this project and focus mainly on patient positioning. Due to feasibility concerns, we will only address the Initial Positioning phase of the patient setup process for now. The fine-precision necessary for the Final Positioning phase will be implemented in future C-HOLO generations. Verification of patient identity and accessory/equipment usage will also only be implemented during this Senior Design project if time permits.

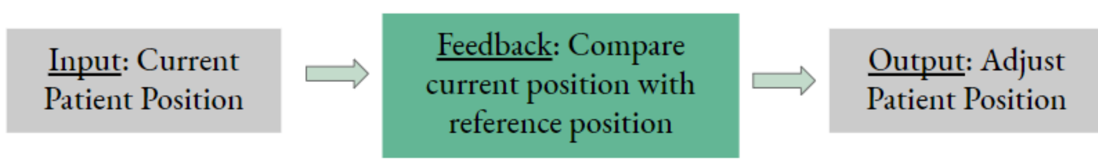
PRIMARY CONCEPT GENERATION & SCREENING

During our initial brainstorm as shown in Workflow 1, we narrowed down our concepts to 3 main categories: Mechanical, Optical, and Simulation. We ruled out Chemical and Biological modalities because we were wary about exposing the already immunocompromised cancer patients to excess chemical and biological compounds. Mechanical, Optical, and Simulation modalities were the least invasive.



Workflow 1: Primary Concept Generation

Because the focus of our device revolves around patient positioning, we formulated our designs around the workflow feedback loop shown in Workflow 2. Each device concept must have a system devised that would take the input of the patient's current position. Then in a feedback loop, the device would compare the current position with the reference position. This reference position is obtained from the Simulation portion of the clinical workflow in which the patient was setup for the very first time. Simulation and the clinical workflow is described in more detail in the Appendix. When there is a difference between the current and reference positions, the device will indicate that the patient must be adjusted in the output.



Workflow 2: Design Feedback Loop

Mechanical Design Concepts

The design concepts generated in the mechanical category required emphasis on engineering principles of motion, energy, and force. These designs rely more heavily on physical and structural components that would verify patient positioning. Understanding of static and dynamic loads and material properties would be needed to create a device in this category. The following bullet points describes each 3 mechanical design concepts in detail.

1) **Force Sensor:** This design utilizes force sensors such as strain gauges/load cells imbedded in a padded couch top to determine how the patient is lying down during treatment. The device would create a real-time force map of the patient that is continuously compared to the reference force map to indicate that the patient is in the correct position.

2) **Immobilization Device:** This design utilizes light sensors such as a photodiode or phototransistor targets imbedded into the immobilization device that detect the lasers used in patient alignment. When the laser hits these sensor targets, the device will notify the therapist that the patient is correctly aligned.

3) **Accessory Lock System:** This design utilizes a snap-lock mechanism to verify that accessories are placed at the correct position on the couch. When the therapist places an accessory down and locks it in place, the

device will confirm that the correct lock position was activated and notify the therapist when there is an incorrect placement.

Table 1 outlines our design screening process. The screening criteria such as ease of use, portability, and reusability are directly related to the user needs which are listed in the Appendix. The categories were ranked on a scale of 1-5 with 1 being the least desirable with 5 being the most desirable. For example, immobilization devices are often custom made for each individual patient and a new device would need to be created each time. Therefore, the Immobilization Device design received a ranking of 1 for reusability. Both the Force Sensor and Accessory Lock System scored 4 for Linac Compatibility because these devices could easily be overlayed on-top of the current treatment couch. Compared to the Accessory Lock System, the Force Sensor was deemed easier to manufacture because the design revolves around one parameter (patient force distribution) instead of accounting for multiple accessories. The Accessory Lock System would be difficult to manufacture because accessories come in all different shapes and sizes and creating a one-size fits all snap-lock mechanism would be a great challenge. The Force Sensor design obtained the highest score and was selected as the number one mechanical design concept.

Table 1: Mechanical Concept Design Screening

Design Screening Criteria	**Weight (1-4)**	**Force Sensor**		**Immobilization Device**		**Accessory Lock System**	
		Rank (1-5)	Weighted	Rank (1-5)	Weighted	Rank (1-5)	Weighted
Cost	3	3	9	4	12	2	6
Manufacturability	3	5	15	3	9	3	9
Ease of Use	4	3	12	5	20	3	12
Portability	2	3	6	4	8	3	6
Reusability	4	5	20	1	4	5	20
Durability	3	3	9	2	6	4	12
Linac Compatibility	3	4	12	3	9	4	12
Total Score			**83**		**68**		**77**

Optical Design Concepts

The design concepts generated in the optical category required emphasis on engineering principles of light behavior. These designs rely more heavily on light ray sensors that would verify patient positioning. Understanding of the electromagnetic spectrum and wave/particle duality properties would be needed to create a device in this category. The following bullet points describes each 3 optical design concepts in detail.

1) **Laser Rangefinder:** This design utilizes laser beams mounted on the ceiling of the treatment room to determine the distance between the rangefinder and specific points of the patient's body. The device would create a real-time distance map of the patient that is continuously compared to the reference distance map to indicate that the patient is in the correct position.

2) **Live Camera Feed:** This design utilizes high resolution cameras mounted on the ceiling of the treatment room to obtain live footage of the patient. The live feed would then be superimposed over the reference image to detect any position discrepancies. When there is a difference in the images, the device will signal that the patient is incorrectly aligned.

3) **Ultrasound:** This design utilizes an ultrasound indoor positioning system that transmits an ultrasonic signal to target nodes to determine the distance between the beacon and the specific points of the patient's body. Similar to the laser rangefinder, the device would create a real-time distance map of the patient that is continuously compared to the reference distance map to indicate that the patient is in the correct position.

Table 2 outlines our design screening process. The screening criteria and ranking scale were the same as the previous screening table. The low score for the Live Camera Feed can be attributed to the score of 2 for durability. This is because radiation scatter easily damages camera lenses, reducing resolution and would require often replacement. Depending on the number of ultrasound positioning detectors used, the high cost of the overall device warranted a score of 2. Ultrasound technology is relatively new, so detectors on the market are more expensive compared to the laser rangefinders. Manufacturability for the laser rangefinder scored a 3 because purchasing the sensors and implementing the time of flight principle would be feasible. The Force Sensor design obtained the highest score and was selected as the number one optical design concept.

Table 2: Optical Concept Design Screening

Design Screening Criteria	Weight (1-4)	Laser Rangefinder		Live Camera Feed		Ultrasound	
		Rank (1-5)	Weighted	Rank (1-5)	Weighted	Rank (1-5)	Weighted
Cost	3	3	9	3	9	2	6
Manufacturability	3	4	12	3	9	3	9
Ease of Use	4	4	16	3	12	4	16
Portability	2	3	6	4	8	3	6
Reusability	4	5	20	4	16	5	20
Durability	3	4	12	2	6	4	12
Linac Compatibility	3	4	12	5	15	4	12
Total Score			**87**		**75**		**81**

Simulation Design Concepts

The design concepts generated in the simulation category required emphasis on manipulating the environment of the user. These designs rely more heavily on modeling and immersive tools that would verify patient positioning. Understanding of software development and simulated realities would be needed to create a device in this category. The following bullet points describes each 3 simulation design concepts in detail.

1) **Augmented Reality:** This design utilizes virtual holograms that are integrated into the real-world. When the therapists wears an AR headset, they are able to interact with hologram panels that display the patient

treatment plan. The device would display a holographic reference image of the patient's correct alignment, and the therapist would adjust the physical patient until they are superimposed within the hologram.

2) **Virtual Reality:** This design utilizes interactive computer-generated experience that takes place within a completely simulated environment. A therapist would wear the VR headset during radiation delivery in which they are outside of the treatment room. By using cameras to track infrared markers on the patient, the device would allow the therapist to monitor patient positioning as if they were in the room with the patient.

3) **Computer Simulation:** This design utilizes a computer to simulate the outcomes of a mathematical model that is associated with the radiation treatment. Performed prior to the patient setup process, a therapist would run the simulation in order to predict if the patient will have any arising weight or tumor changes that would affect their patient positioning and accurate dose delivery. If a prediction is made, the therapist will adjust the patient's positioning accordingly.

Table 3 outlines our design screening process. The screening criteria and ranking scale were the same as the previous screening table. The low score for the Virtual Reality and Computer Simulation can be attributed to the manufacturability score of 2 and 1 respectively. Because creating entirely computer generated environments require extensive programming and modeling knowledge, these design concepts were out of the scope for Senior Design and would not be feasible. Reusability and Portability were strengths for AR and VR designs, scoring 4s and 5s in both categories due to the lightweight of these devices and ability to take them to different treatment rooms and use them on different patients. The Augmented Reality design obtained the highest score and was selected as the number one simulation design concept.

Table 3: Simulation Concept Design Screening

Design Screening Criteria	Weight (1-4)	Augmented Reality		Virtual Reality		Computer Simulation	
		Rank (1-5)	Weighted	Rank (1-5)	Weighted	Rank (1-5)	Weighted
Cost	3	4	12	3	9	4	12
Manufacturability	3	3	9	2	6	1	3
Ease of Use	4	4	16	3	12	4	16
Portability	2	5	10	4	8	3	6
Reusability	4	5	20	5	20	4	16
Durability	3	4	12	4	12	5	15
Linac Compatibility	3	5	15	4	12	4	12
Total Score			**94**		**79**		**80**

THREE DESIGN CONCEPTS

Before treatment starts, patients will start with simulation in which they are positioned to the reference position prescripted by the therapist along with immobilization devices. In simulation, the initial CT scan will also be taken and used as a reference. Our design will be used when patients come in for their daily treatments. The goal is to replicate patient treatment position with the reference position. Therapists will first move the couch to an approximate location before they move the patient's position. Our design improves the accuracy of setting patients to the reference position and gives guidance to the therapist to move the couch and patient.

Design 1: Force Sensor

Our first design concept is a force sensitive couch top. The idea is to put a force sensor mat on the couch top to measure force distribution. When the patient goes in for simulation, the therapist will position the patients normally and then record the force distribution. A force map (See Figure 1) is created using the force distribution data and different levels of forces will be indicated by a color gradient. Before the patient starts the treatment, therapists will set the patient up using the initial sensor readings. If the patient moves, the force sensor will pick up the changes which are reflected in increase/decrease readings and the color of the force map also changes.

Figure 1: Left, patient lying on a pressure sensor integrated pad and pressure being mapped to a screen[P1]. Color changes on pressure map when movement occurs [P3]. Right, a force sensor mat on a couch top [P2].

Inspired by a paper that Akitsugu Misaki wrote on body pressure sensing mattress, we will make a force sensor that consists of a dielectric rubber layer covered by two flexible rubber electrode layers (See Figure 2). The electrode is printed on the rubber substance. When pressure is applied to the sensor, the distance between the two electrode layers decreases. The behavior of the sensor is characterized by C= SD where C is the electrostatic capacity, is the dielectric constant, S is the electrode surface area, and D is the distance between the electrodes [1]. Size of each of this sensor unit is about 5 by 5 cm. Varian's couch top has surface area dimension of 217 by 53 cm and the treatment area of the couch top is 119.5 by 53 cm [2]. Therefore, to cover the treatment area, we need to make a sensor sheet that is consist of 240 sensors placed in 10 by 24 grids. For each sensor, assume that the force measured is located in the middle of the sensor unit. Having more sensors increase the accuracy because there are more data points but a tradeoff is that sensor size decreases.

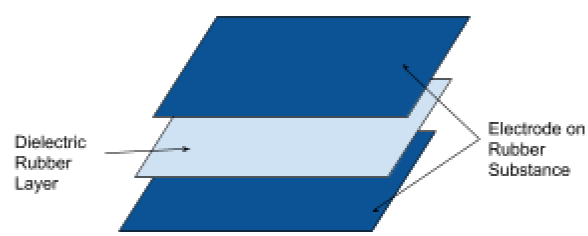


Figure 2: Left: Three layers of the force sensor.

The advantage of the pressure sensors approach is that it can continuously track patient movement and position during and throughout the setup process. The disadvantages are that the metal sensors may interfere with image acquisition and the measurement of patient positioning is not very accurate. This is because the force sensors only detect where weight changes occur but it does not detect where specific body parts are in space. For example, a patient can put an arm on the couch and then lift the arm up. The couch will show the change in weight but it does not show where the arm should be in space, which can be essential to treatment.

Design 2: Laser Rangefinder

Our second approach is to install laser rangefinders on the ceiling of the treatment room, and they will measure the distance between the ceiling and the patient body surface. During simulation, the therapists will record the distance between the ceiling and the patient using the laser rangefinders, and they will create a distance map (See Figure 3) as a reference for patient treatment setup. Changes in patient movement are reflected by an increase or decrease in distance sensor readings and indicated by change in color.

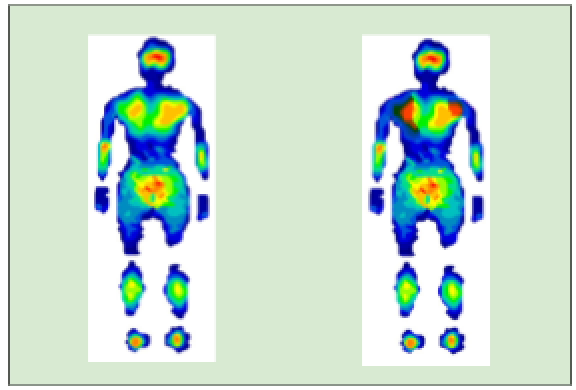


Figure 3: Screen of therapist with distance maps of the patient. The left side is the reference distance map and the right side is the current distance map (change in color is observed when patient position moved) [P4].

Laser rangefinders work by emitting a laser beam and measuring the time the laser beam takes to bounce back from the target surface. The beam travels at the speed of light and given the return time, the rangefinder calculates the distance and displays it to the user [3]. The distance between point A and B can be calculated by $D = \frac{ct}{2}$ [4], where c is the speed of light, t is the time that the beam travels in the round trip between A and B.

We picked the Barumer OM70 laser rangefinder for our design due to its high precision and resolution. The measuring distance of this laser rangefinder is 1.5 to 15 meters. Its resolution is in between 13 to 125 micrometers and the accuracy is in between 3 and 63 micrometers. The minimum area that a laser rangefinder takes up is about 3*6 = 18 cm^2. Assuming the laser rangefinder measures the distance straight down from the ceiling. The total surface area of the couch top is 217*53 = 11501 cm^2 and the treatment area of the couch top is 119.5*53=6333.5 cm^2. To cover the treatment area, we will have a 20 by 18 matrix with a total of 360 laser range finders on top of the couch top (See Figure 4). Having more laser rangefinders will increase the numbers of data points measured which makes the measurement more accurate.

Figure 4: Left: Demonstration of laser rangefinders installed on the ceiling [P5]. Right: Demonstration of the laser rangefinders installed on top of the couch [P6].

The benefits of using laser range finders are that laser rangefinders track patient movement and detect the exact location of surface areas in real time. They also have high precision. Also, the laser rangefinders are safe to use and they are Class I devices [5]. Class I laser products are seen as non-hazardous so patient safety is protected even if the patient accidentally look at the laser [6]. The disadvantages of this method are the laser rangefinders can be blocked by the linac and it is expansive to create a whole body distance map. The linac imaging arms and gantry move and rotate so they may block the laser beam and interrupt distance measurement. To create a whole body distance map, many laser rangefinders are needed to get more data points and the cost is high.

Design 3: Augmented Reality (AR)

Our third design concept is to use an Augmented Reality (AR) system. AR headsets works by having computer generated images, sound, graphics, or information displayed on top of real world environment [7]. AR is special in that it registers real and virtual objects together and displays them in real time with real environment background.

Figure 5 : Left, therapists using AR devices (Microsoft Hololens) to view holograms [P7]. Right, a demonstration of what the therapist see with an AR device. The transparent blue object represents the hologram and there is a panel of patient information [P8].

Currently, patients take CT scans in Simulation, and those scans are used in the treatment planning process. Our project will use these scans to create a 3D holographic image, which will be used to position patients. Through the AR devices, therapists will see the the 3D holographic image of the patient body surface outline, while also seeing the patient in the real environment. Therapists will also see the patient's information (name, date of birth, and sex) and immobilization devices (wedges, rolls, headrests, masks, bite blocks, and breastborads) required, and this information will be shown in a panel overlayed on top of the real environment. With this, the necessary information will be easily displayed in front of therapists to see. To do positioning, therapists will align the patient with the 3D holographic image until the physical body of the patient is superimposed with the hologram.

Advantages of an AR device is that it has the flexibility to display positioning information, patient identity, and accessory usage in front of the user, while letting the user see the real environment around them. Therapists do not need to look at different screens placed around the room to verify information. Disadvantages of the design are that the battery life is limited and the headset is not discrete. Also, the headset is a wearable device and it may take some time for therapists to get used to wearing.

FINAL DESIGN SCREENING & SELECTION

Table 4 outlines our design screening process for selecting the final design. Similar to the selection tables constructed during the primary concept generation, the screening criteria such as ease of use, portability, and reusability are directly related to the user needs which are listed in the Appendix. The categories were ranked on a scale of 1-5 with 1 being the least desirable with 5 being the most desirable. Despite the lower score of 3 in manufacturability because of required software knowledge, the Augmented Reality system outperformed the Force Sensor and Laser Rangefinder in Ease of Use, Portability, and Linac Compatibility with scores of 4s and 5s. These factors can be attributed to the fact that aligning patients to a holographic reference image is more intuitive than deciphering force and distance maps. In addition, the AR device be easily moved to different treatment rooms to treat patients on different linacs while the Force Sensor and Laser Rangefinders must stay in the same treatment room and can be affected by radiation. The AR design also scored 4s for cost and durability compared to the 3s and 4s of the other designs because of long-term maintenance. In the event the sensors in the Force Sensor or Laser Rangefinder designs became faulty over time and require maintenance, patients would not be able to be treated while they are being fixed. Because the AR design has the benefit of portability, a spare headset or device from another room would easily mitigate that issue. Augmented Reality obtained the highest score and was selected as the number one final design concept.

After selecting Augmented Reality, we wanted to ensure patient information is protected during the wireless transfer of data. Our proposed solution is to utilize the hospital's own encrypted network when operating this AR device. Similar to protocols implemented for the use of hospital computers, only authorized personnel would be able to log onto the AR device.

Table 4: Final Design Screening

Design Screening Criteria	Weight (1-4)	Force Sensor		Laser Rangefinder		Augmented Reality	
		Rank (1-5)	Weighted	Rank (1-5)	Weighted	Rank (1-5)	Weighted
Cost	3	3	9	3	9	4	12
Manufacturability	3	5	15	4	12	3	9
Ease of Use	4	3	12	4	16	4	16
Portability	2	3	6	3	6	5	10
Reusability	4	5	20	5	20	5	20
Durability	3	3	9	4	12	4	12
Linac Compatibility	3	4	12	4	12	5	15
Total Score			**83**		**87**		**94**

MATERIALS & MANUFACTURABILITY

In this section, we will look at different AR devices, AR development engines, programming languages, and code version control systems. We will select the best AR device based on the cost, ease of use, open source documentation, battery life, portability, and flexibility in hologram usage. Next, we will pick the AR development engines based on cost, ease of use, and availability of resource documentation. Because our project requires a lot of programming, a code version control system that allows easy group collaboration and task management is selected.

AR DEVICES

DreamWorld Headset

The DreamWorld headset is a light-weight headset that costs $399 [8]. Users can create holograms using Unity (a game engine that can create AR simulations) and upload them to the headset to view. The headset has features that include head tracking, an active camera, a virtual cursor, and gesture recognition. The headset is used with an Android phone or a computer. However, to connect the headset with an Android smartphone, purchase of additional cables are required. User movement is limited with the additional cables [9].

Microsoft Hololens/Microsoft Hololens 2

Microsoft Hololens is a wireless AR device that is Unity-based and requires Visual Studio to program the actions of the holograms [10]. Microsoft Hololens 2 was released on February 24th, 2019 and is an improved version of the original Hololens. The development package for the original Microsoft Hololens is $3000 and Microsoft Hololens 2 is $3500. Users can touch, grasp, and move holograms by using voice commands, gestures, and the virtual cursor. There is a large support community for Microsoft Hololens, including the Hololens forums, Microsoft developer program, Developer Network, Windows Mixed Reality Developer Forum, and Microsoft Visual Studio [11].

Meta 2

Meta 2 is an AR headset that costs $1495 for the developer package. The headset requires a 9-foot cable to connect to a computer for power and transfer of data [12]. Therefore, this headset is intended for stationary use. Users can interact with the holograms using a grab-and-hold gesture and move the hologram around [13]. Like the previous two devices, Meta 2 uses the Unity engine, and there are many online tutorials, setup documents, and forums [14].

In Table 5, Microsoft Hololens has the highest score so we will select Microsoft Hololens as the AR device that we use. Although Microsoft Hololens has the highest cost out of the three devices, it is very portable which is essential for the purpose of use in our design. Longer battery life is also important. DreamWorld and Meta2 need to be plugged in to get their power source and Hololens can run on its battery. Hololens also has a mature online community with open source documentation. In conclusion, Microsoft Hololens fit our need the most and is selected.

Table 5: AR Device Selection Table

Design Screening Criteria	Weight (1-4)	DreamWorld		Microsoft Hololens		Meta 2	
		Rank (1-5)	Weighted	Rank (1-5)	Weighted	Rank (1-5)	Weighted
Cost	2	5	10	3	6	4	8
Online Community	4	2	8	5	20	2	8
Ease of Use	4	4	16	5	20	4	16
Portability	4	1	4	5	20	1	4
Battery Life	4	4	16	3	12	4	16
Interaction with Hologram	3	5	15	5	15	5	15
Total Score			**69**		**93**		**67**

DEVELOPMENT ENVIRONMENTS

Unity

Unity is one of the AR development engines and supports many platforms including mobile, website, and PC. C#, UnityScript, and Boo are the three main types of programming languages used in Unity. Unity is easy to learn and use with a lot of documentation for developer support [15]. Unity has a big community (third-party libraries and tutorials) which provides tool and resources to developers. It is user-friendly for programmers and designers to use. Unity is free for developers who make no more than $100000. If developers make more than $100000, they need to pay $35 per month [16].

Unreal

Unreal is an engine for AR development. The main programming language for Unreal is C++ and it supports mainly PC. Unreal also has an easier scripting language called Blueprint for designers to use. There are not a lot of documentation for Unreal and the tutorials are mainly for designers rather than programmers [17]. The Unified Unreal AR Framework is a framework that allows developers to build AR apps for both iOS and Android systems. Unreal has good graphics and is better for 3D objects [15]. Unreal is free to use but developers need to pay 5 percent of the earning from the app [16].

CryEngine

CryEngine is another popular engine for hologram development and it has great graphics. However, it has restrictive license meaning that users need to pay for additional features. CryEngine doesn't support Mac OS X or GNU/ Linux. Knowledge of programming language and additional applications (such as Flash, ActionScript, and Lua) are needed to be able to use the engine. CryEngine operates using C++. It has a community called CryEngine Answers for users to ask questions and find answers to any questions related to CryEngine. Cost of CryEngine is $9.90 per month [18, 19].

Microsoft Visual Studio

Microsoft Visual Studio is an Integrated Development Environment (IDE) interface for users to write, edit, and debug code before publishing an app. It includes compilers, code completion tools, and features that are helpful for software developers [20]. It is designed for development in Microsoft web applications, websites, and web service. Microsoft Visual Studio is good for team projects with features like version control, application control, task management tools, project collaboration, and project planning. There are also build in tools in Visual Studio for making GUIs. Programming languages that Microsoft Visual Studio supports include C, C++, C#, F#, VB.NET, Python, Ruby, and M [21]. The community version of Visual Studio is free [22].

For Table 6, design criteria like the cost of the AR engine, public sources, ease of use, and programming languages used are evaluated. The categories were ranked on a scale of 1-5 with 1 being the least desirable with 5 being the most desirable. Unity has the highest score compared to Unreal and CryEngine. We are picking unity because it uses C# which is easier to learn compared to C++ that other engines use. Unity is also free to use and has a large online community. We will also use Microsoft Visual Studio because it is integrated with Unity.

Table 6: Screening Table for Development Environment

Design Screening Criteria	Weight (1-4)	Unity		Unreal		CryEngine	
		Rank (1-5)	Weighted	Rank (1-5)	Weighted	Rank (1-5)	Weighted
Cost	4	5	20	5	20	1	4
Online Community	4	5	20	2	8	2	8
Ease of Use	4	4	16	3	12	1	4
Programming Languages	3	4	12	2	6	2	6
Total Score			**68**		**46**		**22**

CODE MANAGEMENT SYSTEMS

Git
Git is a code management system for software development. It is a great tool for team projects and has code version control feature. A repository is a data structure where git stores the change in code information at [23]. In Git, users can create different branches and manage these branches by merging and deleting them. Different levels of permissions can be given to different users to ensure the security of the code [24]. Git is a free platform for multiple users working in the same project [21].

GitLab
GitLab is a Git hosting system. It is free for unlimited users and provides unlimited private repositories. Different levels of permission can be given to different members and the assignment is based on the member's role. There are documents for how to import data into GitLab [23]. GitLab has features that allow users to plan, organize and track the progress of project using issues, Kanban boards, and time tracking [25]. GitLab has more features to help the team focus on the goal and these features include issue weights, milestones, and issue due dates [26].

BitBucket
Bitbucket is a web-based hosting site for repositories that either uses Git or Mercurial revision control system [21]. Users can have unlimited private or public repositories. Features of Bitbucket include code reviews, pull requests, branch permissions, code aware search, and code commit history. Moreover, Bitbucket has Trello boards that are helpful for the organization of the project and collaboration in the team. The code in Bitbucket is secured and different level of permission can be given to different users [27]. The boards are used to manage the project to help the team focus on a goal and organize tasks. It is free for 5 or fewer users [28].

GitHub
GitHub is a web-based Git repository hosting platform and it is a free tool. GitHub has features like revision control, source code management, task management (track and assign tasks), feature requests, and bug tracking. As part of the code vision control, users can compare versions of code side by side and see the parts that are modified. Different members can get read or write access to the repository[24]. GitHub is good for group project because users can work on the same project in real time. Issue is one of the tools that identify bugs. GitHub supports more than 200 programming languages and it is free to use [29, 30].

For Table 7, we look at cost, ease of use, user permission, project planning, task management, and version control for the three code management systems. The categories were ranked on a scale of 1-5 with 1 being the least desirable with 5 being the most desirable. Easy to use and low cost are very important for our selection. Out of the three options, BitBucket has the highest total score, so we will use this as our version control system.

Table 7: Screening table for Code Management Systems

Design Screening Criteria	Weight (1-4)	GitLab		BitBucket		GitHub	
		Rank (1-5)	Weighted	Rank (1-5)	Weighted	Rank (1-5)	Weighted
Cost	4	5	20	5	20	5	20
Ease of Use	4	4	16	5	20	4	16
Permission Management	3	4	12	4	12	4	16
Project Planning	4	2	8	4	16	3	12

Task Assignment	3	3	9	4	12	3	9
Version Control	4	3	12	4	16	3	12
Total Score			**77**		**96**		**85**

KEY SUBSYSTEMS & INTERFACES

There are a variety of methods in which augmented reality can address patient positioning. In order to accurately position the patient, two things must be known: *how* the patient is oriented and *where* the patient is oriented. The *how* ensures that a patient's orientation on the couch during Simulation is exactly replicated during treatment. The *where* ensures that during treatment, the patient lies down in the same location on the couch as they did during Simulation.

ACQUISITION OF HOLOGRAPHIC IMAGES/3D MODELS

AR can allow for the visualization of how patients are oriented. By constructing a hologram of the patient's original orientation during the planning CT, therapists can have a patient's current orientation and the reference orientation in their view at the same time. In order to create a hologram of a patient's correct orientation, a 3D model is needed. Developing a 3D model of the patient's outline during the planning CT can be done using the CT scans that were taken during Simulation or by using 3D cameras.

CT Scans for Hologram Development

CT scans are stored as DICOM (Digital Imaging and Communications in Medicine) files with extension .dcm. Various software programs allow for the viewing and manipulation of these files, such as 3D Slicer [31, 32]. The 3D volume created by concatenating the 2D slices of a CT scan are represented by a 3D grid of voxels (pixels in 3D). The dimension along one edge of a voxel is on the order of 0.5mm [33, 34]. After defining the skin outline in 3D Slicer, the dicom files can be exported as 3D models of file type .obj, which Unity can read and create a hologram from (Figure 6) [35]. See *Converting CT Scans into Holograms* in the Appendix. Anonymized CT scans are available online, which we can use for our project. Additionally, through our connections at the UC Davis Medical Center and UC Davis Veterinary Medical Teaching Hospital, we may be able to arrange a time to validate the performance of our application by taking CT scans of a phantom (a mannequin) carefully positioned on the couch.

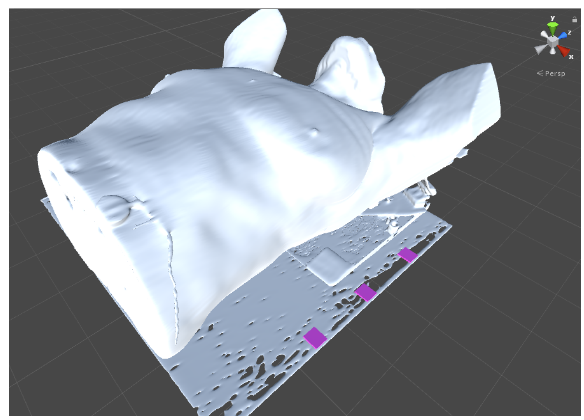


Figure 6: A hologram constructed from a CT scan.

3D Modeling Cameras for Hologram Development

Alternatively, 3D cameras and scanners can be used to construct a 3D model. These vary in complexity and cost. Phone apps, like Scann3D [36] and Qlone [37], require taking pictures from multiple angles to create a rough 3D model in a matter of minutes, but it can have low resolution and can be hard to use. Some 3D scanners are handheld and offer great resolution. One such scanner is Artec's Eva, which offers resolutions up to 0.1mm. However, this accuracy comes at a cost. The Artec Eva costs $19,800, and costs of many other high resolution scanners are of comparable magnitude [38]. Some 3D cameras of lesser, but still reasonable, accuracy are about $3,000 [39]. Other 3D scanners require the placement of the object on a turntable a defined distance from the camera, or for the object to be surrounded by cameras. Turn-table type scanners are not practical for our application.

Table 8 shows that generating 3D models from CT scans scored better over the utilization of 3D Cameras. Both methods are capable of producing high resolution models. Both methods had mediocre score for the time needed to complete the 3D model construction. In the case of using CT scans, dosimetrists would use tools they are already familiar with to define the body contour. In the case of 3D cameras, additional time is need during simulation for the patient to lie still on the couch for the cameras to scan the patient. The differential in weighted scores between using a CT scan and 3D cameras was greatest, and in favor of the CT scan, when comparing cost, as well as the ease of incorporation into the clinical workflow. Since CT scans are already part of the radiation treatment workflow, there is no added cost or devices needed to obtain them. Using 3D cameras would require a multi-thousand dollar purchase, periodic quality assurance inspection, an additional step to the simulation process, and camera operating training.

Table 8: Optimum Method for 3D Model Construction

Design Screening Criteria	Weight (1-4)	CT Scan		3D Camera	
		Rank (1-5)	Weighted	Rank (1-5)	Weighted
Cost	4	5	20	1	4
Accuracy	4	5	20	5	20
Time	3	4	12	3	9
Workflow Incorporation	3	5	15	1	3
Total Score			**68**		**36**

PLACING THE HOLOGRAMS IN THE CORRECT LOCATION

AR can also allow for the visualization of where patients are positioned in space. We consulted with PhD student, Tianchen (Michael) Sun, from the UC Davis Visualization and Design Interface Innovation Lab. Michael provided us with input on methods for aligning virtual holograms in space. He shared an example from his project, in which he used an optical tracking system with infrared tracked markers to determine the spatial location and orientation of a medical device. We also discussed using QR codes placed on the corners of the treatment couch as reference points to which we could precisely align the hologram of the patient contour to. Further research revealed a variety of methods to place holograms at a particular real world location. Here they are discussed and evaluated. We additionally consulted with Steven Lucero in the TEAM Lab. He explained the 3D scanner hardware available to us in the TEAM Lab and suggested looking into using Kinect.

There are two types of hologram placement: at a location relative to the user and at a location relative to the environment [40]. Our goal is to align a hologram of the patient onto the couch, no matter where the therapist wearing the HoloLens is standing. Since the therapist will be turning their head and walking around the room during patient setup, a coordinate system referenced to the environment should be utilized. Coordinate systems can be defined using a reference/target image. Vuforia is an add-on toolkit for HoloLens development in Unity. Vuforia allows for the recognition of target images and the placement of holograms relative to this target [41]. To incorporate clinically, radiopaque markers could be added to the couch in simulation and treatment rooms. They will appear in the patient's CT scan, and thereby also in the holographic model of the patient. When the therapist wears the HoloLens into the treatment room, it will identify the markers on the treatment couch and align the hologram accordingly. This process is relatively automated using Vuforia. This process of aligning markers present in the real world and in a hologram from a CT scan was already demonstrated by a study on the application of HoloLens for external ventricular drainage surgery, published in the Journal of Neurosurgery [42]. They placed radiopaque markers on a patient's head, took a CT scan, and then overlaid the 3D model hologram from the CT scan onto the patient's real head by aligning the real and virtual markers. This allowed the surgeon to visualize internal organs to guide the surgery.

Alternatively, spatial mapping can be utilized for hologram placement [43]. With spatial mapping, the HoloLens takes a scan of a room and makes a 3D mesh model of it. Within Unity, holograms can be placed at certain locations in the room. Since Unity has a model of the entire room, it supports occlusion well. Occlusion is the concept where holograms and real world objects block the view of each other in a realistic way. This contributes to a real-life experience. To incorporate a spatial mapping method into the HoloLens application and into the workflow, the treatment rooms would need to be scanned by the HoloLens. This would only need to be done once, as the generated model of the room could be stored for future use. A task that would need to be repeated for every patient, however, is aligning his/her body hologram on the 3D mesh treatment couch in Unity. Obtaining a precise alignment replicable to how the patient was aligned during the planning CT would be difficult with a course 3D mesh of the room. The 3D mesh of the room has potential to be detailed and fine, but this puts a heavy load on the operating system.

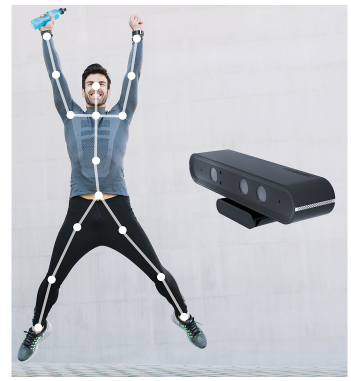


Figure 7: Kinect sensor with person's generated skeleton overlaid on the body [P9]. The skeleton consists of dots, indicating joints, and of lines connecting the joints.

Thirdly, a Kinect scanner could be utilized for hologram alignment. The sensor and associated software has built in functionality to map the human body's skeleton with marked joints and body segments (Figure 7) [44]. The Kinect scanner could be placed in the CT planning and treatment rooms, where it will map the real patient's body. During treatment, the therapist would wear the HoloLens and view a hologram of the patient's original skeleton map from during simulation overlaid onto the patient. The positioning of the original hologram could be determined by using the Kinect in the treatment room to recognize the patient's body. Overlaying the patient's skeleton would provide a sanity check on the patient's orientation. However, as it is just a map of the patient's skeleton, it will not offer detailed positioning information to the therapist.

Given the above analysis and screening in Table 9, utilizing Image Targets with Vuforia was determined to be the best method to position patient holograms precisely on the treatment couch for reference when therapists are aligning the real patients.

Table 9: Couch Coordinates

Design Screening Criteria	Weight (1-4)	Spatial Mapping		Image Targets		Kinect	
		Rank (1-5)	Weighted	Rank (1-5)	Weighted	Rank (1-5)	Weighted
Occlusion	1	5	5	1	1	1	3
Precise Hologram Placement	4	3	12	5	20	1	4
Clinically translatable	4	2	8	5	20	4	16

Total Score			**25**		**41**		**23**

WORKFLOW DIAGRAMS

In this section, we present summarized diagrams of our software and programming workflows. More detailed versions of these workflows can be found in the Appendix under "Detailed Workflow Steps." Those versions include technical details and in depth software manipulations.

In the first stage of our development workflow, we want to convert the reference CT scans into a hologram. To do this, we will make use of two software: *3D Slicer* and *Unity*. The simple workflow is shown in Diagram 1, where we would remove unnecessary scanned objects from the CT before converting the original DICOM (.dcm) file into a 3D model that is saved as an object (.obj) file. For later hologram positioning, we will need three different CT markers to be placed and scanned at couch corners as reference.

After we have our holograms saved onto the device, we need a way to retrieve the respective patient's hologram of their reference CT scan. To do this, we will utilize a QR code to hold the patient's ID number. That will be linked to the hologram generated from that patient's CT scans. This programming procedure in Diagram 2 would end up displaying the hologram in the environment.

Finally, to position our hologram, we will utilize Vuforia's *Target Manager* database, which enables users to upload preferred images as QR codes for their own use. Diagram 3 gives a visual representation of this workflow. We will upload images of each CT sticker pattern before importing the whole database (consisting of these three images) into Unity. In Unity, we will place the overall position of these markers generally in space while keeping their relative positions from each other as accurately as possible. Next, we import the .obj file of the reference CT images, and we align the markers of this 3D model with the three markers floating in space. When we test this in the HoloLens, as long as we look at the stickers in reality, the HoloLens should generate the 3D model of the patient directly on top.

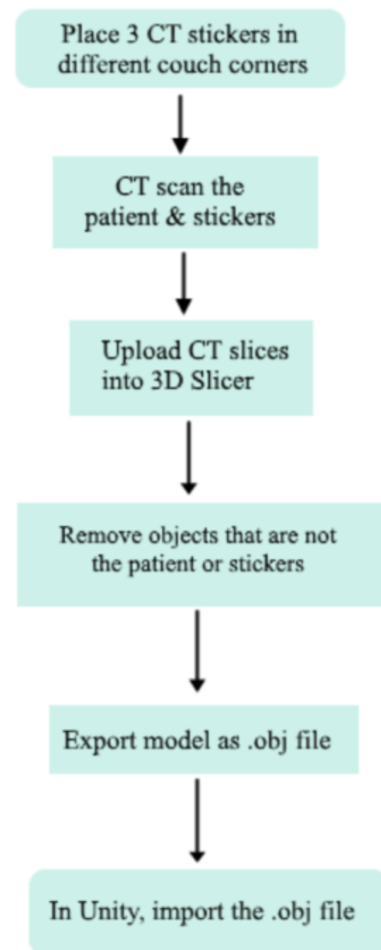


Diagram 1: From CT to hologram.

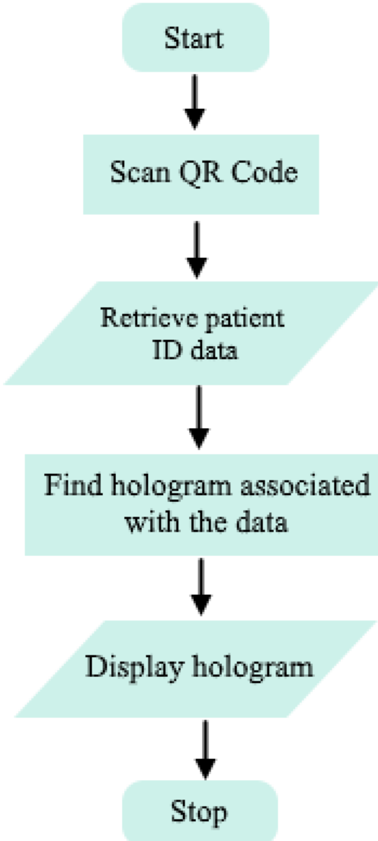


Diagram 2: Programming hologram retrieval

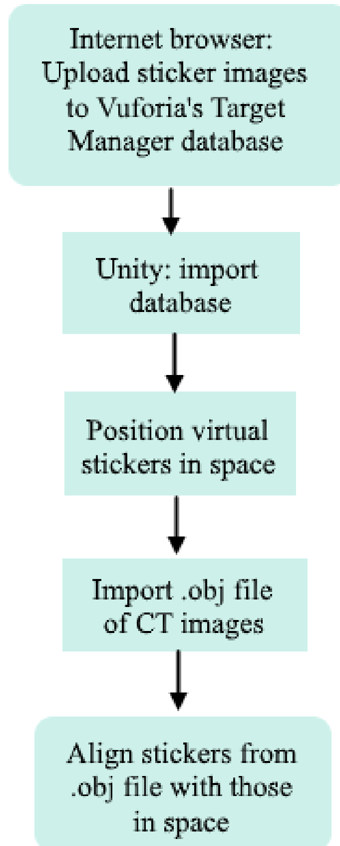


Diagram 3: Hologram Positioning

APPENDIX

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NEEDS FLOWCHART

Essential				
Accuracy of Patient Positioning	Integrates with Current Hardware & Software	Reproducibility of Patient Positioning	Verification of Correct Couch/Gantry Position	Verification of Patient Identity

Important				
Cleanable	Verification of Accessory Usage	Affordable	Easy to Operate	Portable

Nice to Have				
Ergonomic	Reusable	Effective Immobilization	Easy to Maintain & Update	Compatible with Most Machine Brands

Not Necessary				
Requires Minimal Training	Long Battery Life	Ease of Patient Setup	Fast Patient Setup	Wireless Transfer of Verification Data

CLINICAL WORKFLOW

1. Patient receives a *planning CT* during Simulation.
    a. According to the oncologist's directions, the patient lies on the couch in a certain orientation. Therapists construct *immobilization devices* to help keep the patient in position (Figure 3).
    b. In each of the imaging and treatment rooms, there is a universal laser system that produces cross-hairs on the patient's skin or immobilization device (Figure 4). The patient's exact position is recorded by putting tattoos the size of a freckle on these cross-hairs. Come treatment time, aligning the tattoos with the lasers will ensure the patient is in the same position as during the planning CT. It is important that the patient's exact position on the couch is reproducible because the location where the linac irradiates during treatment will be determined by the patient's spatial alignment from this initial scan.
    c. Scan the patient to get CT images of the tumor and surrounding internal body structures.
2. Oncologists and dosimetrists plan where to irradiate.
    a. From the CT scans, a dosimetrist will identify cancerous tissue and plan the treatment by defining the shape and angle of the radiation beam (Figure 5). With the aid of computer software, dosimetrists plan for the correct dose of radiation to target cancerous tissue and leave healthy tissue maximally untouched. The *isodose lines* in Figure 6 show the amount of dose various tissues receive. Dosimetrists must also be wary not to create a plan in which a collision between the gantry and the patient or couch can occur [11].
3. Patients begin their multi-week treatment regime. Each day patients go into the clinic for treatment:
    a. They verify their identity and what body part they are receiving treatment for. This ensures that the correct patient is given the correct treatment [13].
    b. Patients are aligned on the couch. It is of utmost importance that the patient is accurately positioned on the couch, so when the treatment plan is performed, radiation is administered to the correct location in the patient. Without accurate patient alignment on the couch, radiation would

be directed at and damage healthy, non-cancerous tissues. Additionally, the radiotherapy would be ineffective, since the beam won't be focused on the target tissue. The current process for aligning patients can be broken down into three steps.

i. First, the personalized immobilization devices are placed on the couch/patient, along with any machine accessories prescribed in the treatment plan to help focus the radiation.
ii. The couch's 6-degrees of freedom (x, y, z, pitch, roll, and yaw) are adjusted, so that markers placed on the patient's body prior to treatment align with reference lasers in the treatment room (see Figure 4).
iii. Images of the patient's current location and reference location are aligned. This image alignment process can be surface guided using cameras in the treatment room, and/or guided by a new CT scan taken by imaging panels extending off of the linac. The new CT scan is superimposed with the planning CT, and the displacements between the internal body features can be calculated. This is called *co-registering* (Figure 7). The couch is adjusted according to the calculated displacements that were determined during co-registering, and finally, the patient is accurately positioned.

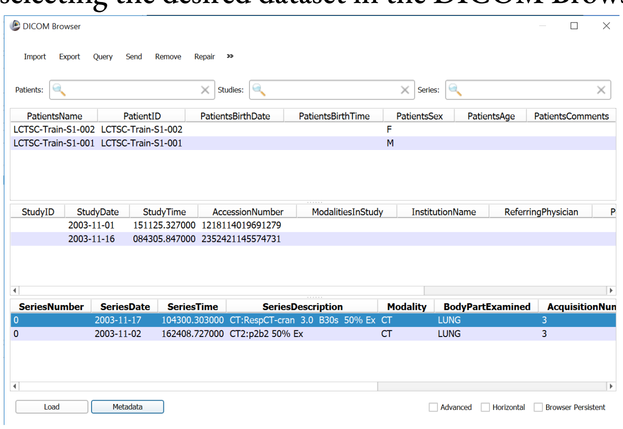
c. The therapist commands the linac to execute the treatment plan.

DETAILED WORKFLOW STEPS

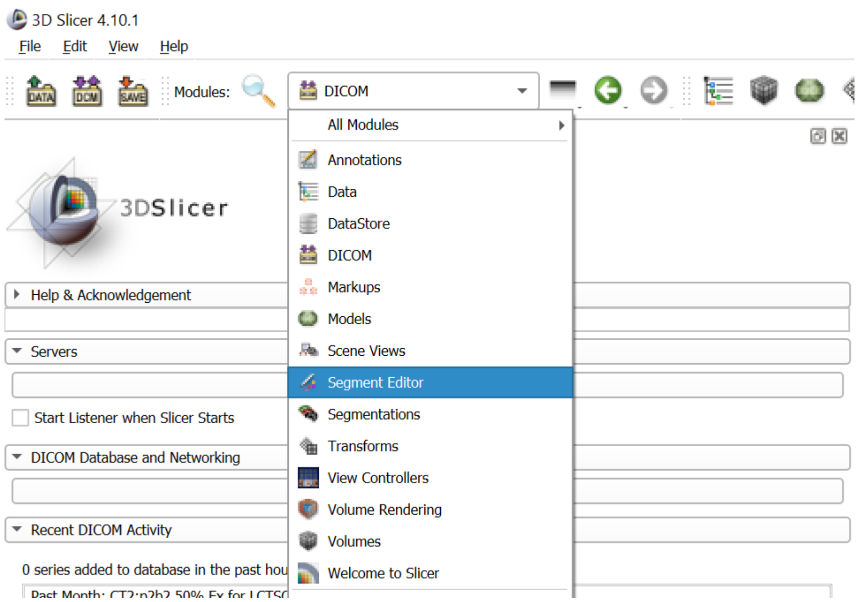
Detailed Diagram 1: Converting CT Scans into Holograms

3D Slicer ("Slicer") is an open source program that can be used to view CT scans. Users can define specific organs in the CT scan, and construct 3D models. The following is the step-by-step outline of defining the patient's skin/outline to convert a CT scan into a 3D model, and into a Hologram in Unity.

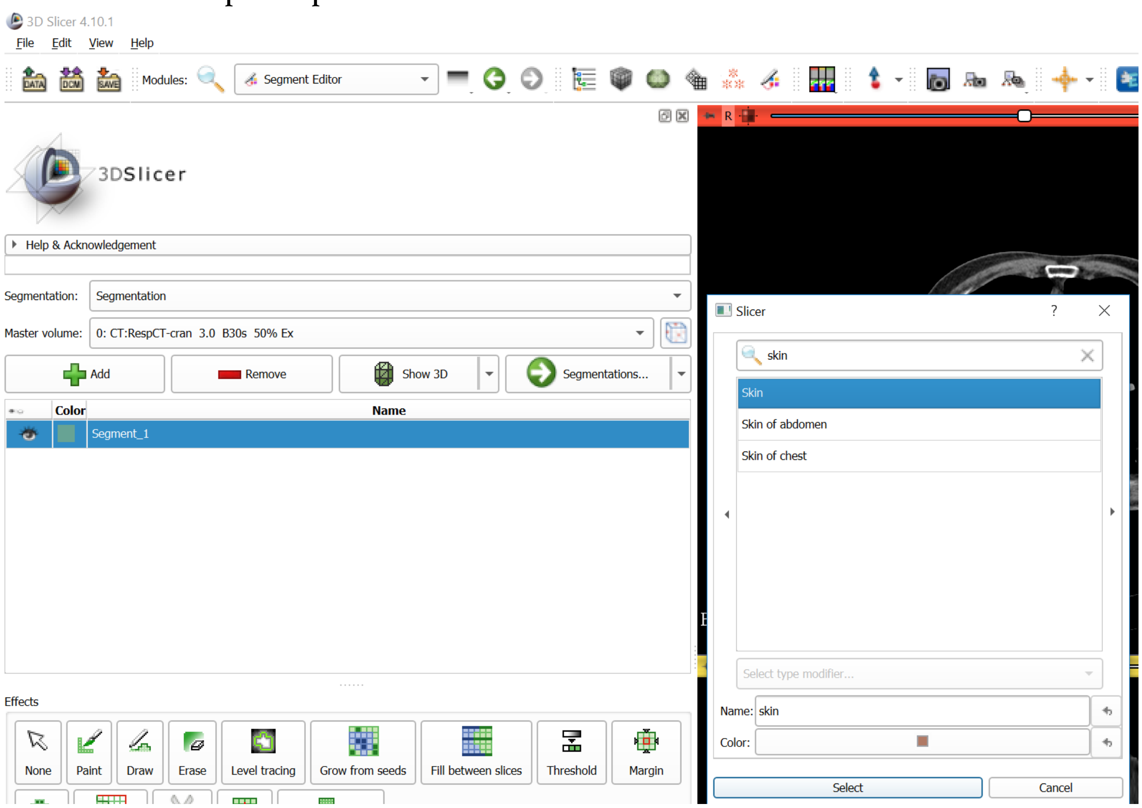
1. Upload the set of CT slices into 3D Slicer by dragging and dropping their folder onto the Slicer window, selecting the desired dataset in the DICOM Browser, and clicking "Load."



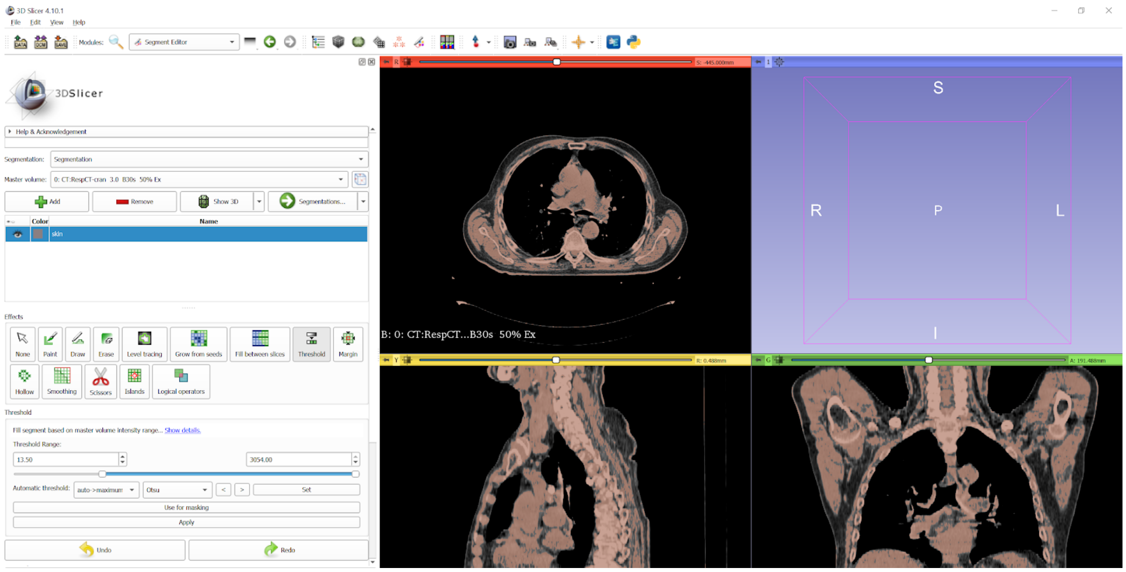
2. Change the Module from "DICOM" to "Segment Editor" using the dropdown menu.



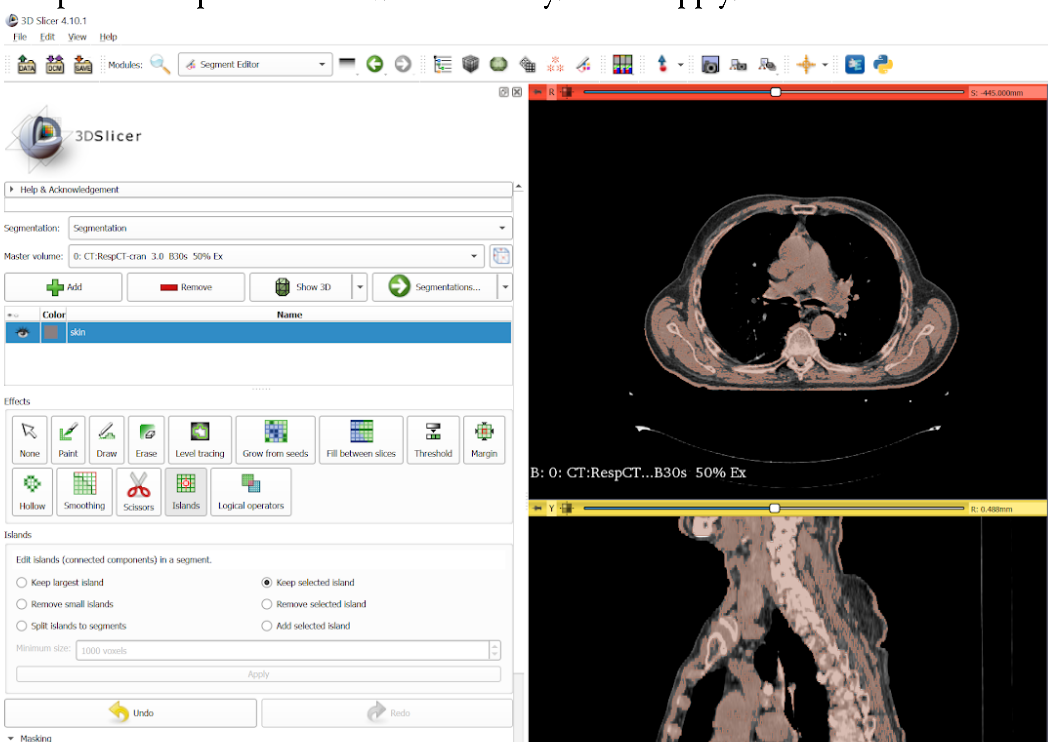
3. Click “+ Add” to add a Segment. Double-click over the “Color” of the newly created segment, and select “Skin” from the options provided.



4. Select the “Threshold” tool. Use the sliders to adjust what level in the grayscale will be included in the skin contour. Adjust so that all of the patient’s skin is colored. Click “Apply.”

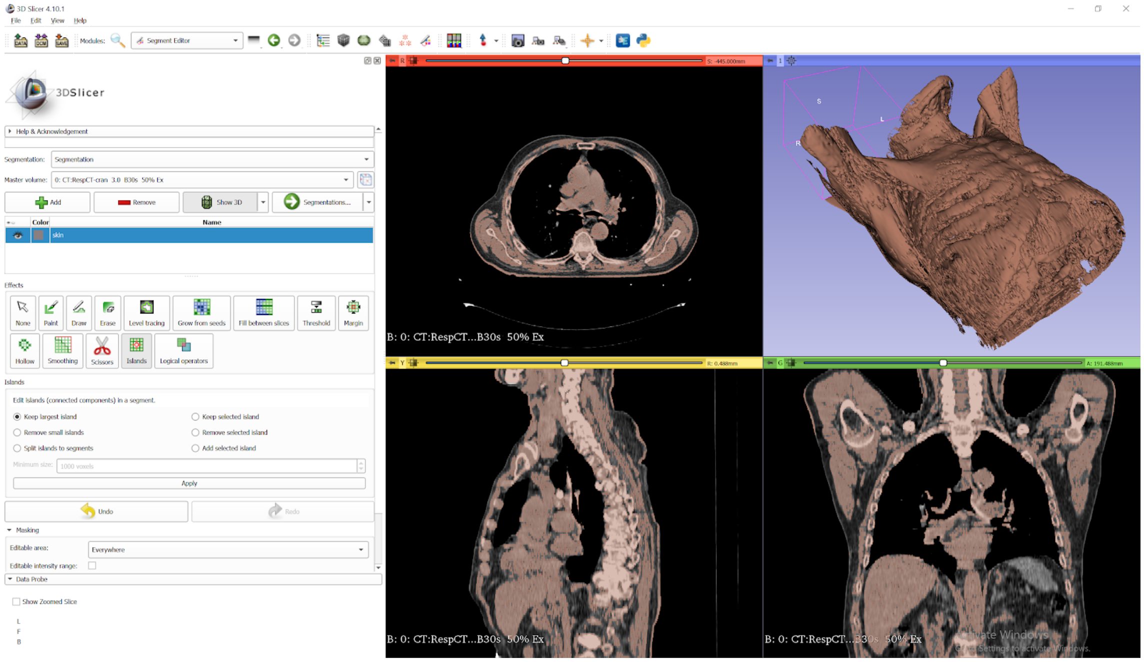


5. Select the "Islands" tool. Choose "Keep selected island." Click on any of the colored parts in patient's body that contains the skin. This will remove noise and other objects that the CT Scan images that are not the patient, evident as they change from the color of the skin segment to grayscale. Alternatively, choose Choose "Keep largest island." Note, since the patient is in contact with the couch, it is likely the couch will be a part of the patient "island." This is okay. Click "Apply."

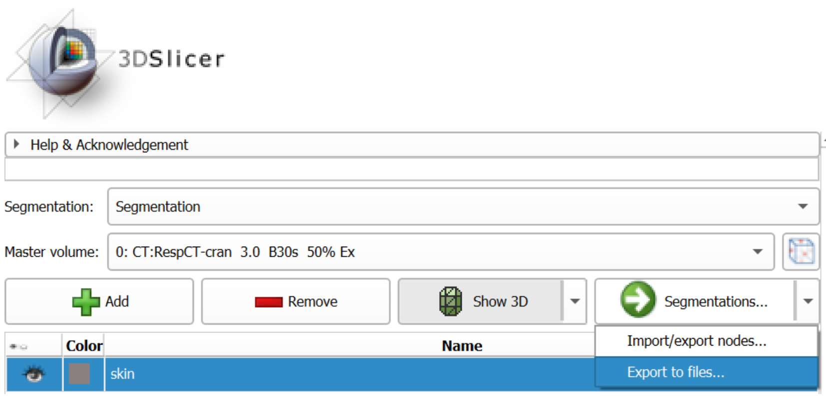


6. Click "Show 3D" to visualize the 3D skin segment model and confirm the desired structures are included. Initially, the segment may be out of view. Place the mouse cursor in the purple 3D window, and scroll, click

and drag, or hold down the scroller and drag in order to zoom, rotate, and pan respectively.



7. From the Segmentation drop-down menu within the Segmentation Editor, click "Export to files..." Choose "OBJ" as the file format. Click "Export."



8. Open a Unity project. From the menu bar, choose File > Import Asset. Select the .obj file you just saved.
9. Add a light to the scene in order to view the patient's shape, beyond just the body outline/contour.

Detailed Diagram 2: Programming Hologram Retrieval

1. Scan QR Code
    a. Will be on patient's ID card
2. Retrieve patient ID data from the scan
3. Look up the hologram (.obj file) associated with that data
    a. Find the .obj file path
4. Display hologram generally in the scene

Detailed Diagram 3: Hologram Positioning

1. On the internet in Vuforia's *Target Manager*, upload images of the three different image markers onto the database
2. In Unity, import the database and place the three (virtual) image markers in space
    a. Import & position the .fbx file (the 3D object) on top of the three virtual image markers, but with the three markers in the 3D object being matched to the three virtual image markers from the database