Open-source software for collision detection in external beam radiation therapy

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ABSTRACT

PURPOSE: Collision detection for external beam radiation therapy (RT) is important for eliminating the need for dry-runs that aim to ensure patient safety. Commercial treatment planning systems (TPS) offer this feature but they are expensive and proprietary. Cobalt-60 RT machines are a viable solution to RT practice in low-budget scenarios. However, such clinics are hesitant to invest in these machines due to a lack of affordable treatment planning software. We propose the creation of an open-source room's eye view visualization module with automated collision detection as part of the development of an open-source TPS.

METHODS: An openly accessible linac 3D geometry model is sliced into the different components of the treatment machine. The model's movements are based on the International Electrotechnical Commission standard. Automated collision detection is implemented between the treatment machine's components.

RESULTS: The room's eye view module was built in C++ as part of SlicerRT, an RT research toolkit built on 3D Slicer. The module was tested using head and neck and prostate RT plans. These tests verified that the module accurately modeled the movements of the treatment machine and radiation beam. Automated collision detection was verified using tests where geometric parameters of the machine's components were changed, demonstrating accurate collision detection.

CONCLUSION: Room's eye view visualization and automated collision detection are essential in a Cobalt-60 treatment planning system. Development of these features will advance the creation of an open-source TPS that will potentially help increase the feasibility of adopting Cobalt-60 RT.

KEYWORDS: Radiation therapy, treatment planning, SlicerRT, Cobalt-60

1. INTRODUCTION

Radiation therapy (RT) is a commonly used form of cancer treatment that uses high-energy radiation such as X-rays, gamma rays, protons or other charged particles to kill cancer cells. The goal of RT is to optimize the amount of radiation delivered to the cancerous cells while minimizing the amount delivered to surrounding healthy tissue. Most treatments use radiation delivered from an external source. This is known as external beam radiation therapy (EBRT).

Currently in developing countries, only 25% of patients who require RT have access to treatment machines. Developing countries make up 85% of the world population, demonstrating a visible gap in accessible treatment[1]. Cobalt-60 (Co-60) machines were used before modern linear accelerators (linac) were developed for common use. The Co-60 machines were heralded as having a simple robust design, with minimal power, maintenance, and technical expertise to operate. Healy *et al.* have taken a critical look at the differences between linacs and Co-60 machines. Their analysis has shown that Co-60 machines are $300 000 - $900 000 cheaper than 6MV and multi-energy linacs, require baseline staff to operate, and have relatively simple physical characteristics[2].These qualities were and still remain important for hospitals and cancer care clinics in low-income countries where it is more difficult to operate complex machines like linacs. Another important consideration that Healy *et al.* discuss is that choice of radiation therapy machine must be based on its sustainability in the clinic for at least 10-15 years. The benefits that Co-60 machines possess position them as the more sustainable choice in low-budget scenarios.

Thus, Co-60 units are being proposed as an effective option to improve this shortage. Unfortunately, many clinics are hesitant to purchase these machines due to fear of the technology being outdated and unable to provide similar quality of treatment as modern linear accelerators. Medical physicists from the Cancer Center of Southeastern Ontario and Queen's University are researching the ability to use Co-60 intensity-modulated RT (IMRT) as an alternative to linac IMRT. Their initial studies have shown that known issues with Co-60 machines are negligible when using rotational RT[3].

Computerized treatment planning systems (TPS) have been developed by medical technology companies to assist radiation oncology teams in determining proper radiation doses and visualizing the treatment plan and machine. However, these commercial systems are expensive, proprietary, and only support linac treatment workflows. A shortcoming for the Co-60 units is that there is no commercially available TPS that is comparable to those offered for linac RT[3].

An important component of these systems is the room's eye view (REV) that is a visualization of the EBRT machine based on the International Electrotechnical Commission (IEC) standard to help visualize the treatment process and eliminate the need for dry-runs that aim to prevent machine-patient collisions and confirm that the chosen beam angles will interact with the patient as intended. REV software modules have been developed by research groups to properly model the EBRT machine that commercial systems are offering. Hamza-Lup *et al.* created a standalone free web-based 3D visual simulator with accurate modeling of the IEC movements of the gantry and patient couch and verified their collision detection was accurate within 5-10 mm[4].

We propose a complete open-source TPS for Co-60 treatments, part of this effort is developing the visualization and safety features. Collision detection is an essential part of these safety features to eliminate the need for dry-runs. They are manual tests performed by the radiation oncology team where patients are taken into the treatment room and the machine is run through all of the chosen angles without the radiation being turned on. This results in additional time and resources being used by clinics, which could be used to treat additional patients. Often times if angles are not chosen carefully then collisions can occur between machine components which can cause irreparable damage to the EBRT machines. More importantly, patient-machine collisions can also occur which cause unintended injuries.

Several research groups have worked to improve collision detection using a variety of methods. Becker developed collision indicator charts specifying gantry and patient support angle combinations that typically result in collisions[5]. The charts make it efficient for radiation oncology teams to verify whether chosen angles will result in collisions between those two parts of the machine and the patient only. This leaves possible collisions between the table top and additional treatment devices that may be used unchecked. Software applications with REV visualizations and automated collision detection have become a main focus of numerous research groups. Szarmes *et al.* have developed a software tool to demonstrate patient-linac collisions visually and have included patient modelling using the Xbox Kinect[6]. Our collision detection aims to work with typical treatment scenarios and those that are used in RT research. Some of these scenarios may involve the use of additional treatment devices such as electron applicators which will be included in our automated collision detection. The room's eye view module aims to provide these essential components for the proposed TPS. Our aspiration is that the development of a fully usable open-source TPS with these features will encourage hospitals and clinics in developing countries to invest in Co-60 machines to help reduce the shortage of accessible RT.

2. METHODS

2.1 RT treatment machine geometric model

The open-source TPS being developed is meant to be extensible and will support multiple modalities and machines while mainly focusing on Co-60 RT. Thus the goal is to be able to model any machine. We used the treatment machine model for the Varian TrueBeam™ STx system, because it is a prevalent linac machine worldwide, and because its model was freely accessible, thus allowing the development of a proof-of-concept module that is later to be extended to contain Co-60 models. The linac model was downloaded from 3D Warehouse[7] in SketchUp (.skp) format and then converted to the stereolithography (.stl) format for compatibility with 3D Slicer (www.slicer.org)[8], our application platform of choice. 3D Slicer is a widely used medical image analysis and visualization platform, and acts as the base platform for the SlicerRT radiation therapy research toolkit[9]. SlicerRT is the environment based on which the proposed open-source TPS is being developed. The original machine model was separated into the linear accelerator, gantry, collimator, table top, patient support, and imaging panels using Microsoft 3D Builder (illustrated in Figure 1). The separated pieces were then loaded into 3D Slicer and translated to ensure that the isocenter of the treatment machine was at the origin. A partial patient model (head, neck, and shoulders) was created in 3D Slicer using the CT data of a head and neck phantom.

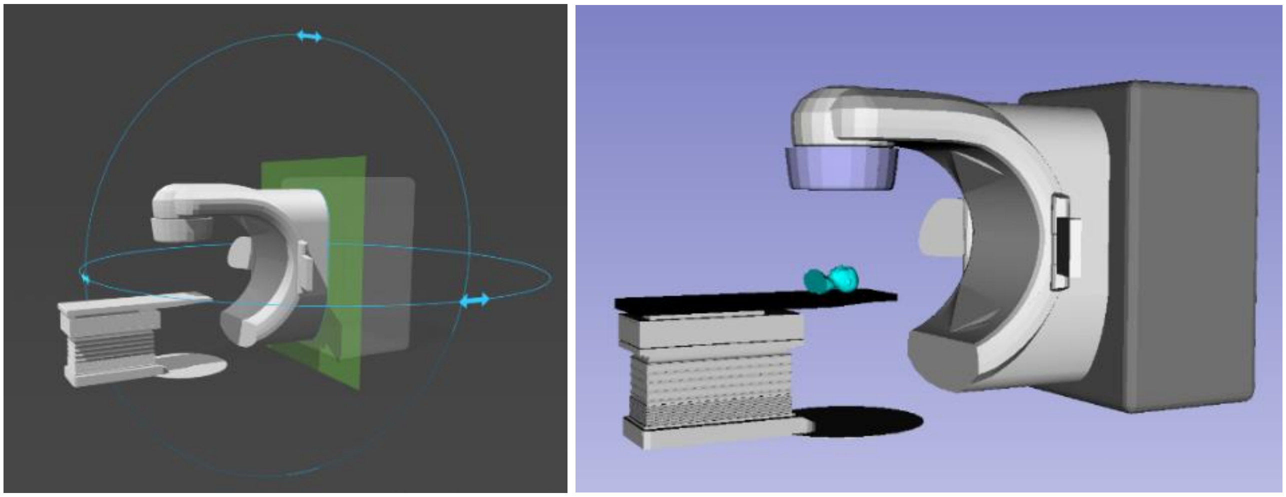
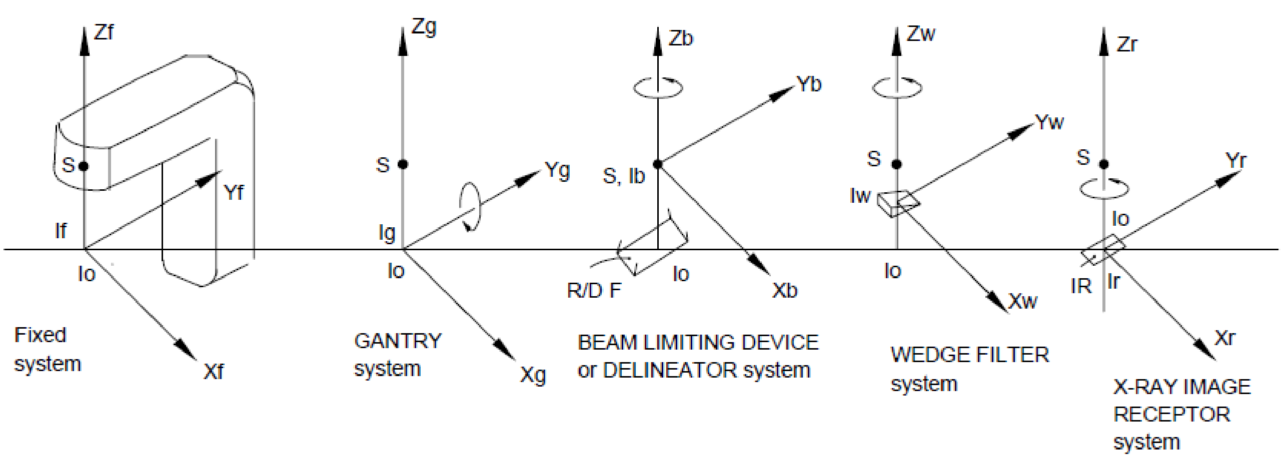


Figure 1. Splicing of the linac model into different hardware pieces using Microsoft 3D Builder (left) which were then loaded into 3D Slicer (right).

2.2 Room's eye view and beam visualization

The IEC standard specifies the set of coordinate systems and movements to be used by all RT machines, helping to reduce ambiguities during treatment planning and simulation (illustrated in Figure 2). The coordinate systems are organized in hierarchies where each major hardware component is assigned a right-handed coordinate system. These coordinate systems are derived from one another with the fixed reference being the common mother system. The transformation hierarchies were developed in compliance with the standard, ensuring compatibility with all treatment machines that follow the standard. The range of motion for each piece of the machine were based on measurements taken by the movements of a Varian Truebeam™ STx linear accelerator at Kingston General Hospital and those specified in the standard. The module follows the rotation scale defined in the standard which is between 0-359°.



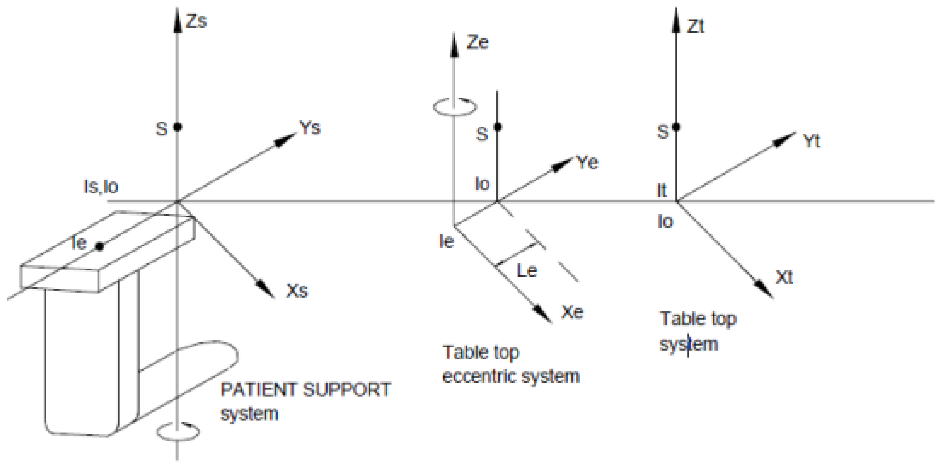


Figure 2. The coordinate systems and movements of each piece in the linear accelerator defined in the IEC standard[10].

The transform hierarchies were implemented using matrices representing rigid transformations. In accordance with the hierarchy described in the IEC standard each transform was set as a parent of another transform until the fixed reference coordinate system was reached (illustrated in Figure 3). This ensured that any change applied to one transform was also applied to its child transforms which is important for pieces of the machine such as the gantry, collimator, and the beam which move simultaneously when the gantry is rotated.

Figure 3. The transform hierarchy for EBRT machines defined in the IEC standard implementation in 3D Slicer using the matrices representing rigid transformations.

2.3 Collision detection

Commercial TPSs include automated collision detection to verify the usability of the beam angles, which affect the treatment machine geometry, and to ensure patient safety. An open-source software library known as vtkbioeng[11] was used as a basis to implement automated collision detection in our module. The vtkCollisionDetectionFilter class determines collisions between two polygonal objects using oriented bounding box trees (OBB trees). They create an oriented bounding box, which is a bounding box that doesn't line up exactly with the coordinate axes[12]. The class creates a tree that defines larger spaces of regions at nodes closer to the root and smaller regions of spaces at nodes deeper in the tree. Each polygon provided as inputs to the collision detection class is used to create their own OBB trees. Then each edge of the first polygon is checked against the second polygon for intersections. Within each check, tests for parallel, coplanar, and overlapping edges are made. Afterwards, each edge of the second polygon is checked against the first polygon. The class returns the first test that results in an overlapping pair of edges.

The collision detection class was applied between the collimator and the table top, the collimator and the patient support, the collimator and the patient, the gantry and the table top, the gantry and the patient support, and between the gantry and the patient. These machine component pairs were chosen as they encompass the possible collisions between different parts of the treatment machine. The collision detection logic determines collisions between two models by checking for intersecting triangles between the bounding boxes of the models.

3. RESULTS AND DISCUSSION

We implemented the treatment machine visualization and collision detection as a Room's Eye View C++ module within SlicerRT. The translations and rotations of the treatment machine were verified using two RT treatment plans, one for a prostate tumor and another for a head and neck tumor. The angles (gantry and collimator) from the beam described in the RT plan were used and manually entered into the module for the purpose of testing with the RT plans. The treatment machine will automatically be transformed based on the beam angles when the module is integrated into the proposed open-source TPS. The module accurately models the movements of the treatment machine in accordance with the IEC standard (illustrated in Figure 3). The success of these tests indicates that the module can verify geometric parameters chosen during both forward and inverse treatment planning.

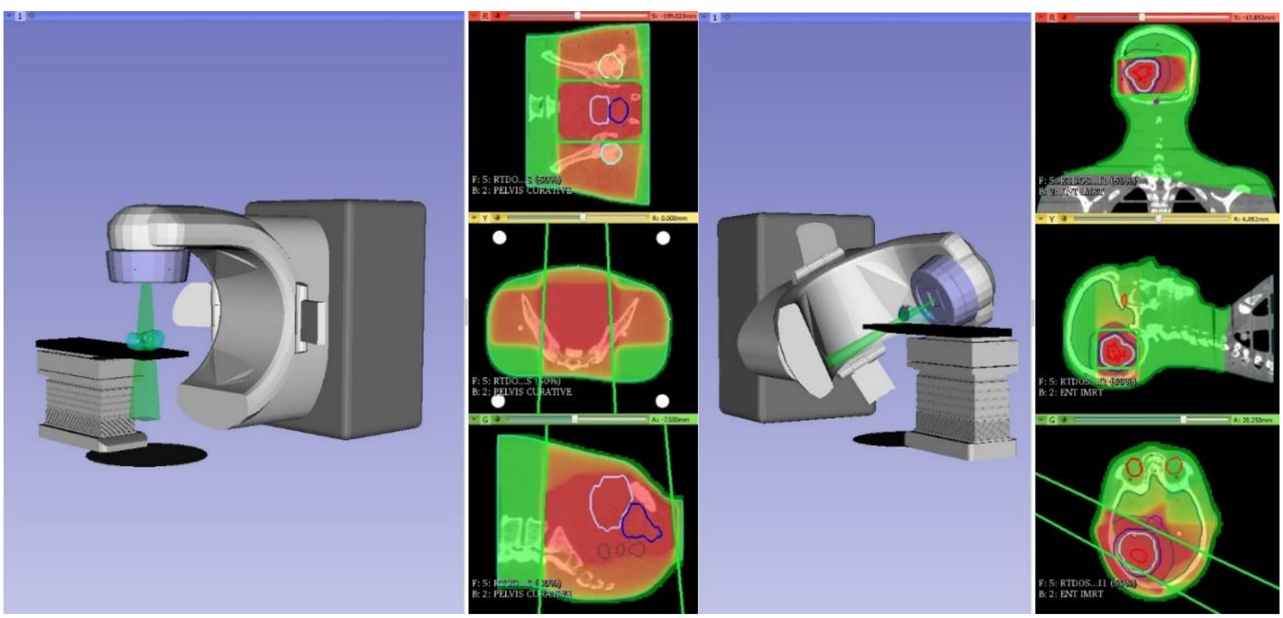


Figure 4. Successful modeling of treatment machine, radiation beam, and room based on geometric parameters (gantry and collimator angle) for both prostate (left) and head and neck (right) RT treatment plans.

The automated collision detection component serves as a safety feature for the open-source TPS. The feature was tested by changing the geometric parameters of the pieces of the treatment machine to cause collisions between each pair of components. A notification label in the UI was used for each collision to verify whether the detection was correct. Each test was successfully completed and tests combining possible collisions were performed together to guarantee the accuracy of simultaneous collision detection between multiple parts of the machine (illustrated in Figure 5).

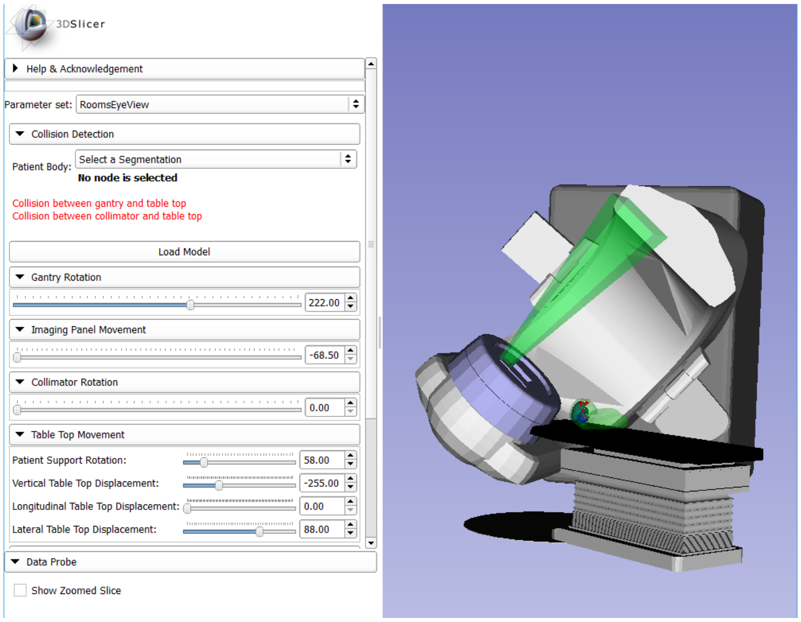


Figure 5. Successful simultaneous collision detection between table top and collimator and the gantry and table top indicated by the red text notification.

This REV module will be integrated into the open-source TPS called External Beam Planning (illustrated in Figure 6) that is being developed as part of SlicerRT. It will provide essential visualization and safety features that will assist in the treatment planning process, and help confirm the usability of selected beam angles. Instead of the initially used Varian TrueBeam™ linac model, a more specific model will be used to provide an exact replication of the Co-60 units, which will enable real collision detection in Co-60 treatments. Additional treatment device models will also be created to provide further accuracy in collision detection for research treatment plans that use devices such as electron applicators. This will provide accuracy in collision detection that is not currently provided by commercial TPSs as they do not include additional treatment devices in their visualizations. The implemented Room's Eye View module successfully models the IEC standard and provides accurate collision detection, enhancing the visualization and safety features of the open-source TPS being developed.

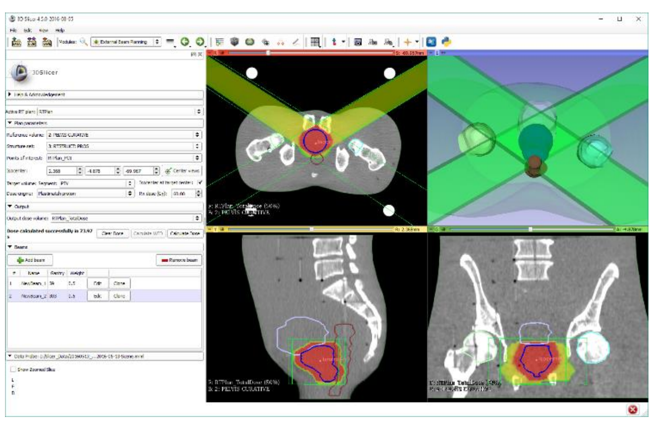


Figure 6. Current open-source TPS being developed in SlicerRT focusing on Co-60 that will integrate the visualization and safety features necessary developed in our REV module.

4. CONCLUSIONS

A room's eye view visualization module with automated collision detection was developed as a component of an open-source TPS in the SlicerRT toolkit to facilitate improvements to Co-60 IMRT treatments. More specific patient modeling based on patient CTs and exact Co-60 machine models will be added to enhance visualization and collision detection accuracy. Additional treatment devices such as electron applicators will also be modeled through visits to Kingston General Hospital which will further improve the collision detection. These devices are not included in commercial TPSs, albeit being prevalent in research settings. Thus, we will be creating generic 3D models of these treatment devices using CAD software to provide an additional level of collision detection. This will ensure that the open-source TPS can support multiple modalities and treatment types.

Another important visualization offered by TPSs is known as the Beam's Eye View (BEV). This visualization places the point of view at the beam source position and directs it towards the isocenter of the beam. BEV helps radiation oncology teams ensure that the beam aperture follows the planned shape and conforms to the shape of the tumor ensuring that all of the cancerous tissue is being irradiated while sparing the surrounding healthy tissue. The BEV visualization will include a digitally reconstructed radiograph (DRR).The treatment machine will be used as an orientation marker in the module to enhance the REV visualization features further.

This visualization module will be integrated into the External Beam Planning module, the open-source treatment planning system being developed in SlicerRT. Geometric parameters from loaded treatment plans will be used to automatically transform the pieces of the treatment machine eliminating the need for manual entering. This open-source TPS will provide complete support for Co-60 RT treatments, which will potentially facilitate more accessible treatment planning for clinics in low-budget scenarios, including clinics in developing countries. We aim to encourage more of these clinics to invest in Co-60 RT as a sustainable way to bridge the visible gap in accessible RT treatment.

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