Development of a Visible Light Tomograph for Teaching Computed Tomography Concepts in Undergraduate Medical Physics Classrooms

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Abstract— **Currently, engineering education faces challenges from needing to adapt to rapid and unpredictable technological changes. Computed tomography (CT) is an imaging diagnostic technique that visualizes internal structures of the human body or other objects, using ionizing or non-ionizing radiation. Tomographic reconstruction (TR) is a process that uses data from measurements at different angles to create a three-dimensional image of an object or region of interest. This technique is widely used in areas such as medicine, engineering, physics and geology, among others. We felt that teaching of CT in our undergraduate medical physics course leaves students without deep knowledge of the technology, so we conducted a survey with undergraduate students and teaching staff to understand this need, in which 78.9% of responders expressed difficulty with learning CT concepts and all felt that didactic equipment would improve their understanding. We developed low-cost CT equipment using visible white light to provide students with experimental contact from which to learn the principles of CT image acquisition and TR. The apparatus acquires projections through photos of the shadow of an object, rotated in various angles; we used 18 projections, from 0°to 170°. Software was developed for filtered and unfiltered TR from the projections, and an image processing pipeline was used to create a binary 3D mask, representing the object's volume in the case of filtered TR, which was 3D printed. Results were reasonable for didactic purposes, although we observed artifacts caused by the small number of projections, which led to high noise in the reconstruction, amplification of the object, diffraction and finite size of light source, non-parallel nature of the rays, which are important sources of error for the modality and important for students to understand.**

Keywords— **Computed tomography, Medical Physics teaching, Tomographic reconstruction, visible light tomograph**

I. INTRODUCTION

Engineering has developed over the centuries, following the advances of society, and being an essential tool in search of solutions to diverse challenges, such as civil construction from the first civilizations and technological progress driven by the industrial revolution. The history of engineering is a narrative of continuous innovation, reflecting the needs and aspirations of societies over time. Engineering education has evolved from a practical emphasis to include a solid theoretical basis, and presents a diversity of educational models, which reflect the dynamic nature of the discipline and the need to prepare engineers for contemporary and future challenges [1].

It may be said that the current challenge in Engineering education is to adapt educational systems to face rapid and unpredictable technological changes [2]. The authors believe that there is a need for the development of teaching resources to provide students with the closest possible contact with theoretical contents learned in the classroom, while encompassing practical and realistic situations found in industry.

The discovery of X-rays in 1895 by the German physicist Roentgen [3] revolutionized the medicine of his time, allowing visualization inside the human body without being surgically opened. In 1917, Austrian physicist Johann Radon [4] proposed a mathematical method for reconstructing functions from their projections. With the mathematical contributions of mathematician Allan Cormack in the 1960s, Godfrey Hounsfield and Dr James Ambrose developed computed tomography (CT), which allowed the acquisition of high-resolution three-dimensional tomographic images using X-rays, which caused a significant impact on diagnostic medicine [5, 6].

In general, CT allows visualization of internal structures in the human body, or other objects, through the use of ionizing or non-ionizing radiation [7, 8]. Tomographic reconstruction (TR) is a process that uses projection data, obtained from measurements at different angles [9], to create a three-dimensional image of an object or bodily region. The technique is widely used in areas such as medicine, engineering, physics and geology, among others [5, 10].

Our undergraduate degree in Biomedical Engineering at Federal University of ABC (UFABC), São Bernardo do Campo, São Paulo, Brazil, contains courses in Medical Physics, one of which includes the physical principles of modalities including X-ray, CT, nuclear medicine (NM) and ultrasound (US). While we possess a laboratory containing US instrumentation, which can be used for educational purposes, the use of ionizing radiation (X-ray, CT, NM) is too expensive for our department to purchase, and would not be allowed for education purposes due to health risks associated with ionizing radiation. Our didactic material relies on photos from books and diagrams; but ideally students could use safe experimental equipment, allowing a better understanding of the physical laws and engineering challenges involved in the design of the instrumentation and software required for TR.

II. Objectives

Our purpose is to develop an easy-to-build educational device for teaching the concepts of CT and TR, as well as algorithms for TR of 3D objects. Specific objectives are:

1. Understand the need for didactic equipment to explain the principles of CT;
2. Develop a didactic prototype of CT equipment using safe radiation (visible light), capable of acquiring images of 3D objects in multiple projections, which will assist in teaching the main concepts of CT;
3. Develop software to assist in teaching the principles of TR, i.e. reconstruct an object's 3D volume from a set of multiple projections.

III. Materials

- Source of visible white light - small flashlight with fairly homogeneous central region;
- Projection screen: baking paper inset in cardboard;
- Object to be imaged, in our case, a wooden flower;
- Cellphone with camera;
- 3D printer (3D Core A3 GTMAX3D-PRO).

- Software written in Google (Mountain View, CA) Colab;
- Python 3 and standard scientific libraries including simple ITK;
- 3D slicer (Surgical Planning Lab, Boston, MA) v5.6.1;
- Blender (Blender Foundation, Amsterdam, Netherlands) v4.1.1;
- Simplify 3D v.1.2 to generate gcode from .stl.

IV. Methodology

A. Survey about medical physics teaching for CT

First we designed a survey for undergraduate students who had taken the medical physics course and for university lecturers who have experience with this material to discover their opinions about the need for equipment for teaching principles of tomographic reconstruction. Appendix A contains survey details and results. The questions had the main purpose of understanding students' difficulties in understanding the content surrounding CT and TR, as well as checking whether there is interest in providing practical contact with teaching equipment.

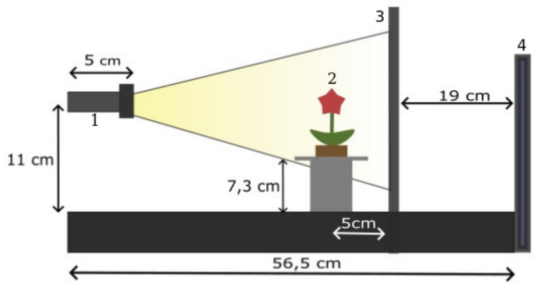
B. Development of a visible-light tomograph

Larsson et al (2023) [11] show the development of a visible-light tomograph using an LED source, a webcam and a microcontroller. We adapted this design to create equipment, using reusable materials where possible, as shown in figure 1. Cardboard was used to create the structure of the tomograph. The object to be visualized was placed on a platform and aligned so that white light shining from the source would hit the object in an approximately horizontal center line and project a shadow on the screen. The distance from the light source to the object was maximized and from the object to the screen minimized to provide an optimized level of shadow sharpness and for the rays to be as parallel as possible. Initially, we used a lens to make the rays more parallel, but this made the design more complex and expensive, while adding little value to the image quality or students' learning experience.

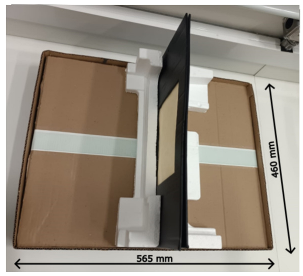
A cellphone was fixed on the opposite side of the screen, positioned so that clear photos of the projection screen could be acquired. The object was manually rotated and 18 images acquired and saved from 0° to 170° in steps of 10°. A single photo was acquired for each rotated angle of the object. A vector of the angles was created in software for TR. Images were cropped to the region of interest, 1550×1550 pixels, as seen in figure 3 and then resized to 387×387 pixels.

C. Reconstruction of volume

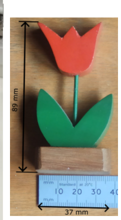
TR was performed row by row according to the Algorithm in figure 2. Two numpy 3D zero `nd arrays`, each of size $387{\times}387{\times}387$ voxels, were created to hold filtered and unfiltered reconstructed volumes. Each row of the images, r has 387 elements. We form an image set, R, by taking row r from each of the 18 images and form S, the sinogram matrix, size $387{\times}18$, by putting the rows of R into the columns of S. V_r is the rth slice of the reconstructed volume. Filtered and unfiltered reconstruction are performed for the set of matrices S; each produces a single slice of the 3D object. As each slice is computed, it is stored in the relevant 3D array. The filtered TR differs from the unfiltered by including the removal of low frequency components in the image, which tend to cause image blurring. Reconstruction was performed in Python3 using the `iradon` function in `sci-kit image`, where options `filter_name='none'` and `filter_name='ramp'` was used to perform unfiltered and filtered TR. Filtering ap-



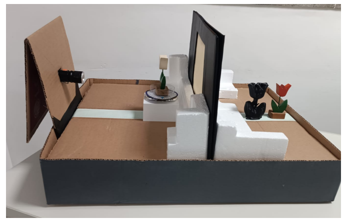
(a) Lateral projection of equipment. 1: torch; 2:platform and imaged object; 3:projection screen; 4:Cell phone camera



(b) Plan of equipment



(c) Object to be imaged



(d) Final plan of equipment, showing torch. Camera was mounted on the right side. 3D printed rescontructed object shown next to red flower.

Fig. 1: Development of the apparatus

Algorithm 1: Reconstruction Algorithm

Data: 18 images of size 1550×1550
Result: Reconstructed 3D volumes, as specified above
for *each image set, R, defined by row r from 0 to 1549* **do**
  Construct S from R;
  Reconstruct slice V_r using the filtered and unfiltered inverse radon transform of S;
  Store reconstructed slices V_r in the 3D matrices;
end

Fig. 2: Reconstruction Algorithm

plies a 1D frequency domain ramp filter to each column of the sinogram,

The TR step is shown in figure 4a., including the filtered and unfiltered TR. The filtered reconstruction had superior quality and sharpness, so was used for the rest of the methodology.

D. Image processing

We designed an image processing pipeline, figure 4, to reduce noise in the reconstructed image and create a 3D binary mask, defining the object volume.

(b.): Voxels were saved as type `float32` for compatibility with the following steps. The volume occupied too much memory for some image processing steps, so images were resized to 387×387×387, 1/64 of the original volume. (c.): reconstructed slices for rows at the height of the flower and at the height of the leaves (left, filtered; center, unfiltered). (d.): Volume slice after low-pass filtering of the volume with a Gaussian filter ($\sigma = 8$); high frequency image noise interfered with segmentation of the figure. (e.): The histogram was plotted, and a threshold was identified for volume segmentation, found to be voxel grayscale values less than 0. These voxels were set to `True` in the 3D binary mask, otherwise `False`. (f.): Slice of binary mask at the level of the leaves. (g.): 3D binary mask saved in .nrrd format for importing into 3D slicer. Since there were some small volumes not connected to the main flower, we removed these with a connected components analysis, creating a new mask with the voxels from the majority class. (h.) .nrrd file exported to .stl in 3D slicer, and opened in Blender for visualization. The final 3D volume was 3D printed. The authors made a video to describe the methodology in a more visual manner[1]

V. Results

A. Survey: medical physics teaching of CT

We can see that many students had some type of difficulty in learning the topic, as demonstrated in question 4, where 78.9% admitted to having some type of difficulty in the topic. Although more than half of the interviewees demonstrated a good understanding of CT concepts, all participants agreed that contact with teaching equipment in a practical setting could be useful to assist understanding of theoretical concepts.

B. Reconstruction of volume

Acquired images are shown in figure 3. We notice that there is considerable inhomogeneity of illumination and also that the top of the flower, due to non-parallel light rays and varying distance of source to object, is higher on one side than the other (effect particularly visible in the 30°rotation, where the petal closer to the light source is higher than the petal further from the source.)

[1] `https://youtu.be/HNbFG6FbK2U`

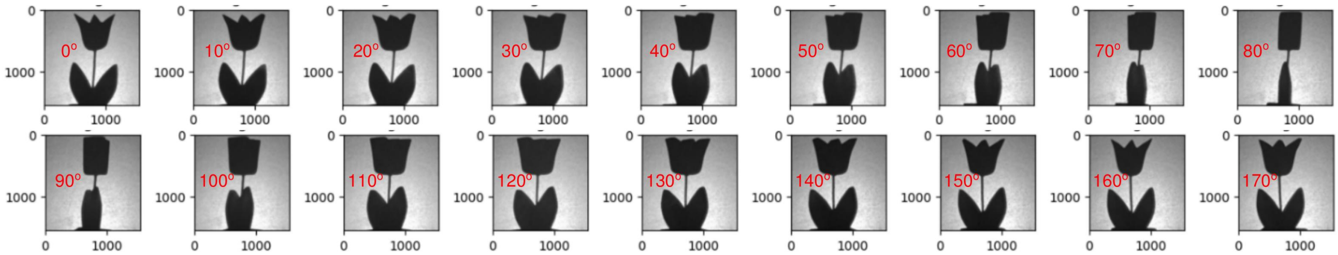


Fig. 3: Acquired shadow images of object projected on the screen, from 0°to 170°

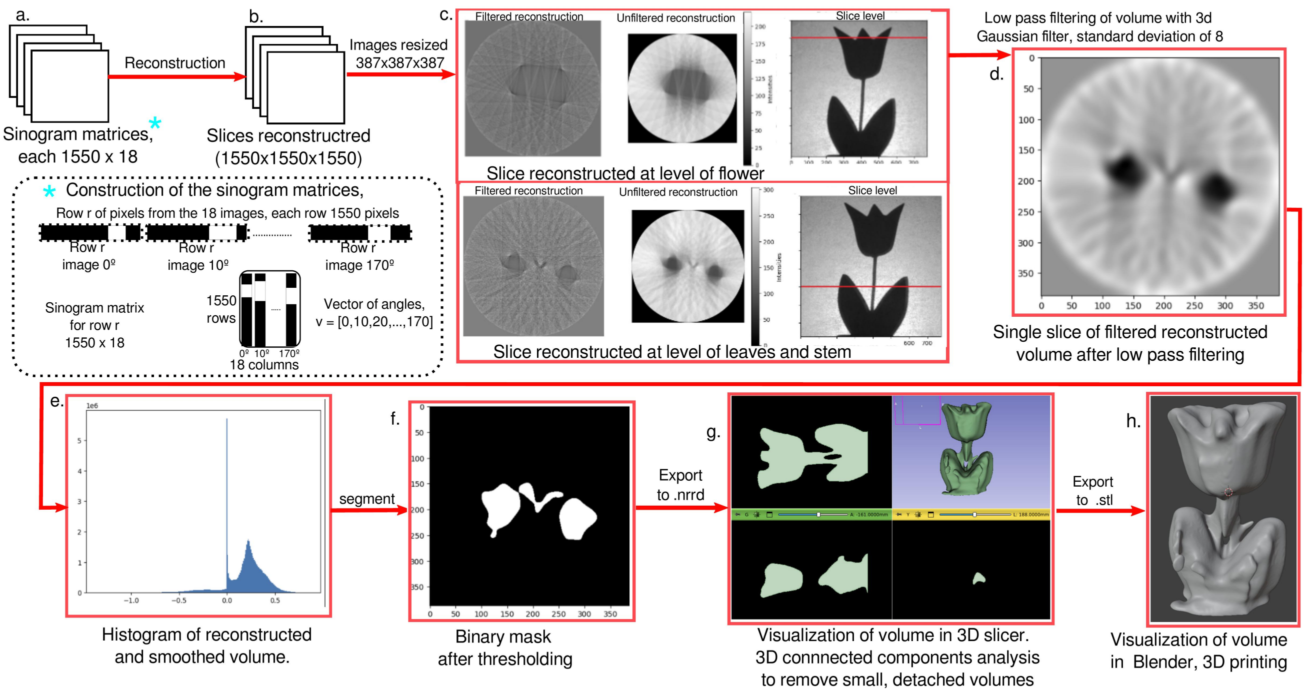


Fig. 4: Image processing pipeline. Stages are labelled from a to h. The figures in the dotted box shows how the sinogram matrices were constructed, for the inverse Radon transform. To construct a sinogram for row r, we take the grayscale values from row r from each image and put them as columns of a new matrix. In our case, the 18 projections create 18 columns in the matrix for row r. We form a vector with the angles, which is also required for the transform.

While we attempted to place the object as near as possible to the screen to get a sharp image, it is still blurred due to the finite size of the source and diffraction effects.

Filtered reconstruction was found to be less blurred than unfiltered, but there was a lot of high frequency noise in the image, seen in the variation of contrast in the regions towards the outside of the circles in figure 4

C. Image Processing

Gaussian filtering smoothed the high frequency noise to the point where the object could be segmented by thresholding, figure 4e. shows the histogram after filtering, and there are few voxels with negative values, mainly the voxels pertaining to our image. Before filtering, there were a lot more negative voxels in the histogram, pertaining to false detections outside the object volume. Thresholding led to a reasonable binary mask, showing the object voxels, but there is considerable misrepresentation of small object volumes, like the flower stem, which is a thin wire, and distortion of the top and bottom of the image.

VI. Discussion

There is a perceived need for low cost and practical equipment to teach concepts in medical physics. The academic community may benefit from a practical approach, but producing this equipment requires time, skills and resources.

Students, who do not understand the concepts in a deep sense, may not possess the necessary self-reflection to find alternative ways to understand, and may not imagine that learning through the use of didactic equipment.

Our survey could be improved by creating separate surveys for Professors, asking whether they teach or use these concepts in their research, and for students, who may have or not have taken the relevant courses in our program yet. Further, it might be useful to survey other Brazilian universities about didactic equipment in medical physics courses; perhaps some universities already use similar equipment or have different needs to ours. It might be possible to describe the teaching equipment in a video, to be watched before taking the survey.

Images were acquired in large angular steps, partially because of the difficulty in rotating the object and taking the photos without any mechanical assistance. The acquisitions of the images for every 10°might contribute to the high noise content in the reconstruction. Therefore, a larger number of projections (e.g. every 1 or 2°) would reduce noise. This limitation can show learners the influence of a sparse angular resolution.

Blurring due to the finite size of the light source and diffraction effects could be investigated by the student in experiments. They limit the acquired images sharpness, and therefore the quality of the reconstruction. The flower stem, which is a thin structure, was seen to be poorly reconstructed, much thicker than expected, perhaps due to blurring and the small number of projections in acquisition.

Object structures, particularly the top of the flower, were seen to be distorted, perhaps due to our use of a fan beam, when TR algorithm assumes parallel rays. It may be possible to limit the angle of the light source to a narrower and more homogeneous beam, allowing a small variation of angular distribution and only near parallel rays to illuminate the object. However, this may prove to be challenging to implement and could increase the cost of the equipment significantly. Students could learn from this limitation about the artifacts introduced in the reconstruction.

Visible light does not penetrate the wooden object that we used in this study, and we ended up with a 3D binary volume of visible light absorbed / not absorbed. However, the frequency of X-rays in CT penetrates naturally occurring materials in the body to some extent, resulting in a 3D map of absorption of X-ray. The corresponding visual effect with visible light would be a variety of opacity in an object, like in glass or water, where air does not absorb visible light, but glass or water partially absorb the visible radiation. Perhaps these phantoms could be used, which create partial shadows on the screen and increase similarity to CT.

VII. Conclusion

1. Our survey suggests room for improvement in the teaching of CT. 78.9% of of the responders said they had at least some difficult in understanding the concepts of CT. All responders said they felt that closer contact with teaching equipment would improve their understanding;
2. A didactic prototype of CT equipment using visible light was constructed and used to acquire images in multiple projections of a 3D object. We observed some image artifacts, such as large high-frquency noise due to a small number of angular projections, diffraction and amplification;
3. Software was developed to perform tomographic reconstruction of object's 3D volume from the acquired images (set of multiple projections), assuming parallel beams. An image processing pipeline was used to create the 3D volume, low-pass filtering the projections with a 3D Gaussian low-pass filter. Segmentation used thresholding, and connected components analysis removed small volume artifacts, not connected to the main 3D object.

In the future we hope to use a Raspberry Pi (RPi) to control the angle of rotation of the object and acquire images for a given set of angles. We would also like to develop software to make the process of tomographic reconstruction more visible, thus deepening student understanding.

VIII. Compliance with ethical requirements

Statement of human and animal rights

No human or animal subjects were used in this study.

Conflict of Interest

The authors declare that they have no conflict of interest.

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APPENDIX A: SURVEY

A form was created on the Google Forms platform and sent to biomedical engineering students at the federal university of ABC. In total, 20 responses were obtained, 68.4% from regularly enrolled students, 21.1% from former students and 10.5% from Professors. Below is the result of the collected responses and analysis.

1. How do you rate your understanding of the CT concepts presented in the courses Principles of Medical Imaging and Medical Physics? (Table 1)

Excellent, perfect understanding	20%
Good understanding of fundamentals and applications	65%
Average, basic understanding - it uses X-rays	5%
Poor, I know that it is a modality	5%
Little or no understanding	5%

Table 1: Results for question 1

2. Do you consider that the current theoretical explanation of CT in the Medical Physics course is sufficient, or would you like to add some practical laboratory sessions, where you have the opportunity to acquire and reconstruct images using teaching equipment? (Table 2)

No, I had little or no contact with practical resources	55%
No, but I had some contact with practical resources	10%
In general,, I feel I had sufficient practical contact	30%
Yes, existing practical resources are sufficient	0%
Yes, but I had some practical contact with	5%

Table 2: Results for question 2

3. Do you understand the concepts of tomographic reconstruction well? (Table 3)

Very well	5%
Reasonably well	35%
I have a basic understanding	50%
I have no idea	10%

Table 3: Results for question 3

4. Do you consider that you had difficulty understanding the concepts involving Computed Tomography? (Table 4)

Yes, a lot of difficulty	0%
Yes, a little difficulty s	78.9%
No, I understood easily	21.1%
I have no idea	10%

Table 4: Results for question 4

5. Do you believe that closer contact with teaching equipment would assist your understanding of the topic? (Table 5)

Yes	100%
No	0%
No strong opinion	0%

Table 5: Results for question 5

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