Teaching the principles of X-ray CT and SPECT using optical CT, glowsticks and a scaled anthropomorphic phantom

Yves De Deene
School of Engineering, Macquarie University, North Ryde, Sydney, Australia
E-mail: Yves.DeDeene@mq.edu.au

Abstract. Teaching demonstrations of computerized tomography (CT) and Single-Photon Emission Tomography (SPECT) to biomedical engineering and medical physics students is hampered by a limited accessibility to clinical scanners, especially during day time. The use of ionizing radiation and radioactive sources in X-ray CT and SPECT further complicates the design of a teaching laboratory session. We here propose an inexpensive and safe educational demonstration of CT and SPECT on an anthropomorphic phantom whereby a visible light source serves as source and a CCD camera serves as detector. The equivalent of a SPECT radionuclide in optical CT scanning is a chemiluminescent material which can be obtained relatively inexpensive in the form of party glow sticks. The proposed teaching tool comprises several learning outcomes such as hands-on construction of the scanner, the acquisition of images and image reconstruction. Also, different imaging artefacts can be simulated and investigated.

1. Introduction
‘Medical imaging’ is gaining a lot of interest in the medical physics curriculum as there is an increasing importance on accurate tumour volume definition and the non-invasive assessment of tumour biology. Practical laboratory teaching modules have been developed for many medical imaging technologies such as for ultrasonic imaging [1] and MRI [2,3]. Commercial MRI benchtop scanners for teaching the principles can be purchased from companies such as Pure Devices, SpinCore Technologies, Magritek and NiuMag. Clinical laptop ultrasound scanners are ideal for in class demonstration of ultrasound. Laboratory models for X-ray CT and nuclear imaging (SPECT and PET) are not so widely available because of the involvement of ionizing radiation. A demonstration experiment to illustrate the principle of back projection, the underlying principle in Computed Tomography has been proposed previously using optical components [4,5]. While these demonstration experiments are useful in helping students to understand that an internal image can be constructed from a combination of projections, they do not provide a realistic picture of current X-ray CT scanning and do not illustrate SPECT scanning. These designs need to be extended to demonstrate the principle of cone beam CT scanning of realistic humanoid geometries.

Most modern X-ray CT scanners and dual modality SPECT-CT scanners are cone beam CT scanners in which an X-ray beam is directed to the patient and transmission projections are acquired in a plane where the beam leaves the patient. Cone beam CT scanning is also used in dental imaging, radiotherapy planning and interventional radiology. The 3D reconstruction from the obtained set of planar projection data in cone beam scanning is performed using an extension to the fan beam reconstruction algorithm [6]. A commercial optical CT scanner for teaching the principles of conebeam CT scanning has recently been marketed by Modus QA under the name DeskCAT™. In this benchtop system, the X-ray source
is replaced by a diffuse light source and a CCD camera is used to capture projection images of transmitted light. Where in X-ray CT, the source and detector are rotated around the patient, in the optical cone beam CT scanner, the object is rotated while the source and detector are kept fixed in the laboratory frame of reference. As light in the visible spectrum is not transmitted through opaque objects, optically transparent phantoms are used instead. Where in X-ray CT the image contrast relies on differences in absorption of high-energy photons, the image contrast in optical CT relies on differences in optical absorption at the operating wavelength of the scanner. The absorption of visible light in an optical CT scanner can be varied by adding different amounts of color dye to a crystal clear optically transparent phantom.

A recent breakthrough in X-ray CT has been the implementation of dual energy CT (DECT) where two sets of CT images are acquired with different X-ray tube voltages [7]. Dual energy X-ray CT scanning can be simulated by a dual wavelength optical CT scanner [8]. Until now, no laboratory demonstration has been proposed to illustrate Single Photon Emission Computed Tomography (SPECT). We here propose an optical conebeam CT scanner and the first miniaturized humanoid phantom for illustrating the principles of dual energy cone beam CT and SPECT scanning. For the principles of optical CT and back projection reconstruction, the reader is referred to a comprehensive published in one of the earlier conference proceedings [9].

2. Methods and Materials

2.1. Test phantoms

Three phantoms were developed to illustrate the principles of dual energy CT and SPECT:

(1) A first phantom was given a humanoid shape which was based on a male fashion doll (Ken). Based on the formulation of a 3D radiation dosimeter developed in our group previously [10], the phantom was composed of a transparent silicone elastomer (Sylgard™ 184) and a solution of leucomalachite green (LMG) in chloroform, which gave the phantom a green color. A negative cast was made of another silicone elastomer, named Pinkysil™ that was obtained from a local handcraft store (Barnes). The negative cast was coated with a thin film of petroleum jelly that acted as a releasing agent. The phantom was suspended on the lid of a jar that acted as a tray which could be easily mounted on the rotation stage of the optical CT scanner. A 1 mm diameter hole was drilled from the left shoulder of the phantom in an oblique direction and filled with a chemiluminescent dye to emulate a radionuclide in SPECT imaging.

(2) A second phantom consisted of a 3D printed skeleton in translucent red poly-lactic acid (PLA).

(3) A third phantom consisted of transparent silicone elastomer in which a PLA skeleton was immersed. The phantom also contained a cavity in the shape of the myocardium in which a chemiluminescent dye was inserted. A chemiluminescent dye was extracted from party glow sticks that were purchased from a local store.

To mimic a SPECT radionuclide in the visible spectrum, a chemiluminescent material was purchased in the form of glow sticks which were obtained from a local supermarket. Glow sticks contain diphenyloxalate with a catalyst (sodium salicylate), a colour dye and hydrogenperoxide which are separated by a thin glass wall.

When the glow stick is squeezed, the glass wall that separates the hydrogen peroxide from the other chemicals is broken and the chemicals mix, upon which a chemical reaction occurs that oxidizes diphenyl oxalate to phenol and 1,2-dioxetanedione. The peroxyacid 1,2-
dioxetanedione spontaneously decomposes to carbon dioxide, releasing energy that excites the dye, which then relaxes by releasing a photon.

2.2. Optical scanning

Our multi-colour conebeam optical CT scanner was based on the Modus Vista™ scanner in which both the light source and camera were replaced. The light source was developed in house using 10 strips of 12 tri-color RGB Light Emitting Diodes (LEDs). The camera was replaced with a higher resolution scientific grade CCD camera (AVT Stingray F-145B). A MATLAB program was developed in house to control the scanner and to reconstruct the images. A photograph of the optical conebeam CT scanner is shown in figure 1.

For each scanning experiment, 256 projection images were recorded at equi-angular increments of 1.40625 degrees which corresponds to a total revolution of the phantom over 360 degrees. Projection images can be recorded with the light source switched to different colors or with all light sources switched off for luminescence imaging. For dual wavelength scanning, projection images were acquired with the blue-light source (reference) and with the red-light source (data). A similar technique to luminescence imaging has been applied using fluorescence tracers in optical emission tomography of xenografts [11].

3. Results and discussion

3.1. Humanoid shaped phantom with luminescent needle insert

The humanoid shaped phantom containing the chemiluminescent dye is shown in figure 2. A structural scan is acquired with the red-light source switched on and a luminescent activity scan is acquired with the light source switched off. After filtered back projection, 3D data sets of the humanoid phantom and the luminescent region are obtained. As both scans are obtained without repositioning the phantom in the optical CT scanner, both data sets can be easily co-registered. A sharp spatial resolution in the luminescent scan can be appreciated. The contours of the phantom show hyperintense in the image which can be attributed to light scattering and a small refractive index mismatch at the surface of the phantom.
Figure 2. Humanoid shaped silicone phantom with chemiluminescent dye injected in the left shoulder. Photograph in ambient light (a) and in a darkened room (b). A coronal reconstructed image through the 1 mm wide cavity shows the luminescent signal.

3.2. 3D printed skeleton
The 3D printed PLA phantom was scanned in the optical CT scanner with the red-light source. As the PLA phantom is translucent red, some of the light will still be transmitted through the phantom. The reconstructed CT images and the volume rendered image match remarkably well with clinical X-ray CT images of the human skeleton.

Figure 3. 3D printed PLA phantom (a) and corresponding reconstructed sagittal image (b) and 3D volume rendered image (c).
3.3. Anthropomorphic phantom with skeleton and luminescent myocardium cavity

The luminescent dye is clearly visible with the naked eye in a darkened room (Figure 4). The luminescent light is significantly attenuated by the ribs which is also apparent in the luminescence projection images. Unfortunately, several air bubbles in the silicone phantom create significant image artefacts. It is concluded that regardless these artefacts, the phantom is useful as a qualitative impression of SPECT-CT imaging.

![Anthropomorphic phantom with skeleton and myocardium cavity](image)

**Figure 4.** Anthropomorphic phantom with PLA skeleton and myocardium cavity containing a chemiluminescent dye. Photograph in ambient light (a) and in a darkened room showing chemiluminescence (b). A projection image acquired with the red light source (c) and a reconstructed coronal slice with the luminescent signal superimposed in a colourwash image (d).
4. Conclusions
A realistic laboratory demonstration to illustrate the principles and concepts of both conebeam X-ray CT and SPECT imaging is proposed. A chemiluminescent dye can be injected in the phantom that simulates the radionuclide in SPECT imaging. Like the radioactive decay of a radionuclide, the activity of the chemiluminescent dye decays exponentially. Several realistic demonstration experiments and hands-on exercises can be designed. Using multi-colour LEDs, the principle of dual energy scanning can be demonstrated. While in this study, a scientific grade scanner was used, for demonstration purposes, an inexpensive optical cone beam scanner can be constructed relatively easy using a webcam, an Arduino controlled stepper motor and a diffuse light source built with off-the-shelf LED strips. Alternatively, optical CT scanners for teaching have also been marketed as commercial products.

The creative component of the learning experience can be enhanced as students can fabricate their own phantoms with either mould casting or 3D printing and can import the acquired optical CT scans in image processing software.

5. References
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