Dual energy subtraction imaging in radiotherapy

Intro

The 21st century has welcomed several new imaging modalities into the radiotherapy treatment room [1]. However, one could argue that what has defined progress in image-guided radiotherapy over the past two decades is not the introduction of techniques such as cone beam computed tomography (CBCT), but the increasing availability of computational power and dedicated software [2].

Image post-processing is now an integral part of the imaging workflow. From reconstruction to noise reduction or automatic artefact removal, a large part of the image formation occurs only after acquisition. Moreover, some images are rendered completely virtual: think digitally reconstructed radiographs or synthetic computed tomography (CT) [3,4].

Yet not all new imaging technologies that were introduced to radiotherapy over the past decade rely solely on the post-processing of standard images. Some still require us to go back to the basics of imaging physics and the imaging systems themselves. One such modality is dual energy (DE) subtraction imaging, a technique which requires both a specific acquisition protocol and dedicated post-processing. After all, we do find ourselves in the middle of the digital age.

Theory

The attenuation of X-rays in any material heavily depends on the energy of the X-ray photons. At low diagnostic-imaging energies, photoelectric absorption is non-negligible and varies significantly among tissue types due to high dependence on the atomic number of the absorption material (~Z4-Z5). At higher energies, Compton scatter dominates but varies less among tissues due to its approximately linear dependence on the electron density of the material with which it interacts. The combination of both these photon-matter interactions is exploited in DE subtraction imaging with the intent to remove a specific tissue type from a planar radiograph in post-processing [5,6].

The technique requires two images: one acquired at relatively high energy (ImHE); and one at low energy (ImLE). The intensity of the image of the tissue to be removed is matched between the two images and through a weighted (w) subtraction, so that only the tissue of interest remains in the final image (ImDE). In radiotherapy, often the bony anatomy is matched and removed to improve the visualisation of the soft-tissue, as shown in Figure 1.

$$\ln(ImDE) = \ln(ImHE) - w^* \ln(ImLE)$$

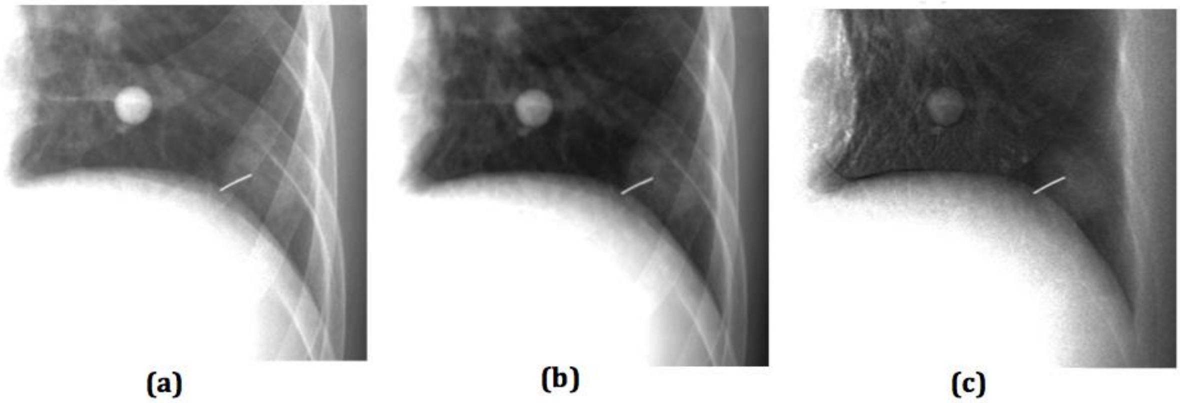

Figure 1: Example of a 60 kV low-energy (a), a 120 kV high-energy (b) and corresponding dual-energy soft-tissue image (c). An implanted marker indicates the location of a lesion.

Dual-energy CT (DECT) and multi-spectral CT are techniques that are based on the same physical principles and increasingly used in radiotherapy [7]. While the acquisition principle is similar to that of 2D DE radiography, the goal in DECT is not necessarily to remove tissue by subtraction but to exploit the varying response of tissues to different X-ray energies in post-processing for a wide range of other applications such as artefact removal, electron-density and stopping-power estimation as well as material decomposition, e.g. for virtual non-contrast imaging [8]. The latter is of interest especially in proton therapy, as it has the potential to reduce beam range uncertainties. An excellent overview of current and future applications of DECT in radiotherapy was given recently by van Elmpt et al [9].

Technology

DE subtraction imaging can be accomplished through either single- or dual-shot exposure. Single-shot exposure relies on a dual-layer detector that is separated by a thin copper filter to capture the low and high energy photons at different detector layers. In dual-shot exposure imaging, a low- and a high-energy image are each acquired sequentially, preferably with the use of a fast-keV switching X-ray source. Typical energy combinations are 120keV and 60keV, but new X-ray sources up to 150keV enable further separation of the energy spectra, which results in more effective subtraction [10].

Inherent disadvantages of the single-exposure technique are the low signal-to-noise ratio in the high-energy image and overlap of the energy spectra. Double exposure also has disadvantages: it can suffer from motion artefacts due to the time delay between capture of the images, and it gives a slightly higher radiation dose, though the latter is minor (~ 15%) due to the relatively higher efficiency of digital detectors. Promising developments in technology of detectors that allow energy discrimination, storing not just the X-ray photon detections but also their energy levels, are currently under development [11].

Other recent developments worth mentioning are the use of deep neural networks (NN) in DE imaging. Several groups have independently proposed NN topologies that can be trained on a dataset of regular or high energy (= input) and corresponding DE (= output) images. During inference, these networks are able to render a virtual soft-tissue image from a single regular X-ray image in real-time, without the requirement for any dedicated imaging technology [12,13].

Applications and conclusions

While DE subtraction imaging was originally introduced to filter out overlapping ribs and clavicles to increase lung nodule detection sensitivity, the technology today is used in the detection and monitoring of a wide range of cardio-thoracic pathologies [14]. More interestingly to this community, its efficacy in radiotherapy treatment has been investigated by several groups, and this work has led to promising developments, including on-board fast-kV switching X-ray sources [15-17].

DE subtraction imaging is especially relevant in markerless tumour tracking, in which poor tumour visibility on real-time X-ray images is the main limiting factor [18-20]. For imaging angles where the tumour overlaps with bony anatomy such as ribs, clavicles or even the spine, filtering out the bony anatomy could aid automatic detection significantly [21]. Increased tumour visibility on planar X-ray images could aid in other motion-management strategies as well. With increasing evidence that 4D-CT and 4D-CBCT offer limited performance in estimating the real extent of respiratory-induced tumour motion, orthogonal fluoroscopy might be an interesting substitute [22, 23].

While use of DE subtraction imaging leads to the removal of the overlapping bony anatomy, often there is also overlap of multiple soft-tissue structures such as the heart or diaphragm, especially in non-anterior posterior images. Unfortunately, low tumour contrast due to overlap with other soft-tissue structures, or overall low differentiation with surrounding soft tissue such as in the liver, is not solved through DE imaging. Further studies are necessary to evaluate in which patients DE imaging could enable or improve markerless tumour tracking.

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