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Additive manufacture of custom radiation dosimetry phantoms: An automated method compatible with commercial polymer 3D printers

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ABSTRACT

There exist significant opportunities for the improvement of radiation therapy procedures by the development of custom dosimetry phantoms for training, quality assurance, and clinical research. Additive manufacture enables custom phantom manufacture, however there exist technical challenges, namely the lack of specialised materials to mimic radiation interaction properties of natural materials, and a lack of automated methods to reduce the manual effort required to convert medical scan data into an additive component. This work demonstrates a novel approach to overcome these challenges to enable the automated manufacture of customised radiation dosimetry phantoms using commercial ultraviolet cured printers.

1. Introduction

Radiation dosimetry phantoms exist to "simulate the modification of the radiation field caused by absorption and scattering in the body tissues or organs of interest" [1]. The radiation dosimetry phantom can be applied to numerous scenarios for which the radiation interaction properties of tissues are of interest, including: the diagnosis and treatment of disease; design of processes and apparatus to manage health risks of ionising radiation; the study of effects of ionising radiation on living tissue; and, the use of ionising radiation to kill cancerous cells [1].

The phantom composition and geometry is determined by its intended application (Section 2) [2]. Earlier phantom design was of simple materials and geometry. The need for increased coherence between phantom and tissue behaviour led to the development of customised materials with complex geometry (Section 3). Especially for radiotherapy applications, the criticality of correct phantom geometry and material fidelity is high, as any error between the representative phantom and patients under treatment may result in poorer treatment outcomes.

Customised, scenario specific phantom manufacture is of high importance for clinical oncologists and medical physicists, as the phantom properties can be tailored to the requirements of the specific scenario. Additive manufacture provides opportunities for economic production of low-volume customised geometries, and can therefore enable the development of customised phantoms to enhance radiation therapy technique development and treatment.

Despite the opportunities associated with additive manufacture, there exist technical limitations which preclude their utilisation for phantom design, including (Section 4): a lack of custom materials compatible with the phantom requirements; and, a lack of design methods to automate the design of the specific radiation phantom. This work materially contributes to the clinical application of additive manufactured radiation phantoms by providing an automated method to fabricate a phantom in such a way that currently available materials can be used to generate contrast detail phantoms. The method is automated such that it can be applied by clinicians with no additive manufacturing experience.

2. Phantoms in medicine

The function of a medical phantom is to represent the tissues of the human body [2]. To approximate the required radiation and geometrical properties, a number of phantom types are available, which range from simple vessels of liquid, or solid homogenous materials; to, complex

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multi-material models that replicate the geometric parameters and radiation absorption or transmission properties of a specific subject.

Phantoms range from mannequins for resuscitation practice and needle placement to objects that mimic tissue compositions or radiological properties. In radiotherapy the latter is of importance and can either be realised as *contrast detail* phantoms or *anthropomorphic* phantoms. Contrast-detail phantoms provide some radiological material contrast for evaluation of imaging detection capabilities and observer perception; contrast detail phantoms may consist of regular geometries (as for the cylindrical test specimens developed in Section 5), or may represent the shape of a human patient (as for the custom skull phantoms developed in Section 7). Anthropomorphic phantoms have the same size and shape as humans and provide tissue equivalent radiological properties for at least some of the internal structures. Anthropomorphic phantoms are ideal for end-to-end verification of procedures and typically quite expensive.

Medical phantoms are also subject to a number of non-radiation requirements in order to be useful in a clinical setting (Section 3.2).

2.1. Application of radiation dosimetry phantoms

The phantom material and geometry is dependent on the intended application [3]. There exist several distinct application domains for radiation dosimetry phantoms, including [1]:

2.1.1. Radiodiagnosis

Radiodiagnosis refers to the use of medical imaging techniques, such as X-ray, computed tomography (CT), ultrasound and medical resonance imaging (MRI), to diagnose disease and plan treatment. Radiodiagnosis may utilise contrast-detail phantoms, or anthropomorphic phantoms, depending on whether the intent is machine calibration, system evaluation, training, or simulation of a patient diagnosis.

2.1.2. Radiation protection

Ionising radiation damages living tissue and can pose a serious health risk [4,5]. Radiation protection refers to the design of procedures and apparatus to mitigate the health effects of ionising radiation [6]. Radiation protection may require anthropomorphic or contrast-detail phantoms, depending on whether the research objective requires quantitative measures of the degree of radiation exposure to various organs, or the optimisation of the amount of radiation needed to achieve a required level of diagnostic information.

2.1.3. Radiotherapy

Ionising radiation damages living tissue. In the context of oncology, high dose radiation is delivered to a target (for example, a tumour) within a patient. The cell-kill from ionising radiation is exploited to treat and cure cancer. The aim of radiation therapy (radiotherapy) is to deliver a lethal dose of radiation to a target while avoiding untargeted healthy tissue. Radiation dosimetry is the branch of medical physics which deals with ensuring that the administered radiation dose is in fact delivered accurately. Radiation dosimetry has two main aspects:

1) Ensuring correct radiation dose
2) Ensuring geometric precision

where the International Commission on Radiation Units and Measurements (ICRU) defines that the aim of clinical dosimetry is to "plan and deliver the required pattern of dosage as accurately as possible, i.e. with an uncertainty of less than 5%" [1]. The needs of radiation dosimetry phantoms for radiotherapy are the focus of this work.

3. Radiation therapy phantoms

Historically, radiotherapy measurements were conducted on very simple phantoms, such as blocks of wood or polymer, and vessels of water due to the radiological similarities between these materials and tissue (Section 3). Simple phantoms may be sufficient for radiotherapy beam characterisation and the quality assurance of some traditional radiotherapy techniques. However, increasingly more sophisticated equipment is able to deliver complex, customised treatments. For example, the use of intensity modulated radiotherapy (IMRT) allows us to shape radiation dose distributions to conform to complex target shapes [7]. As such, more sophisticated means of testing the precision of these treatment deliveries and phantoms which replicate actual patient anatomy are fast becoming essential [8].

To be clinically useful, a radiation dosimetry phantom must satisfy radiation and non-radiation requirements.

3.1. Radiation requirements

Tissue substitute phantoms should be made from materials that exhibit similar radiological properties to body tissues — specifically radiation attenuation due to absorption and scattering. These properties define the fundamental function of X-ray computed tomography imaging, and the penetration of therapeutic radiation beams in radiotherapy.

Computed tomography (CT) refers to the digital processing of a series of two-dimensional X-ray projection images to reconstruct a three-dimensional image of the subject including being able to view 'slices' through the object being scanned. Since its development by Hounsfield [9], the CT scan has become an essential radiodiagnosis tool [10].

The CT scan data is normally represented as a 'stack' of two-dimensional slice images where the grey-scale map of the image represents the varying radiation attenuation of the different tissues present. Each pixel actually represents a volume corresponding to the slice thickness penetrated by the width of the imaging beam. Thus the full CT scan data consists of three-dimensional voxels, each with an associated attenuation value. The average voxel attenuation value for each voxel volume is assigned to the associated pixel and scaled according to the *Hounsfield* scale.

Hounsfield units (HU) quantitatively describe radiodensity and are applied to medical grade CT scans [11]. The Hounsfield number is an index of X-ray attenuation based on a normalized scale of -1000 (air), to 0 (water). The Hounsfield number is of particular interest to this work, whereby the additive manufacture of a contrast-detail phantom requires a distinct difference between relevant materials under CT scan.

To assist in image visualisation, the full dynamic range of measured attenuation coefficients may be restricted to a subset of increments that can be distinguished on the display device. A central HU, termed window level, and HU range of interest, window width, are selected, and HU values outside this range are compressed to the window maximum or minimum levels (for display only) [12]. This accommodates the fact that most biological tissues occupy a narrow range of HU values and so feature relatively low contrast. Manufactured phantoms should therefore ideally feature regions and materials that exhibit similar degrees of image contrast arising from their radiological attenuation properties.

Volume averaging or *partial volume effect* occurs when the reconstructed voxel resolution cannot differentiate between multiple tissue types within a single voxel [13]. A combination of tissue types within a single voxel will produce a combined average value of radiation absorption as the attenuation value or Hounsfield number [13]. This leads to the importance of the relationship between manufacturing resolution and the imaging system resolution.

3.1.1. Other key radiation properties

Tissue substitute material should have absorption and scattering properties that closely resemble the body tissue being modelled [1]. However, literature review completed in this work identifies that scant data is currently available on the radiographic properties of AM materials and processes (Section 4.4). A significant opportunity exists