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Use of maxillofacial laboratory materials to construct a tissue-equivalent head phantom with removable titanium implantable devices for use in verification of the dose of intensity-modulated radiotherapy☆

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Abstract

The dose of radiotherapy is often verified by measuring the dose of radiation at specific points within a phantom. The presence of high-density implant materials such as titanium, however, may cause complications both during calculation and delivery of the dose. Numerous studies have reported photon/electron backscatter and alteration of the dose by high-density implants, but we know of no evidence of a dosimetry phantom that incorporates high density implants or fixtures. The aim of the study was to design and manufacture a tissue-equivalent head phantom for use in verification of the dose in radiotherapy using a combination of traditional laboratory materials and techniques and 3-dimensional technology that can incorporate titanium maxillofacial devices. Digital designs were used together with Mimics® 18.0 (Materialise NV) and FreeForm® software. DICOM data were downloaded and manipulated into the final pieces of the phantom mould. Three-dimensional digital objects were converted into STL files and exported for additional stereolithography. Phantoms were constructed in four stages: material testing and selection, design of a 3-dimensional mould, manufacture of implants, and final fabrication of the phantom using traditional laboratory techniques. Three tissue-equivalent materials were found and used to successfully manufacture a suitable phantom with interchangeable sections that contained three versions of titanium maxillofacial implants. Maxillofacial and other materials can be used to successfully construct a head phantom with interchangeable titanium implant sections for use in verification of doses of radiotherapy.

Keywords: Dosimetry verification; radiotherapy phantom; titanium; implants; cancer; IMRT

Introduction

Head and neck cancer is the eighth most prevalent cancer worldwide, equating to about 3300 deaths/year in the UK.[1] Treatments include radiotherapy, chemotherapy, resection and reconstruction, or a combination, and each case is different.[2] In the NHS choices are discussed at a multidisciplinary team meeting, during which specialists evaluate the severity and complexity of the cancer and together devise the best treatments for each individual patient.

Titanium is widely used to achieve internal rigid fixation and to reconstruct the anatomical form in maxillofacial surgery[3–7] and, because it is extremely biocompatible, such devices often remain in position for the remainder of a patient's life.[8]

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Table 1
Hounsfield units (HU) in tissue calculated from randomised computed tomographic data of the head.

CT	Age (years)	Sex	Orbital volume	Cranial volume	Skull			Total	Soft tissues				Total
					Glabella	Temporal	Sphenoid		Cheek	Temporal scalp	Occipital scalp	Auricular scalp	
						l							
1	71	F	1.27	30.07	1380.53	1285.09	312.3	992.64	43	32	78	27	45.00
2	65	M	-0.79	31.33	882.56	802.66	298.77	661.33	33	87	92	27	59.75
3	20	M	9.87	31.01	1087.97	1300.68	473.87	954.17	17	24	35	35	27.75
4	21	F	21.12	26.29	1417.5	1160.82	583	1053.77	51	39	28	66	46.00
5	51	M	3.12	23.94	1246.36	747.92	490.62	828.30	47	72	24	29	43.00
6	49	F	6.44	28.84	743.26	1349.65	237.07	776.66	61	56	48	25	47.50
7	28	F	4.25	33.35	1026.28	1666	569.63	1087.30	82	25	57	72	59.00
8	44	M	11.32	30.84	1313.78	937.58	466.91	906.09	65	31	24	62	45.50
9	47	F	8.23	33.03	1358.7	1211.9	667.25	1079.28	47	45	80	45	54.25
10	28	M	1.02	26.74	916.35	1562.8	378.71	952.62	45	29	43	53	42.50
Mean (HU)	–	–	6.6	29.5	–	–	–	929.2	–	–	–	–	47.0

Radiotherapy requires accurately calculated doses of irradiation to damage the DNA of the targeted cells and kill them. However, the presence of high density materials such as titanium within the field of radiation can cause appreciable backscatter of protons and electrons, which can damage neighbouring tissues beyond the limits of biological repair.[9] Undesirable effects include xerostomia, mucositis, trismus, radionecrosis and, in severe cases, radiation sickness.[10,11] Irradiation backscatter at the implant-tissue junction has been widely investigated,[12–14] and two distinct alterations to the prescribed dose have been recorded: an increased dose in front of the implant, and a reduced dose behind the implant. This backscattering effect reduces the dose delivered to the target volume and can result in inadequate irradiation.[9,15,16] The highest recorded alteration in dose was 30.4% deviation from the planned dose.[15]

As a result of the wide use of titanium in maxillofacial surgery and its well-documented effects on an irradiation beam, it is essential to consider such high density medical devices when calculating the dose of irradiation and planning radiotherapy.[13,15,17]

An understanding of tissue tolerance is imperative in radiation oncology to assist calculation of the dose required, predict the risk of toxicity, and effectively irradiate the target volume while sparing nearby healthy tissues.[18] The concept of postirradiation toxicity was first proposed by Rubin and Cassarett,[19] and provided the foundations of limits of tissue tolerance in therapeutic radiation.[19] Emami furthered their work by reviewing existing publications exhaustively, and he considered the volume of tissue irradiated as well as the dose.[20]

Although phantoms have been used to investigate the effect titanium implants have on a radiation beam,[9,13,15–17] we could find no evidence of a commercially available phantom with implantable titanium medical devices incorporated into it for use in verification of the dose when planning radiotherapy.

In this study we propose an anthropomorphic head phantom with interchangeable sections, which incorporates three variations of titanium maxillofacial devices used in reconstructive surgery that can be used to verify the dose of radiotherapy to the head.

Material and methods

Published mean values of Hounsfield units (HU) in human tissues differ considerably.[21,22] To find out which ranges were most accurate we randomly selected 10 existing computed tomographic (CT) scans and studied them to obtain HU for five sites on the head and neck using Mimics™ (Materialise NV) 18.0 computer software. Data from five men and five women of various ethnic backgrounds and aged between 20 and 71 years were used. A density tool was used to calculate the mean HU for three sites: intercranial volume, orbital volume, and bony tissue.

The mean values of each anatomical volume were calculated using Microsoft Office Excel™, and the mean values of the three bony tissue points were recorded for each individual patient's skull. The overall mean value was then calculated to achieve a total value (Table 1). The results, together with the previously published ranges, were used to select the most tissue-equivalent materials to mimic bony tissue (skull), intercranial volume, orbital volume, and combined soft tissues.

Testing material

Forty samples of various laboratory and rapid prototype materials were manufactured to fit accurately inside the Scanplas Tissue Characterisation Phantom. Each sample measured 25 mm in diameter x 20 mm high. Each sample was scanned using the Philips Brilliance CT (Big Bore) machine following standard variables from the departmental head and neck protocol (scan mode: Head= voltage (kV): 120; mAs: 300;