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Comparing Technologies of Additive Manufacturing for the Development of Modular Dosimetry Phantoms in Radiation Therapy

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Abstract: In radiotherapy, X-ray imaging and dose quality assurance is often carried out using physical phantoms, which simulate the X-ray attenuation of biological tissue. Additive manufacturing (AM) allows to produce cost-effective phantoms that can easily be adapted to different purposes. The aim of this work was to compare mechanical and X-ray attenuation properties of a selection of AM technologies, machines, and materials. The average Hounsfield Units (HU) were measured by means of computed tomography (CT). The materials displayed tissue-equivalent CT numbers ranging from -104 HU to 1627 HU, showing a broad field of application for phantoms in radiotherapy.

I. Introduction

In radiotherapy, quality assurance in imaging and pre-treatment dosimetry is essential to ensure a precise dose delivery to tumors while sparing healthy tissue as much as possible, especially since new developments in image-guided radiotherapy allow for dose escalation in the target volume and therefore an increased treatment success without increasing toxicity. Physical phantoms are used to ensure that, among others, the uncertainties of delivered dose and patient position during treatment remain within the defined tolerances. These phantoms ideally need to reproduce anatomic details, accommodate different dose measuring devices, or contain various quantities of x-ray contrast agents. Also, the used materials should have x-ray absorbing properties that are equivalent to those of different human tissues.

Additive manufacturing (AM) technologies provide the possibility to produce such geometrically complex phantoms in a cost-effective and modular way. Many different kinds of phantoms were already produced with AM [1,2] but rarely all factors for choosing a given process were taken into account nor were many different materials and printing technologies analyzed in the same study. Knowledge about the range of AM materials and technologies should help choosing the more appropriate manufacturing method for various desired applications.

The aim of this work was therefore to analyze a selection of various AM technologies, machines, and materials for their use in phantom production for computed tomography and radiation therapy.

II. Material and methods

We analyzed five different AM processes, as summarized in Table 1, with sixteen different printing materials that were available from a previous study [3]. The AM procedures comprised powder bed, light polymerization, and material extrusion processes, but are nevertheless only a selection in a broad field, which is increasing daily.

The material analysis covered parameters such as x-ray absorption properties (in terms of Hounsfield Units) as well as spatial resolution, and took production costs, availability, and type of printer into account. The available material samples, each with a volume of 1.37 cm^3 and max. infill value, were scanned using a clinical CT (Siemens Somatom Definition AS; Siemens Healthcare GmbH, Erlangen, GER). The scans were carried out with a voltage of 80 kVp and a tube current of 32 mA. The spatial resolution was 0.6 mm and the reconstruction volume 400 x 400 x 400 mm^3.

Model costs are also considered as a general criterion. The models were graded by cost per sample in three groups: low cost (€, below 50 €), middle cost (€€, between 50 € and 100 €), high cost (€€€, higher than 100 €). The prices of in-house productions were calculated analogously [3].

Table 1: Analyzed AM processes and their acronyms

Analyzed AM process	Acronym
3D-Printing	3DP
Fused Deposition Modeling	FDM
Stereolithography	SLA
Material Jetting (PolyJet)	MJ
Laser Sintering	SLS

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Table 2: Measured HU values of the AM materials investigated in this work, together with their standard deviation and respective spatial resolution (Res) based on manufacturer information and costs: €: below 50 € per sample, €€: between 50 and 100 € per sample, €€€: above 100 € per sample.

Modell ID	Printer	Material	Res (µm)	Costs	HU values (HU)	Tissue equivalent
3DP1	Z Printer 510	ZP150 Cast	100	€	1627 ± 93	bone (compacta)
FDM1	HP Designjet	3D Clear ABS	254	€	-104 ± 93	adipose tissue/ water
FDM2	HP COLOR CE 709A	ABS	250	€	8 ± 34	water
SLA1	SLA 500	WaterShed	-	€€	458 ± 62	bone (compacta)
SLA2	EOS max 600	WaterClear Ultra	150	€€	468 ± 25	bone (compacta)
SLA4	Prodwayd M1 20	FotoMed.LED.A	75	€€€	239 ± 22	bone (compacta)
SLA5	Formlabs Form1+	Flexible material	50	€	154 ± 36	soft tissue
SLA7	Formlabs Form1+	Clear resin	50	€	106 ± 61	soft tissue
MJ1	Object500 Connex	TangoPlus FLX930	30	€€€	130 ± 39	soft tissue
MJ2	Object260v Connex	VeroClear	16	€€	176 ± 13	bone (compacta)
MJ3	Object Connex	TangoBlack95	100	€€	226 ± 38	bone (compacta)
MJ4	Object350 Connex	VeroWhite	28	€€€	277 ± 31	bone (compacta)
MJ5	Projet 3000	EX200	30	€€€	267 ± 57	bone (compacta)
SLS1	EOS – Formiga P110	PA 220/ Nylon	100	€	67 ± 22	soft tissue
SLS2	EOS – Formiga P110	PA3200 GF	100	€€	490 ± 53	bone (compacta)
SLS6	-	DF-Flex	100	€€€	175 ± 2	bone (spongiosa)

In CT imaging, the Hounsfield scale is defined as

$$HU = \frac{\mu_m - \mu_w}{\mu_w - \mu_a} \times 1000, \quad (1)$$

where μ_m is the attenuation coefficient of a given material, μ_w and μ_a those of water and air, respectively. Water has by definition 0 HU and air -1000 HU. To evaluate the HU of the examined materials, we defined a region of interest in 2D of 5 mm x 5 mm in the center of the respective CT images and evaluated the maximum, minimum, mean and standard deviation values using Fiji by NIH Image.

III. Results and discussion

Table 2 shows the measured HUs of the sixteen materials analyzed in this work, together with the AM procedure, the printer type, the spatial resolution, and the approximate costs. Appropriate tissue equivalence for the materials is also given, classified according to typical values from literature [3]. Further material information like elasticity and transparency of the materials can be found in [4].

The analyzed AM materials resulted to be suitable for mimicking x-ray absorption properties of bones (> 170 HU, soft tissue (20-155 HU), and water (0 HU). The deviations within the materials mimic the inhomogeneity found in human tissues, which homogenous materials otherwise used in phantoms often lack. By varying the infill value in the FDM process absorption can also be greatly influenced resulting in different tissue equivalents for one material, varying from e.g. air to soft tissue [5]. The combination with other materials, e.g. gypsum for the periosteum (bone shell) [6], can also provide a broader application range.

IV. Conclusions

In order to find suitable printing materials for use in computed tomography, which is still the most important imaging modality in radiation therapy, since it provides information for an exact dose calculation, we analyzed a selection of sixteen AM samples that were produced with different printers and printing processes. The HU values of these materials are mainly in the area of cancellous and compact bone. However, potential surrogates for fat, water, and soft tissue are also represented. In conclusion, AM shows great potential for the development of phantoms that are inexpensive, easy to adapt, and accurate, thus enabling their use for several tasks in the quality assurance of radiotherapy and imaging devices.

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AUTHOR'S STATEMENT

Conflict of interest: Authors state no conflict of interest. Informed consent: Informed consent has been obtained from all individuals included in this study. Ethical approval: The research related to human use complies with all the relevant national regulations, institutional policies and was performed in accordance with the tenets of the Helsinki Declaration, and has been approved by the authors' institutional review board or equivalent committee.

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