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Considerations on the Requirements for Additive Manufacturing Related Medical Imaging

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Considerations on the Requirements for Additive Manufacturing Related Medical Imaging

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ABSTRACT
Additive manufacturing offers a vast range of medical applications, with parameters typically defined case by case. This requires efficient communication across disciplines, most notably physicians and engineers. The transmission of requirements for medical imaging is particularly crucial in order to achieve clinically useful AM models, and inevitable tradeoffs within the process should be understood by all parties involved.

KEYWORDS: Additive manufacturing (AM); rapid manufacturing (RM); medical imaging; computed tomography (CT); magnetic resonance imaging (MRI).

INTRODUCTION
Additive manufacturing (AM) refers to the assortment of techniques allowing completely freeform manufacturing of digital 3D models by material addition. Traditionally, these methods have been used in industrial prototyping (rapid prototyping). With advances in knowledge of bioadaptive materials, additive manufacturing has also found increasing use in medical applications.

We have proposed earlier [1] a five-category classification for medical applications of AM. Classes are (1) models for preoperative planning, education and training, (2) medical aids, supportive guides, splints and prostheses, (3) tools, instruments and parts for medical devices, (4) inert implants, and (5) bioengineering of artificial tissue. As can be seen, the application range is broad.

The primary medical imaging modalities used in additive manufacturing are computed tomography (CT) and magnetic resonance imaging (MRI). They provide three-dimensional anatomically accurate images. Ultrasound (US) is less used; its resolution is inferior to CT and MRI, but considering its safety, US might prove useful in e.g. the design of customized surgical tools (Class 3). Nuclear isotope imaging methods –
single photon emission computed tomography (SPECT) and positron emission tomography (PET) – are used for functional imaging, and could be employed in applications such as AM of preoperative tumor models (Class 1). Table 1 provides a comparison between mentioned modalities. In addition to these, non-medical methods such as laser scanning or coordinate measuring machines might prove useful in certain applications [2].

CONSIDERATIONS FOR IMAGING REQUIREMENTS

The quality of a medical image can be assessed by three variables: spatial resolution, contrast resolution, and temporal resolution.

A. Spatial resolution

Improving spatial resolution means reducing the image voxel dimensions. With CT, all other factors being constant this both increases the image noise and lowers the signal intensity (less photons per voxel), thus rapidly deteriorates the signal-to-noise ratio. High spatial resolution can be most easily pursued when there is adequate contrast between radiodensities of matters to be imaged, for example imaging of detailed bony structures.

Computed tomography devices offer spatial resolutions up to 0,25 mm [4]. Magnetic resonance imaging is less accurate; in-plane voxel dimensions are of scale 0,5-1 mm, and longitudinal resolution (slice
thickness) is typically above 1 mm. With suitable imaging parameters (sequence type, matrix size, etc.) voxel sizes can be diminished, but this will greatly increase the imaging time, or might cause artifacts between adjacent slices.

B. Contrast resolution and partial volume effect

The contrast resolution is the difference between signals of adjacent heterogeneous voxels - that is, the ability to distinguish between different substances. As stated earlier, CT gives excellent contrast for bone. MRI is more applicable for imaging of soft tissue, as its imaging parameters can be adjusted diversely to maximize the contrast at different tissue interfaces. Contrast resolution might be improved by the use of contrast agents, such as iodine (in CT) or gadolinium (in MRI). Regrettably, this increases the invasiveness of the imaging process.

With large voxel sizes, a single voxel may contain a mixed signal from several types of tissues. This is known as partial volume effect [5], and appears as blurring in the images. Algorithmic correction and increasing spatial resolution decrease this effect.

C. Temporal resolution and motion artifacts

Temporal resolution refers to the time that is needed to construct one image. When imaging live patients, a high temporal resolution is desirable for patient convenience and image quality. Long imaging times cause motion artifacts due to involuntary movement of the patient, breathing, etc. The duration of a CT scan depends on the chosen parameters (required spatial and contrast resolution). A high-resolution 3D image is scanned typically in 20 seconds. This is quick enough to allow breath holding, if motion artifacts are of issue.

Magnetic resonance imaging times for high-resolution images are typically much longer – several minutes. Applications of real-time MRI do exist [6], but with compromised resolution. This is usually not applicable when the aim is to create a 3D CAD model.

D. Radiation dose and other risks

Legislation in the European Union regulates the allowed radiation dose to the patient. The exposure must show a sufficient net benefit, weighing the total potential diagnostic or therapeutic benefits it produces. [7] The radiation dose \(D\) is proportional [8] to the image signal intensity (signal-to-noise ratio, SNR), voxel dimensions \(P\), and slice thickness \(T\) by

\[
D \propto \frac{SNR}{PT}.
\]

Eq. 1 illustrates the inherent nature of medical imaging: the need for compromise. Spatial and contrast resolutions can usually be improved by increasing the tube current or overlaying slices, but this affects the imposed dose. Since the legislation does not allow
routine CT scanning with habitual parameters, imaging parameters and their clinical acceptability needs to be defined case by case.

Magnetic resonance imaging does not involve ionizing radiation. However, ferromagnetic objects both internal (e.g. bone nails, implants) and external (e.g. life-supporting devices) to the patient cause a hazard. Some patients may also suffer from claustrophobia during the scan.

CONCLUSIONS

Most medical AM applications resort currently to various ad hoc solutions; since additive manufacturing is merely a means to an end (i.e. clinical application which in turn leads to improved patient care), there cannot be any universal set of requirements for imaging – instead, they depend on the application. Some tradeoffs need to be made.

We are currently developing a process framework for simpler medical applications of additive manufacturing. More complicated cases, such as very advanced surgical operations, require intensive collaboration and communication between physicians and engineers to ensure the benefits to patient which additive manufacturing offers.

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