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Classification of phantoms for medical imaging

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Abstract

Phantoms are physical models that mimic biological tissue and its properties in medical imaging. They play an important role in medical quality assurance, research, education, and training, since they can offer an adequate test environment. As the use of medical imaging modalities is a growing field in medicine phantoms are likewise evolving very rapidly. The variety of these phantoms is as wide as the modalities and applications, thus ranging from simple to highly detailed in the representation of anatomy. The objective of this paper is to propose a categorization of the objects defined under the term "phantom" in the literature, to reduce the misuse of this term and maintain a common understanding of the topic as well as ensure that future research efforts are based on solid foundations. This field of expertise is driven by the connection between engineering design and the field of medical technology since engineers are essential in the development of phantoms and require a clear understanding of terminology and applications. Based on a literature analysis a novel classification into distinct categories for phantoms, consisting of possible purposes, applications, manufacturing techniques, and custom design features, is developed.

Keywords: classification; phantom; medical imaging; image-guided therapy

1. Introduction

Medical imaging technologies for accurate diagnostics, visualization of the human body, and treatment planning have become crucial in the last few years. New technologies are being developed and well-established ones are further improved or combined with each other. With these medical imaging modalities, so-called phantoms have been developed as well [1]. In medical imaging, a phantom is a test specimen that imitates the original clinical object with regard to certain selected features. A phantom is therefore a model that mimics tissue and its properties in medical imaging. These properties can be either quantitative, such as X-ray attenuation coefficients, or magnetic resonance relaxation times, or qualitative, such as tissue-like visual contrast. There are numerous types of phantoms fulfilling different tasks, ranging from quality control, or calibration, to education. In radiation therapy, for example, phantoms are often used for treatment plan verification.

Phantoms can range from simple geometric to sophisticated human-like models. Next to those commercially available, phantoms are often produced in-house. This comes from the need to address specific research questions, where more complex and customized phantoms are needed. With medical imaging modalities and therapeutic applications further evolving [2], the need for a systematic support for the development of phantoms rises as well.

This can be demonstrated in the increasing number of publications. Fig. 1 shows the number of articles from 1992 to 2022 listed in Scopus and published in English, with the terms *phantom** (title) and *imaging* (title/abstract/keyword), for a total of 8,688 publications. The ascending trend of published

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research articles related to medical phantoms emphasizes that this research field is thriving. Most of the articles were published in *Medical Physics* (611), *Progress in Biomedical Optics and Imaging* (578), *Physics in Medicine and Biology* (530) and *Radiation Protection Dosimetry* (224).

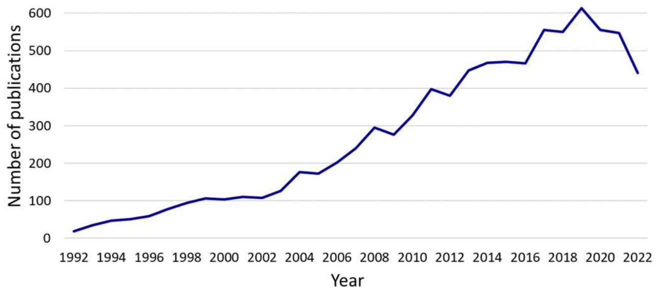

Fig. 1. Research articles with the terms *phantom** (title) and *imaging* (title/ abstract/ keyword) published per year between 1992 and 2022 and listed in the Scopus database.

The word “phantom” traces back to ancient Greek φάντασμα (phántasma) and stands for apparition, ghost, or mirage [3]. According to the dictionary, a phantom in the medical field means a replica of a body part or an organ for teaching purposes or experiments [3]. However, this definition is not clear and there is no uniform designation of the term “phantom” in the medical literature. Often, it is used without much explanation. The book *The Phantoms of Medical and Health Physics* states in the introduction “Phantoms, devices that represent the human body” [1], which is not a fitting definition either, leaving out, for instance, the difference to an anatomical education model, which represents the human body but can only be used for an optical visualization. To define the medial term “phantom” appropriately, the connection to medical imaging must therefore be clear.

In this study, we define a “phantom” as a medial model that mimics a clinical object with regard to certain selected features in medical imaging and therapy. The difference, for example, to a medical simulator or anatomical demonstration model is that a phantom is used at least in one medical imaging modality. A phantom is not limited to the human body, but can also be the model of an animal. This is important to not exclude the research role of small animals in pre-clinical tests, like in pre-clinical radiotherapy [4]. Furthermore, there is no uniform categorization of phantoms in the literature. Since phantoms are used in different medical applications, categories have been made in sub-fields, which are often missing other perspectives. This article structures phantoms used in medical applications for the first time into a novel uniform systematic classification and gives an overview through a literature analysis of the big variety of applications, purposes, and designs of phantoms. Joining the engineering design and the medical technology fields this research gives an essential understanding for the design of phantoms, that can be used in medical imaging applications.

2. Phantom classification in literature and keyword analysis

Different reviews in the field of phantoms have recently been carried out with different motivations as focuses, like tissue-mimicking materials, applications of phantoms in a specific modality or using a special manufacturing process. For example, the review of Tino et al. [5] focuses on 3D-printed phantoms for radiotherapy and divides those into homogeneous, heterogeneous, and anthropomorphic phantoms. The review of Lennie et al. [6] deals with clinical multimodal positron emission tomography (PET) and magnetic resonance imaging (MRI) phantoms, and provides a division into geometric, homogeneous and anthropomorphic phantoms. Moreover, the authors offer a list of commercial and custom-designed phantoms in each category. On the other hand, in the work of Valladares et al. [7], physical phantoms for PET, MRI, and computed tomography (CT) are looked into, and grouped by modality. In contrast, Filippou and Tsoumpas [8] consider the main imaging techniques but only take 3D-printed phantoms into accounts. They cluster phantoms by imaging modality and spatial accuracy, phantom values and body region, and fluids and radiotracers. In a further review by McGarry et al. [2], who focus on materials, phantoms are grouped according to their use for different imaging modalities. In addition, they acknowledge radiotherapy, therapeutic surgery, and thermal therapies. In the book by DeWerd and Kissick [1], phantoms in the field of imaging and radiotherapy are listed. Here, phantoms are considered in a more general view and divided into (i) physical phantoms for dosimetry and imaging and (ii) computational phantoms. Moreover, preclinical phantoms are mentioned. Therefore, since the cited studies were motivated by different kinds of applications, no clear categorization can be derived.

To get an impression of where medical phantoms are typically used and what the main topics are, a keyword analysis in VOSviewer [9] is constructed. A total of 11,682 author keywords from the literature that are used to obtain Fig. 1, are analyzed by their occurrences and connections. The top 30 keywords, visualized in VOSviewer by occurrence, with at least 35 occurrences, can be seen in Fig. 2. Here, equal notions are combined (e.g., “phantom models” = “phantom”). The keywords will later be analyzed in the different sections in terms of application, like medical imaging modalities.

3. Phantom Applications

The application of a phantom defines where and for which purpose a phantom is used. First of all, one can differentiate between virtual and physical phantoms. Furthermore, one can classify phantoms by purposes and applications. The purpose decides what the aim of the phantom is, while the application is the imaging or treatment area where the phantom is used. A phantom, which is, for example, designed for quality assurance in radiation therapy treatments, will be drastically different from a phantom developed for ultrasound training.

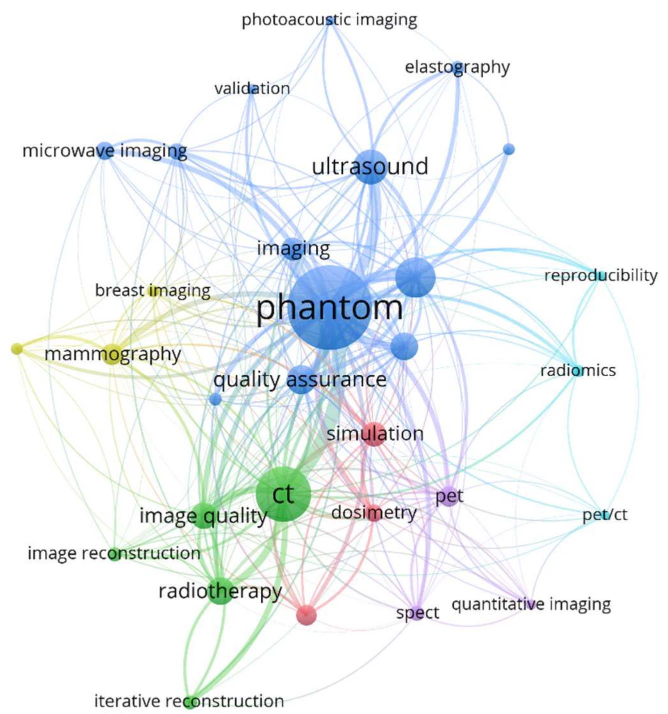

Fig. 2. Most frequently used author keywords in the literature of phantoms visualized in VOSviewer.

3.1. Phantom type

Virtual phantoms, which are also referred to as computational phantoms by DeWerd and Kissick [1] and Xu [10], are used for computer simulations, while physical phantoms are replicas made of appropriate materials. Depending on the application's purpose, virtual or physical phantoms are used accordingly. The effort and its relation to the achievable benefit must be considered. In the development of an image processing tool, virtual phantoms are often more suitable and faster to use. Nevertheless, physical tests for validation and calibration are an integral part of a virtual simulation. In addition, physical phantoms can be examined in a clinical environment when the parameters influencing the image are unknown.

3.2. Phantom purposes

It is clear that different types of phantoms are used for different purposes. In general, three main purposes for phantoms can be identified. The first and also main purpose is quality assurance and calibration. This can be quantitative or qualitative but the focus is always on controlling and evaluating the imaging or treatment. This includes phantoms to evaluate image quality under several aspects (i.e., spatial resolution). Dosimetry phantoms, which are a big part of quality control in radiotherapy, are also a part of this group. In addition to quality assurance, the research purpose focuses on new developments, like the design of new instruments, procedures or set-ups. Phantoms in this area can be used to simulate a surgical operation, a treatment, or to develop a new intervention modality or medical instrument. Investigating new methods often relies on phantoms or simulations to work free of human subjects and to avoid or reduce animal testing. Furthermore, phantoms can be used for education and training purposes, for example, to train a procedure under image guidance [11, 12] or to teach surgical treatments [13]. This can be applied to well-known treatments, e.g., to educate new personnel, like radiologists, as well as to new technologies. Training in complicated cases can be essential in some fields and help to further improve treatment techniques [12].

3.3. Area of application

For the area of application, one has to differentiate between medical imaging and image-guided therapy. A medical imaging application can be a classical medical modality or something very specific and new. A therapy application, like radiotherapy, and other interventions, during which an imaging modality is integrated into the workflow, is also an important field for phantom development. Additionally, a phantom can be used for more than one imaging application. In this case, it is referred to as multimodal.

3.3.1. Medical imaging modalities

Depending on the medical examination, various techniques provide images of organs, tissues, or anatomical structures. The choice of the imaging technique depends on the clinical question. To analyze the modalities where phantoms are commonly used, the occurrence as author keyword is illustrated in Fig. 3. The main modalities, i.e., CT, MRI, and ultrasound (US) and, in nuclear medicine, PET and single photon emission computed tomography (SPECT), are all represented. Further modalities are, among others, mammography, microwave imaging, or photoacoustic imaging (PAI).

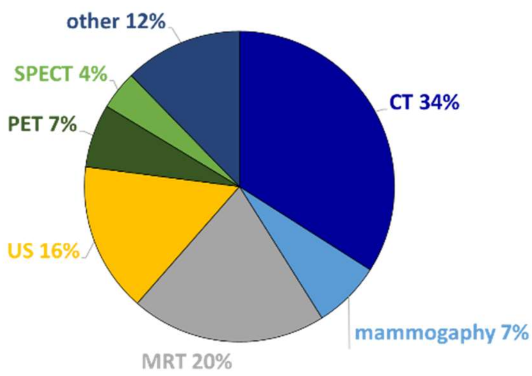

Fig. 3. Percentage of imaging modalities found in phantom research articles.

For further classification, in Fig. 4. the imaging modalities are subdivided first between clinical and preclinical modalities and, secondly, according to the technique used to generate the image. One could further differentiate by structural or functional imaging, 2D or 3D imaging, external or internal, or list them by their spatial resolution. Among the clinical modalities shown in Fig. 4, X-ray imaging techniques, also known as radiology, include CT and, e.g., mammography as well as angiography. Nuclear medicine includes PET, SPECT, and scintigraphy. Further imaging techniques are ultrasound (US) and MRI. This is just a general overview since there are also modalities like elastography, where the elastic properties of soft tissue can be mapped.

In the preclinical field, common clinical modalities are used. However, some imaging modalities are solely used in the preclinical field, e.g., PAI, or optical imaging, like fluorescence imaging (OFI).

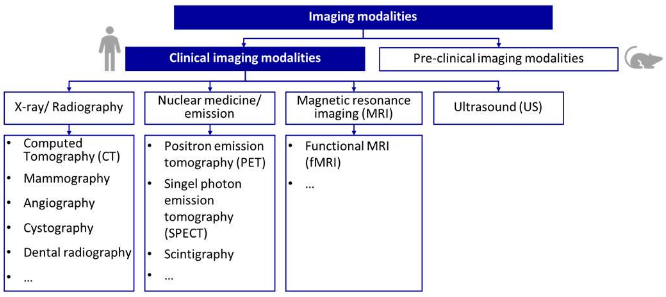

Fig. 4. Overview of a selection imaging modalities where phantoms are used.

3.3.2. Image-guided therapy applications

Next to the imaging focus, phantoms can also be used in therapeutic applications. The most common application for phantoms according to the literature is radiotherapy (RT) [1]. This is also highlighted by the keyword analysis, with 219 occurrences. In addition, other therapy applications can be thermal therapy or intervention procedures, like biopsy or laparoscopic surgery. An overview can be seen in Fig. 5. In RT one can differ between external beam RT and brachytherapy. In brachytherapy, the radiation source is either placed directly inside or in the immediate vicinity of the tumor.

In RT, dosimetry phantoms are a majority. These phantoms are used to measure radiation dose at certain points of interest [1]. There is a big variety of dosimeters that can be used to measure a point, a planar, or even a 3D dose within a phantom, each dosimeter having a number of advantages and disadvantages [14]. Biglini et al. [14] give a summary of detectors currently available and their advantages and disadvantages.

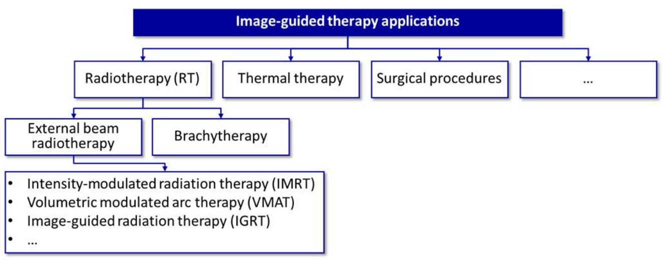

Fig. 5. Overview of a selection of therapy applications where phantoms are used.

3.4. Anatomy

After the phantom type, purpose, and application, the last phantom classifying feature is the anatomy, e.g. tissue, organ, or body part, which the phantom should represent. Phantoms can exemplify the whole body, a body region (e.g. torso, abdomen), a single organ, or one or more tissues. In total 101 anthropomorphic phantoms from five reviews [2, 5–8] and 40 other phantoms produced commercially (17) or in-house (23) are sorted by their anatomy in Fig. 6. The percentages are merely an illustration of the distribution, since these can vary with the application. For example, Lennie et al. [6] look at human organs and tissues used for anthropomorphic PET and MRI phantoms. They show that, in this application, especially head and brain phantoms are more common, since PET/MRI application targets i.a. neurology [6]. This evaluation shows that all kinds of tissue and body region can be of interest.

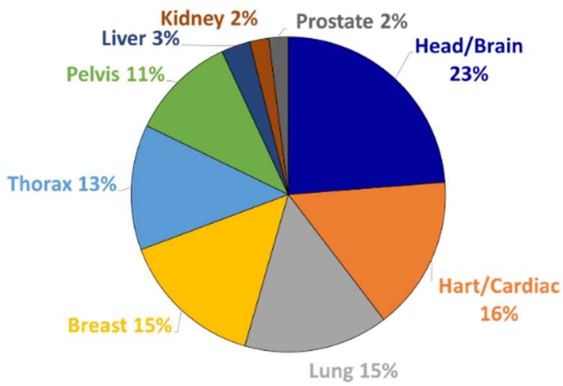

Fig. 6. A selection of anthropomorphic phantoms categorized by the area of human anatomy.

4. Custom design characteristics

In section 3, an overview of phantoms is given by their classifying characteristics (applications). In this section, examples are given for different custom design characteristics a phantom might have. These characteristics are strongly dictated by the phantom's purpose. The essential categories are homogeneity, the degree of realism, deformation, and production technology.

4.1. Homogeneity (homogeneous and heterogeneous)

Homogeneous phantoms have a uniform material simulating some form of tissue. They are often used for testing medical imaging techniques and provide indications of image uniformity and image noise [6]. Single, homogeneous fluids, like water, are widely used in imaging due to their suitability for quality assurance, machine performance calibration, and radiation dose measurements. A disadvantage of homogenous phantoms is that they do not represent human tissue structure correctly [7]. Heterogeneous phantoms, on the other hand, mimic the inhomogeneous composition of tissue and thus provide a more patient-realistic scenario.

4.2. Degree of reality (Geometric and anthropomorphic)

Geometric phantoms, e.g. technical phantoms, consist of simple shapes and geometries composed with one or more materials. Examples could be acrylic containers with inserts of cylinders or spheres. These phantoms are typically used to perform image analysis or for dosimetry checks and are often commercially available. More realistic anthropomorphic (human-like) phantoms mimic specific human anatomy and are both commercially available or producible in-house. Such phantoms are often used in research, whereby the selection of *ad-hoc* design and manufacturing processes can improve clinical scenarios and answer specific research questions. In contrast to geometric phantoms, anthropomorphic phantoms often focus on tissue inhomogeneity and realistic shapes, and tend to mimic human-like tissues more accurately. In addition, phantoms for preclinical research can also be zoomorphic (animal form).

4.3. Motion and deformation (Dynamic and static)

To represent the effect of organ movement, like the change in lung volume, dynamic phantoms are developed. These phantoms are designed to study image artifacts in terms of motion and deformation or to adapt treatment to anatomical changes. Requirements for a deformable phantom are (i) reproducibility, (ii) dynamics, and (iii) showing a similar motion and deformation as humans. An example would be the anthropomorphic PET phantom with elastic lungs and respiration modeling from Black et al. [15]. Dynamic phantoms are sometimes also referred to as motion phantoms [1]. Every phantom that is non-dynamic can be referred to as static.

4.4. Production (commercial and in-house)

It is also vital to note that phantoms are not always manufactured in-house, but there are also lots of commercial phantoms available. The medical phantom market consists of several key players. Some of the companies that currently dominate the market are Carville, Computerized Imaging Reference Systems, Inc., Pure Imaging Phantoms, Biodex Medical System, Inc., Leeds Test Object Ltd., Bartec Technologies Ltd., Gold Standard Phantoms, Kyoto Kagaku Co., Ltd., Modus Medical Device Inc., and PTW Freiburg GmbH [16].

5. Phantom material and manufacturing process

Each imaging and therapeutic application has specifications that are distinctive to the modality used. Tissue-mimicking materials (TMM), also called surrogates, are selected according to their imaging characteristics. These could be, e.g., adequate X-ray attenuation properties or magnetic resonance relaxation times.

Next to the materials, the manufacturing process has an important influence on the phantom design, since the degree of geometric freedom for the design depends on the chosen manufacturing process. Additive manufacturing processes (AM), so-called 3D printing, recently offer the possibility of producing phantoms with a high degree of geometric freedom in a patient-based or even patient-specific manner. The potential of AM for phantom fabrication has been evaluated by recent publications [8, 17–19].

5.1. Phantom materials

Materials that can be used as a surrogate are the key to phantom production. Recently, McGarry et al. [2] gave an extensive overview of on TMMs. Their work focuses on a diverse range of imaging modalities as well as therapeutic applications providing a general survey on TMMs.

There are, on the one hand, studies focusing on a specific material, like Li et al. [20], who are looking at polyvinyl chloride (PVC) and its use as a multimodal TMM, or Madsen et al. [21], who test agar/gelatin materials for use in elastography phantoms. On the other hand, there are also studies testing all kinds of materials for a specific property, e.g. Zeqiri et al. [22], who carried out measurements and testing of the acoustic properties of materials. It is also typical to look for a tissue surrogate for a specific organ or tissue one wants to represent, e.g., the prostate phantom by D'Souza et al. [23].

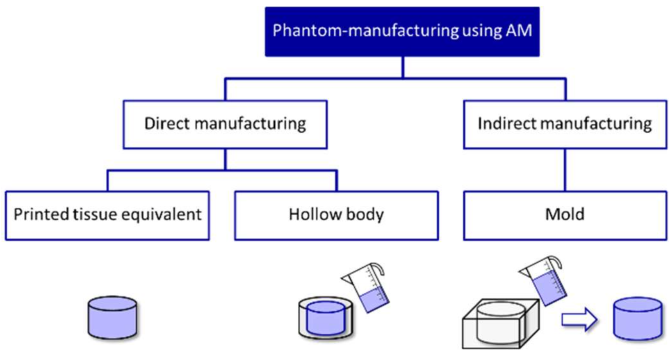

Fig. 7. Phantom manufacturing methods using additive manufacturing [24].

5.2. Additive Manufacturing

Recent reviews highlighting the use of different AM materials and their raising potential for phantoms are those of Filippou and Tsoumpas [8] and Tino et al. [5]. An advantage of AM is the production of anatomically realistic structures, since three-dimensional patient data sets from medical imaging can be used as a basis for the design. Next to the AM methods, it is also essential to evaluate the used materials for phantom applications, since the material has to be equivalent in an imaging modality. For AM manufacturing of phantoms, imaging is typically used for data acquisition, followed by segmentation, editing, and slicing [8, 17]. It is possible to differentiate between the use of direct and indirect AM (see

Fig. 7) [24]. With direct AM, the desired part or the entire model can be produced with AM. This can be realized by printing either a tissue-equivalent or a hollow body, which can be filled with a surrogate in the post-processing phase. Using an AM mold is an example of indirect production.

6. Summary and Outlook

This research contributes to the enhancement of the term "phantom" in medical applications. A universal definition was lacking, since research is often carried out under one imaging or therapeutic perspective. This paper gives a generic definition of a phantom that can be applied throughout different medical fields. Furthermore, the first universal categorization of phantoms, their applications, and unique design characteristics is derived from the literature. First, the phantom classification characteristics, for which the application and purpose is the phantom used, are given. This considers the phantom type (virtual or physical), the purpose (QA, research, or education and training), the medial application (imaging modalities and/or therapy), and the anatomy. In addition, different custom design characteristics of phantoms are considered. These include the degree of (i) homogeneity (homogeneous and heterogeneous), (ii) reality (geometrical and anthropomorphic), (iii) deformation (dynamic and static), and (iv) production (commercial and in-house). Finally, phantom materials and the additive manufacturing process are highlighted.

However, this overview still has limitations, since phantom development is a wide and complex field. Not every unique modality or function can be considered. A next step in the field would be to document the design, manufacturing methods, and materials used. Material-catalogues could be used to collect the knowledge of tissue-mimicking materials across the increasing field of imaging modalities. Specific development methods would help the in-house production of phantoms as well. To sustainably support the rise in demand for medical phantoms and their development, experts in the field of engineering design need to be enabled to understand the medical field. By clarifying essential terminology this paper allows an easier access to the required medical knowledge for product designers. In this research, a first classification of phantoms is proposed, which contributes to both an understanding of phantoms and provides a basis for this growing field and its future direction.

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