ORIGINALARBEIT

Design of a multimodal (^{1}H/^{23}Na MR/CT) anthropomorphic thorax phantom

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Abstract

Objectives: *This work proposes a modular, anthropomorphic MR and CT thorax phantom that enables the comparison of experimental studies for quantitative evaluation of deformable, multimodal image registration algorithms and realistic multi-nuclear MR imaging techniques.*

Methods: *A human thorax phantom was developed with insertable modules representing lung, liver, ribs and additional tracking spheres. The quality of human tissue mimicking characteristics was evaluated for ^{1}H and ^{23}Na MR as well as CT imaging. The position of landmarks in the lung lobes was tracked during CT image acquisition at several positions during breathing cycles. ^{1}H MR measurements of the liver were repeated after seven months to determine long term stability.*

Results: *The modules possess HU, T_1 and T_2 values comparable to human tissues (lung module: -756 ± 148 HU, artificial ribs: 218 ± 56 HU (low $CaCO_3$ concentration) and 339 ± 121 (high $CaCO_3$ concentration), liver module: $T_1 = 790 \pm 28$ ms, $T_2 = 65 \pm 1$ ms). Motion analysis showed that the landmarks in the lung lobes follow a 3D trajectory similar to human breathing motion. The tracking spheres are well detectable in both CT and MRI. The parameters of the tracking spheres can be adjusted in the following ranges to result in a distinct signal: HU values from 150 to 900 HU, T_1 relaxation time from 550 ms to 2000 ms, T_2 relaxation time from 40 ms to 200 ms.*

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Zusammenfassung

Ziel: *Diese Arbeit präsentiert ein modulares, anthropomorphes, MRT und CT kompatibles Thorax-Phantom, welches eine quantitative Evaluierung multimodaler Bildregistrierungsverfahren und realistische multi-nukleare MR-Bildgebung ermöglicht.*

Methoden: *Das Thorax-Phantom besteht aus einsetzbaren Modulen für Lunge, Leber, Rippen und zusätzlichen Positionsmarkern. Die Qualität der Gewebepräsentation wurde mit ^{1}H und ^{23}Na MRT sowie CT-Bildgebung evaluiert. Mittels CT-Bildaufnahmen wurde die Bewegung in den Lungenflügeln über mehrere simulierte Atemzyklen hinweg bestimmt. Das Lebermodul wurde nach sieben Monaten erneut im ^{1}H MR gemessen, um die Langzeitstabilität des Modules zu bestimmen.*

Ergebnisse: *Die Module weisen HU-, T_1- und T_2-Werte auf, die mit menschlichem Gewebe vergleichbar sind (Lunge: -756 ± 148 HU, künstliche Rippen: 218 ± 56 HU (niedrige $CaCO_3$ Konzentration) und 339 ± 121 HU (hohe $CaCO_3$ Konzentration), Leber: $T_1 = 790 \pm 28$ ms, $T_2 = 65 \pm 1$ ms). Die Bewegungen der Lunge sind ähnlich zu menschlichen Atembewegungen. Die Positionsmarker sind in beiden Modalitäten (MR/CT) gut erkennbar. Die Parameter lassen sich innerhalb des folgenden Bereichs*

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Conclusion: *The presented anthropomorphic multimodal thorax phantom fulfills the demands of a simple, inexpensive system with interchangeable components. In future, the modular design allows for complementing the present set up with additional modules focusing on specific research targets such as perfusion studies, ^{23}Na MR quantification experiments and an increasing level of complexity for motion studies.*

Keywords: Anthropomorphic phantom, thorax phantom, multimodal imaging, multi-nuclear MRI, quantification

anpassen: HU Werte von 150 HU bis 900 HU, T_1- Relaxationszeit von 550 ms bis 2000 ms, T_2- Relaxationszeit von 40 ms bis 200 ms.

Zusammenfassung: *Das hier vorgestellte Phantom stellt eine kostengünstige Realisierung eines anthropomorphen, multimodalen Thorax-Phantom mit austauschbaren Komponenten dar. In Zukunft kann dieses Modell für Perfusionsstudien, ^{23}Na MR Quantifizierung und Bewegungsstudien mit hoher Komplexität erweitert werden.*

Schlüsselwörter: Anthropomorphes Phantom, Thorax Phantom, Multi-modale Bildgebung, Multi-nukleare MR-Bildgebung, Quantifikation

Introduction

Image-guided interventions rely on real-time imaging and the fusion of data sets with previous images from CT and MRI [1,2]. Furthermore, image guided radiotherapy planning is an emerging field with a high potential to improve therapy selection and outcome [3]. Within this, image registration algorithms have to take up numerous challenges such as varying resolutions and slice thicknesses as well as altered patient positions between different acquisitions [4]. Geometric phantoms exist for various imaging modalities and allow precise measurements of parameters such as slice thickness, resolution and relaxation time. Also, they can be used to assess image quality assurance which is a crucial factor e.g. in image guided radiotherapy or interventional settings [5]. Anthropomorphic phantoms for validation of algorithms under near real-world conditions serve as an important additional stage between geometric phantoms and in vivo studies; for example as done with perfusion models to measure the flow in the human hemodynamic system [6] or a dynamic phantom to model heart, lung and blood motion for validation of MRI techniques [7].

Anthropomorphic phantoms are designed to simulate properties, geometries or functions of body tissues. The materials used for such a phantom are designed to behave like a particular body tissue with respect to a set of physical characteristics [8]. To this end, Steidl et al. defined a set of criteria for the minimum functionality of a phantom for use in ion beam radiotherapy [9]. Haas et al. refined these criteria for a motion management radiotherapy research phantom [10]. Most of them also hold true for a multimodality imaging phantom and were therefore adapted for this work. The requirements are, firstly, the representation of a suitable anatomical site, e.g. thorax, which includes realistic human anatomy and tissue equivalent material. Secondly, the phantom should include deformable parts to evaluate the effects of organ or structural deformation on motion detection algorithms. Additionally, it has to be compatible with commercial and research motion monitoring systems and, besides 4D-CT and MRI compliance, it is also desirable that the phantom is compact and easy to set up.

However, only very specific multimodal phantoms of the human thorax without biological material were developed so far. Here, we present the design and validation of an anthropomorphic phantom with complex geometry, morphological as well as physiological characteristics and tracking features that enables quantitative evaluation of multimodal, dynamic and deformable image registration.

Materials and methods

Phantom construction

The thorax phantom (Fig. 1) consists of four main modules (lung, liver, ribs and tracking spheres) satisfying the above mentioned requirements. They are placed in an acrylic case (outer dimensions 300 mm × 300 mm × 230 mm ($L \times W \times H$)) that can be flooded with water for MR imaging. A detailed description of each module follows.

Lung module

A lung module is built from two breathing bags with a volume of 2 l each filled with cubical natural rubber foam as suggested by [11]. Side length of the cubes is 5 mm in one bag and 20 mm in the other bag. Two different cube sizes were chosen to examine whether a smaller size had any influence on the attenuation of CT values or might decrease relative standard deviation due to a firmer packing with smaller air cavities. Inflation of the breathing bags is performed manually by a connected resuscitator such that varying states of respirations can be imitated. Inferiorly, the bags can be attached to a movable diaphragm made of an acrylic plate. The diaphragm plate moves posterior – in the direction of the liver module – if the breathing bags are inflated with the use of the resuscitator. During deflation, the diaphragm plate is retracted by