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Original article

Non-invasive thermotherapy of abdominal organs

Thermotherapie non invasive des organes abdominaux

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Abstract

Objective. – Thermal therapies are rapidly gaining importance in oncology as an alternative to radiotherapy and surgery. The possibility to locally deposit thermal energy in a non-invasive way opens a path towards new therapeutic strategies with improved reliability and reduced associated trauma leading to improved efficacy, reduced hospitalisation and costs. Liver and kidney tumors represent a major health problem because not all patients are suitable for curative treatment with surgery. Currently, radiofrequency is the most used method for percutaneous ablation and the development of a completely non-invasive method based on MR-guided high intensity focused ultrasound (HIFU) treatments is of particular interest, since the energy source is located outside the body. This project addressed technological challenges for the treatment of liver and kidney, related to their motion and their location within the thoracic cage.

Material and methods. – This project proposed safe and non-invasive methods for MR-guided thermal ablation of malignant tumors of liver and kidney with HIFU. Real-time MRI was used to precisely control heat deposition with HIFU within the targeted pathological area despite the motion of these organs, in order to provide an effective treatment with a reduced duration and an increased level of safety for the patient. New technologies were studied for the development of matrix transducers able to generate high acoustic power.

Discussion. – 3D Real-Time MRI guidance of a HIFU intervention as well as intercostal firing were realized in vivo in pig liver during breathing under real-time MR-thermometry over sustained periods of several minutes. The ability to generate acoustic power as high as up to five time the usual level was demonstrated in vitro thanks to the development of the new transducer technology proposed in this project.

Conclusion. – A fully MR-integrated HIFU treatment platform dedicated to the treatment of cancer in mobile abdominal organs was developed.

Keywords: Abdominal organs; Oncology; Real-time MRI; Thermotherapy; Focused Ultrasound; HIFU transducers

Résumé

Objectifs. – Les thermothérapies gagnent rapidement en importance dans le domaine de l'oncologie comme alternative à la radiothérapie et à la chirurgie. La possibilité de déposer localement l'énergie thermique de manière non invasive ouvre une nouvelle voie vers des stratégies thérapeutiques plus fiables et moins agressives pour les patients, et permettront une réduction des temps et des coûts d'hospitalisation. Les tumeurs du foie et du rein représentent une problématique majeure, la chirurgie ne convenant pas à tous les patients. À l'heure actuelle, la méthode d'ablation par radiofréquences est la plus utilisée. Le développement d'une méthode non invasive basée sur les ultrasons focalisés guidés par IRM s'avère particulièrement intéressante, car la source d'énergie est extracorporelle. Ce projet adresse des challenges technologiques pour le traitement du foie et du rein, associés à leur mouvement et à leur localisation en dessous de la cage thoracique.

Matériel et méthodes. – Ce projet propose des méthodes non invasives destinées au guidage d'une ablation thermique des tumeurs malignes du foie et du rein par ultrasons focalisés. L'IRM temps réel est utilisée pour contrôler le dépôt d'énergie avec prise en compte du mouvement de l'organe ciblé. De nouvelles technologies de transducteurs matriciels capables de générer de forte puissance sont étudiées.

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Discussion. – Le guidage 3D en temps réel d'une intervention par ultrasons focalisés avec un tir intercostal a été réalisé in vivo sur le foie de cochons en respiration libre, en combinaison avec une thermométrie temps-réel pendant une durée de plusieurs minutes. La possibilité de générer des niveaux de puissance acoustique plus de cinq fois supérieurs aux niveaux habituels a été démontrée in vitro grâce à la mise en œuvre de la nouvelle technologie de transducteur proposée dans ce projet.
Conclusion. – Une plateforme ultrasons focalisés intégrée à l'IRM et destinée au traitement du cancer sur les organes abdominaux a été développée.

Mots clés : Organes abdominaux ; IRM temps réel ; Thermothérapie ; Ultrasons focalisés ; Transducteurs HIFU

1. Introduction

Thermal therapies are rapidly gaining importance in oncology as an alternative to radiotherapy and surgery. The possibility to locally deposit thermal energy in a non-invasive way opens a path towards new therapeutic strategies with improved reliability and reduced associated trauma leading to improved efficacy, reduced hospitalisation and costs. Liver and kidney tumors represent a major health problem because not all patients are suitable for curative treatment with surgery. Currently, radiofrequency is the most used method for percutaneous ablation and the development of a completely non-invasive method based on MR-guided high intensity focused ultrasound (HIFU) treatments is of particular interest, since the energy source is located outside the body. This project addressed technological challenges for the treatment of liver and kidney, related to their motion and their location within the thoracic cage.

2. MR-Temperature of mobile organs

Magnetic Resonance Imaging (MRI) systems was used for two tasks:

- non-invasive thermometer: MR-guidance offers the benefits of excellent target visualization and continuous temperature mapping using the proton resonance frequency (PRF) shift technique (the phase of the MR signal is directly proportional to the local PRF and thus the local temperature). Although the local temperature is a precise indicator for the energy deposition, it does not directly allow to estimate tissue damage and thus to determine the therapy endpoint. For this purpose, the concept of the equivalent thermal dose was introduced to reflect the biological effects of elevated temperatures on tissue. The tissue destruction is achieved when the equivalent thermal dose exceeds the lethal dose (which is taken as 43 °C during 240 min);
- combined with advanced image-processing techniques, MR systems can be used for continuous target identification and tracking.

This implies increased temporal resolution of MR-imaging and effective removal of motion related artefacts in real time. For that purpose, the separate sub-work packages were addressed.

2.1. Acceleration of MR-based thermometry imaging with help of parallel imaging methods

Although modern MRI scanners offer the possibility of acquisition acceleration using parallel imaging techniques, the TSENSE reconstruction has been investigated in the field of thermometry [1]. This method was of particular interest since it provides a dynamic update of calibration data sets, which is of particular interest for flexible array coils positioned around the abdomen.

2.2. Development of real-time adaptive temperature imaging

It is difficult in practice to acquire on-line 3D isotropic images because of the technical limitations, spatial and temporal resolution trade-offs, and low SNR associated with fast 3D acquisition sequences. One approach consists of aligning the normal vector of the slice orthogonal this motion vector and thus to contain the entire motion cycle within a 2D imaging slice. This, however, imposes severe constraints on the imaging geometry, which might be for anatomical or diagnostic reasons unfavorable. It is also not possible to ensure that the target area remains during the entire motion cycle observable by a single static image slice. We developed an alternative approach, which dynamically adapt the image location to the current target location. The slice position was continuously adjusted to the current target location using fast pencil beam navigator echoes. Subsequent real-time image processing on the image stream allows to obtain two types of information: first, the in-plane target position is located with sub-voxel precision. This, in combination with the retained slice tracking position may describe the complete target position in 3D space [2,3].

2.3. Real-time data processing and communications

The update rate and latency of a measured information are two crucial points when this information is used to drive the therapy. While the image sampling frequency is purely limited by the MR-acquisition time, the latency is determined by the remaining acquisition time after echo-formation, the image processing time, the switching time of the HIFU-generator and the required data transport. Since commercially available MRI systems have several limitations for real-time adaptive imaging and fast real-time image transfer, two basic problems had to be addressed: (1) the MR-data transport from the MR-scanner to an external reconstructor; (2) the data reconstruction process. To ensure