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Review article

Magnetic resonance imaging for the study of mummies

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ABSTRACT

Nondestructive diagnostic imaging for mummies study has a long tradition and high-resolution images of the samples morphology have been extensively acquired by using computed tomography (CT). However, although in early reports no signal or image was obtained because of the low water content, mummy magnetic resonance imaging (MRI) was demonstrated able to generate images of such ancient specimens by using fast imaging techniques.
Literature demonstrated the general feasibility of nonclinical MRI for visualizing historic human tissues, which is particularly interesting for archeology. More recently, multinuclear magnetic resonance spectroscopy (MRS) was demonstrated able to detect numerous organic biochemicals from such remains. Although the quality of these images is not yet comparable to that of clinical magnetic resonance (MR) images, and further research will be needed for determining the full capacity of MR in this topic, the information obtained with MR can be viewed as complementary to the one provided by CT and useful for paleoradiological studies of mummies.
This work contains an overview of the state of art of the emerging uses of MRI in paleoradiology.

1. Introduction

The scientific study of human remains from archeological contexts can provide information about the evolution of disease patterns, including infectious disease, and the environment, the culture, and traditions [1–5]. In general, mummy studies performed with invasive techniques such as dissection on well-preserved mummified organs have often been hindered from museum curators or mummies descendants. In this context, radiological techniques employment may act as an efficient alternative method for non-invasive studies.

Koening was the first researcher that studied human and animal mummies using x-ray techniques [6]. However, the term paleoradiology was coined much later, by Notman in 1987 in his study on two frozen sailors from Franklin expedition (1845–1848) [7]. We can define "paleoradiology" as the study of biological materials from archeological excavations using modern imaging methods (e.g. x-ray radiography, magnetic resonance imaging, computed tomography and micro computed tomography). Since the early '70 of the last century, the use of computed tomography (CT) scanners and the ongoing development of CT methods and investigations allowed better visualization of anatomical characters and pathological lesions in skeletal remains and mummies [5,8], being able to provide a good bone/tissue contrast [9]. Unfortunately, the ionizing radiation is of uncertain safety to the samples and x-ray imaging can hardly differentiate between soft tissues, which is a potentiality of magnetic resonance imaging (MRI) in clinical practice. The general feasibility of nonclinical MRI for visualizing historic human tissues is particularly interesting for archeology, while multinuclear magnetic resonance spectroscopy (MRS) can help to detect numerous organic biochemicals from such remains.

The advantages of MRI over CT are the possibility to refer the signal to specific elements and use magnetic resonance (MR) contrast for further improving the images quality. In particular, while CT provides good visualization of hard tissues in extant and fossil specimens, MRI is the gold standard technique for investigating soft tissues and the ontogeny of the skeleton. Such complementarity may provide useful information for the study of phylogenetic change mechanism in evolutionary studies [10].

This work reviews the applications and the emerging methods of MRI and multinuclear spectroscopy for the study of specimens from mummies, able to show their morphology and chemical composition. Literature data are presented by using a chronological subdivision by age in Egyptian, medieval and recent mummies. Since the MRI methods for approaching the issues for imaging mummies and the different strategies for overcoming them are substantially the same for the three mummy types, the text of Egyptian mummies section is organized according to specific MRI

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methods while medieval and recent mummies sections summarize the current state of such mummies MRI.

2. Egyptian mummies

2.1. Issues for imaging Egyptian mummies

Artificial mummification process directly affects the MRI properties of the tissues [11]. In ancient Egypt, mummification was performed by using Natron, a mixture of sodium carbonate decahydrate ($Na_2CO_3 \cdot 10H_2O$), sodium bicarbonate ($NaHCO_3$) and small quantities of sodium chloride (NaCl) and sodium sulfate (Na_2SO_4). The effect of Natron, which is accumulated in the bone, was to cause excessive dehydration. After dehydration, the body was covered with embalming resin obtained from trees, then the skin was wrapped with multiple layers of linen [12,13].

Chemical analysis of tissue samples, which were exposed to extreme physical conditions of temperature, pH levels and mineral accumulation over long time periods, revealed that mummified bone consists of hydroxyapatite-based crystals and decreased amounts of proteins and lipids, while protons are primarily found in the skin and other soft tissues.

In such mummified samples, the dominant component of the proton MR signal is generated by semicrystalline hydroxyapatite (HAP) which is the major part of the inorganic content of the bones.

In a general way, MRI signal intensity of mummified tissues is very low, due to their low water content and the short T2 values, and early works on mummy MRI reported no results in mummy imaging studies from a variety of pulse sequences [14–18]. In particular, Notman et al. [18] employed a body coil and different scanning sequences but failed, except for acquiring a free-induction decay (FID) signal which was too weak for generating an image. Also, fossil bone could only be imaged with MR by immerging the sample into water or a hydrocarbon-based solvent [19]. Successful visualization of mummified tissue by ^{1}H spin-echo imaging [20] was reported only on modern mummified dogs up to 6 months post mortem after invasive acetone wetting for increasing MR relaxation times [21], in a very preliminary report for the naturally mummified Neolithic Iceman [22] and re-hydrated mummified tissue [23] but this destructive method is not suitable for the valuable ancient objects. Moreover, MRI study performed on a 8000 year-old brain recovered from a swampy pond was possible because the brain was preserved in an aqueous environment [24].

Mummified tissues MRI detectability is largely limited by the conversion of normal water-laden tissues to adipocere, a firm waxy substance [25] formed in a desiccated environment like Egyptian desert as a result of hydrolysis of triglycerides into glycerin and free fatty acids [26].

This fact seems to suggest that MRI of an ancient desiccated mummy brain can detect only lipid materials.

Ohrstrom [27] described a comparative study of CT and MRI in ancient mummified tissues. Portions (one head, two left hands) of three artificially embalmed ancient Egyptian mummies (ca. 1500–1100 BCE (Before Current Era), formerly in the Musée d'Orbe, Orbe, Switzerland).

While at CT the major anatomic structures appeared homogeneous and with high spatial resolution, MRI provided a greater variability in signal intensity, especially in bone and in bandages soaked with embalming resin, and the anatomic structures presented different visibility on all selected images. However, MR images of the Egyptian mummy hands permitted to distinguish spongy bones from cortical bones.

In studies of ancient mummies, in general CT images are easier to analyze and interpret respect to MR images, but the hyperintense structures on the MR images, which represent skin or bandages soaked with embalming resin, may help to quantify the extent of the embalming resin spread, which may be more difficult to assess with CT.

Although CT remains the imaging modality of choice for ancient mummy research due to its higher spatial resolution, some anatomic structures such as the tongue and the orbit region which have low contrast at CT, can be successfully studied with MRI thanks to its high signal intensity. Since additional information may be obtained with MRI imaging, it should be viewed as complementary to CT.

Regarding localized spectroscopy, invasive $^{1}H/^{13}C$-NMR spectroscopy has been used for analyzing the molecular composition of nodular crystalline radiopacities of ambiguous intra vitam or post mortem nature, as found in the intervertebral spaces of ancient Egyptian mummies [28–30], which confirmed the apparent absorption of artificial mummification-related substances deep into a human corpse.

2.2. Fast MRI sequences

Karlik [31] examined the morphology of an intact specimen (brain of a mummy). The brain belonged to a male teenage weaver who lived in the XX Egyptian Dynasty. The two cerebral hemispheres of the brain were removed in 1975 when a dissection of the mummy was performed [32,33]. The specimens ad a firm waxy texture consistent with conversion to an adipocerous material [34].

Karlik described that they found bound water remained in the sample, able to generate images of an ancient brain by using fast imaging techniques. Furthermore, multinuclear spectroscopy permitted to detect sodium and phosphate ions and numerous organic biochemicals from temporal lobe extracts.

The images were acquired by using a 1.5 T MR scanner and a coil setup comprising a surface coil and a phased-array coil. After the brain localization, performed with a three-plane fast gradient echo sequence, MRI parameters were set as those generally employed for studying solid anatomic structures, with very short repetition time (TR) and echo time (TE), due to the solid consistency of the sample. Two-dimensional coronal T1-weighted fast spoiled gradient-recalled (FSPGR) acquisition in the steady state (GRASS) images was then acquired, followed by an axial 3D FSPGR pulse sequence and a single-shot fast spin-echo for axial T2-weighted images acquisition.

The same 1.5 T MR scanner was employed for the acquisition of stimulated echo acquisition mode (STEAM)-localized ^{1}H spectra with and without water suppression by using an 8-channel head and neck coil.

A ^{23}Na spectrum was acquired on the mummy brain using a 4.0 T MRI scanner with a 16-element hybrid birdcage coil, successively 1D $^{1}H/^{31}P$ spectra were acquired from mummy tissue extracts on a 14 T spectrometer.

The ancient mummy brain was viewed only in the T1-weighted sequence thanks to the residual water in the tissue, while no signal was detected in the T2-weighted images due to the short T2 relaxation times. The brain images obtained in coronal and axial views resulted quite homogeneous in signal intensity and contained internal structure.

The localized proton spectrum of the samples revealed two principal water signals in the mummy brain while the nonlocalized sodium spectrum from the two hemispheres showed a single broad resonance.

NMR spectroscopy on the tissue extractions revealed various soluble components. The ^{31}P spectrum, by showing a single peak in the D_2O extract, seemed to be consistent with the phosphate ions recovery from the mummified tissue. The proton spectrum in $CDCl_3$ revealed that the samples did not have paramagnetic contamination and analysis of the 1D spectrum showed different resonances consistent with the presence of free fatty acids [35].