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# Hierarchical dictionary compressive sensing (HDCS) method in microwave induced thermal acoustic tomography

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ABSTRACT

Aiming to reduce the reconstruction time and enhance the image quality of microwave induced thermal acoustic tomography (MITAT), a new image reconstruction method named HDCS-MITAT (HDCS: hierarchical dictionary compressive sensing) is proposed. Different from the recently demonstrated CS-MITAT (CS: compressive sensing) imaging method in which only one level dictionary is applied, hierarchical dictionaries are used in the HDCS-MITAT. In this method, the dictionaries with different spatial resolutions are constructed which constitute a hierarchical structure. During the image reconstructions, first the coarsest level dictionary is utilized to roughly estimate the position of the targets in the original image domain. A reduced interested image domain can be set based on this estimation. Then the next level dictionary which has higher resolution than the above level is applied to further estimating the position of the targets and so on. Finally, the finest level dictionary is used to reconstruct the image of the targets. Compared with the CS-MITAT, this HDCS-MITAT has much less computational time and better image quality. The effectiveness of the method has been validated through some simulations and real breast tumor experiments.



## 1. Introduction

Breast cancer has become the most diagnosed cancer among women according to the American Cancer Society (ACS), and early detection in breast cancer is important to more effective treatment [1]. In recent decade, microwave induced thermal acoustic tomography (MITAT) has attracted lots of attentions for its potential in early breast tumor detection [2–10]. MITAT employs contrasts in tissues' dielectric properties while reconstructing images with ultrasound resolution. In MITAT, the tissue is stimulated with short microwave pulses. Tissues with higher conductivity strongly absorb microwave energy and induce acoustic waves due to thermal-elastic expansion. These thermal acoustic signals are collected by ultrasound transducers around the tissues and processed for image reconstruction [11].

Many image reconstruction methods in MITAT have been studied, such as filtered back-projection (BP) [12] and time reversed mirror (TRM) [13]. All these methods require large number of acoustic sensor data to ensure high spatial resolution. However, large number of sampling data usually means long data acquisition time. Moreover, longer scanning time indicates that more microwave radiation will be imposed on patients. To mitigate this problem, Zhu et al. proposed an imaging method in MITAT from compressive sensing prospective (CS-MITAT) which significantly decreases the amount of the sampling data leading to a reduction in measurement time [14]. In some related works [15–17], the concept of multi-level or multi-scale dictionary is utilized. In this paper, we proposed a more effective imaging framework under compressive sensing (CS) scheme named hierarchical dictionary compressive sensing in MITAT (HDCS-MITAT). Compared with the CS-MITAT, the HDCS-MITAT decomposes single reconstruction step into multiple steps using hierarchical dictionaries with different spatial resolutions.

The HDCS-MITAT is an evolution of the CS-MITAT. In CS-MITAT, imaging reconstruction is performed by means of one measurement associated with a fixed dictionary of selected spatial resolution. The key procedure of the CS-MITAT is to create a dictionary that segregates imaging area into a large number of cells which determine image resolution [14]. MITAT image is reconstructed with resolutions corresponding to these cells. In the HDCS-MITAT,

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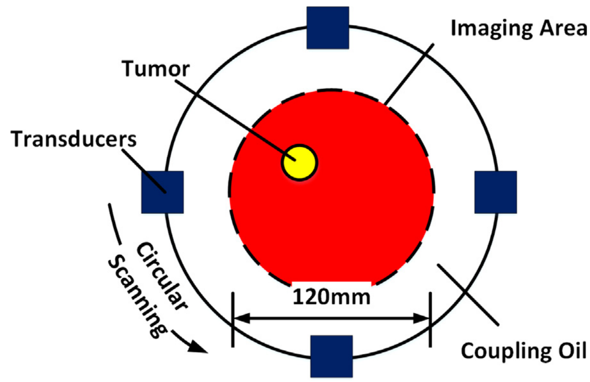


**Fig. 1.** Sketch map of detection environment. Four transducers are uniformly distributed on the wall of the container and a tumor specimen is immersed in the coupling oil.

multiple levels of dictionaries with different spatial resolutions are built. These dictionaries are applied with different sizes of imaging domain. Because a finer dictionary is applied in a smaller image domain, this strategy saves more computation time. As a bonus, the image reconstructed by the HDCS-MITAT has clearer background because of the reduced imaging domain at different levels.

The remainder of this paper is organized as follows. In Section 2, a creation of dictionary is described and a hierarchical dictionary framework is proposed. In Section 3, simulation results are presented to compare the performance of the HDCS-MITAT with the CS-MITAT. Experiments using breast tumor and adipose are conducted to validate the effectiveness of the HDCS-MITAT both on reconstruction time and image quality. Conclusions are drawn in the final section.

## 2. Theory for HDCS-MITAT

### *2.1. MITA propagation model and dictionary of MITAT for breast tumor*

In MITAT prototype [18], tumor specimen is immersed in the coupling oil, transducers are uniformly distributed around a detection container at different spatial positions. Fig. 1 shows a sketch map of the detection environment with four transducers and a tumor specimen.

The dictionary proposed in the CS-MITAT segregates image area into a large number of resolution cells. Each resolution cell represents a MITA signal propagation model which contains spatial information and dielectric properties of the tissues. In MITAT, a tissue is considered as a source that generates MITA signal due to thermal-elastic expansion. This expansion and the propagation process can be described in a wave equation given in the following equation [9].

$$\nabla^2 p(\mathbf{r},t) - \frac{1}{{v_s}^2}\frac{\partial^2 p(\mathbf{r},t)}{\partial t^2} = -\frac{\beta}{C}\frac{\partial H(\mathbf{r},t)}{\partial t} \tag{1}$$

where $p(\mathbf{r}, t)$ denotes the acoustical pressure with the target at the spatial position $\mathbf{r}$. $v_s$ is the sound velocity and $H(\mathbf{r}, t)$ is the heating function. $\beta$ and $C$ are the heat expansion coefficient and the capacity, respectively. Eq. (1) can be solved with a volume integration at time $t$ represented in the following equation,

$$p(\mathbf{r}_0,t) = \frac{\beta}{4\pi C}\int_V \frac{\partial H(\mathbf{r}, t-|\mathbf{r}_0-\mathbf{r}|/v_s)}{\partial t}\frac{d^3\mathbf{r}}{|\mathbf{r}_0-\mathbf{r}|}. \tag{2}$$

In Eq. (2), $\mathbf{r}_0$ and $\mathbf{r}$ denote the spatial position of transducers heat sources, respectively.

If each propagation process determined by the spatial position $i$ is defined as a MITA propagation model, a MITA dictionary can be represented as $\boldsymbol{\Psi} = \{p_1(\mathbf{r}_0, t), p_2(\mathbf{r}_0, t), \ldots, p_i(\mathbf{r}_0, t), \ldots, p_N(\mathbf{r}_0, t)\}$, where the subscript $i (i \in 1, 2, 3, \ldots, N)$ denotes the $i$th resolution cell in the image domain. Fig. 2 is a schematic diagram of the MITAT dictionary. The dashed-line circle in Fig. 2 represents the image domain and the red spots are resolution cells. The external square guarantees the over-complete property of the MITAT dictionary.

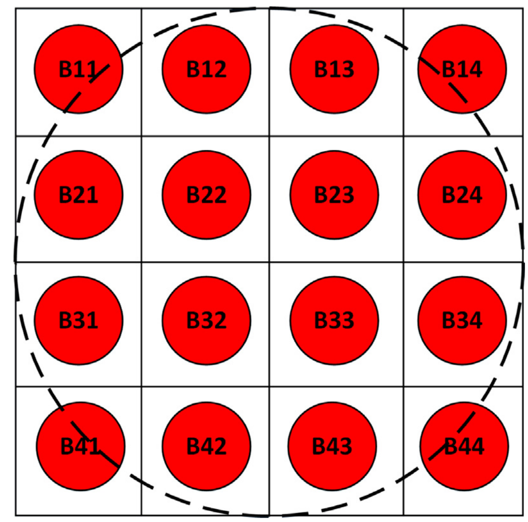


**Fig. 2.** Schematic diagram of a MITA dictionary. Red spots represent spatial positions of the resolution cells which can be uniquely described as a MITA propagation model. (Red spot just indicates spatial position in the image domain, and the real shape of cells is rectangular which guarantees spatial continuity in the image domain.). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

### *2.2. Hierarchical dictionary compressive sensing (HDCS) framework*

#### *2.2.1. Hierarchical dictionary compressive sensing (HDCS)*

HDCS-MITAT framework is based on the basic CS scheme which is briefly reviewed as follows [19–21]. Suppose a signal $\mathbf{x} \in \mathbf{R}^{N\times 1}$ has a sparse representation in a dictionary $\boldsymbol{\Psi}$, where $\boldsymbol{\Psi} \in \mathbf{R}^{N\times N}$ is an over-complete dictionary. $\mathbf{x}$ can be represented as $\mathbf{x} = \boldsymbol{\Psi\theta}$, where $\boldsymbol{\theta} \in \mathbf{R}^{N\times 1}$ is the coefficient of the dictionary $\boldsymbol{\Psi}$. In CS theory, it is a common assumption that $\boldsymbol{\theta}$ has very few nonzero elements. Given $\mathbf{y} \in \mathbf{R}^{K\times 1}$ $(K \ll N)$ as a measurements of $\mathbf{x}$ acquired by a measurement matrix $\boldsymbol{\Phi} \in \mathbf{R}^{K\times N}$, $\mathbf{y}$ can be written as

$$\mathbf{y} = \boldsymbol{\Phi\Psi\theta}. \tag{3}$$

Because $\boldsymbol{\Phi}$ and $\boldsymbol{\Psi}$ are given, $\mathbf{y}$ is the CS measurement, one can use CS reconstruction algorithm such as OMP [22], GPSR [23] and Bayesian Compressive Sensing (BCS) [24,25] *etc.* to recover the coefficient $\boldsymbol{\theta}$.

The main contribution of this paper is the hierarchical dictionary framework. The core idea of the HDCS-MITAT is one measurement, multiple reconstructions, versus the one measurement, one reconstruction in the conventional CS-MITAT.

Sparse coefficient $\boldsymbol{\theta}$ is a position indicator in the CS-MITAT which shows target position. $\boldsymbol{\theta}$, reflects spatial position of targets as well as amplitude of MITA signals generated by the targets. Because of sparse spatial distribution of early-stage breast tumor, only few elements in $\boldsymbol{\theta}$ are nonzero. This satisfies the pre-condition of CS. Resolution of MITAT image is determined by the resolution cells in the dictionary $\Psi$. In the HDCS-MITAT, data compression is mainly on the number of sensor positions $K$ (i.e. CS measurement). Reduction in the number of sensor positions directly leads to less measurement time.

Compared with the only one dictionary in the CS-MITAT, the HDCS-MITAT has multiple dictionaries with different spatial