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Quantitative Photoacoustic Imaging of Chlorophyll Using a GPU-Accelerated Finite Element Method

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Abstract. Chlorophyll in leaves is tightly associated with physiological status of plants. Chemical extraction or hyperspectral estimation is the conventional method to estimate the concentration of Chlorophyll in leaves. However, chemical extraction is invasive and time consuming, and hyperspectral method is extremely sensitive to background light. In this paper, we develop a quantitative photoacoustic imaging technique based on a finite-element-based reconstruction algorithm accelerated by a multicore GPU card to image morphological features and derive distribution of Chlorophyll A in rice leaves. The results suggest that this new method holds great potential in various studies of plant physiology.

AMS subject classifications: 65N30, 65Y05

Key words: Photoacoustic tomography, finite element method, GPU-acceleration, chlorophyll.

1 Introduction

There are three major types of pigments in most plants: chlorophyll, carotenoid and anthocyanin. The primary function of these pigments is photosynthesis, which is largely

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responsible for oxygen supply for life on the earth [1,2]. Photosynthesis converts solar energy into chemical energy which supports the activities of organisms. Chlorophyll plays a key role in photosynthesis due to its strong light absorbing capability [3–5]. Several methods have already been used to estimate the content of chlorophyll in leaves including chemical extraction, spectrophotometric measurement, and high performance liquid chromatography [6–8]. However, all of these procedures are time-consuming and invasive, making it impossible to monitor the longitudinal variations of the chlorophyll [9]. As a non-invasive method, hyperspectral measurement is capable of deriving accurate chlorophyll content in a leaf by analyzing its reflectance spectra [10]. Unfortunately, it is extremely sensitive to background light, and thus requires a dark room to avoid noise from outer light sources, which makes it challenging for outdoor use [11]. Photoacoustic imaging (PAI) is an emerging noninvasive imaging technique that combines the merits of rich optical contrast and high acoustic resolution in a single modality [12]. Comparing to hyperspectral measurement, PAI is not sensitive to background light and holds the potential for outdoor use. In PAI, photon absorption of nanosecond laser pulses by the target leads to rapid thermal expansion and generates wideband photoacoustic waves, which are detected to produce images. PAI has been extensively applied in the fields of biology and medicine [13–16]. Photoacoustic computed tomography (PACT), a reconstruction-based modality, utilizes an area illumination and scans flat acoustic transducers to obtain multiple detections for image reconstruction [17]. Although the spatial resolution is lower than photoacoustic microscopy, it has a large field of view (FOV), a deep penetration depth and a high imaging speed. In addition, apart from photoacoustic microscopy which is reconstructed by directly back-projecting the depth-resolved photoacoustic signals, PACT is able to derive absolute absorption coefficients of targets using model-based quantitative reconstruction methods [18–20]. Commonly, in quantitative PACT reconstruction, the generation and propagation of photoacoustic waves in targets is described using Helmholtz-like photoacoustic wave equation, and the photon diffusion equation which is the first-order approximation to the rigorous radiative transfer equation is used to depict the light distribution. By using finite element method (FEM), the quantitative reconstruction algorithms have been developed and extensively applied in breast cancer detection, arthritis diagnosis, and brain investigation [21]. Previously, we proposed a time domain based FEM method to solve the partial differential equations, which provides better image quality with much more accurately recovered value and less artifacts compared to its frequency domain counterpart [22]. However, the time domain approach is extremely time consuming, which usually requires dozens of hours reconstruct a two-dimensional PACT image with a typical mesh size. Hence the use of the graphic-processing-unit (GPU) based parallel strategy appears to be a natural choice [23, 24]. In this study, we propose the utilization of FEM based quantitative PACT to derive the absolute optical absorption coefficient of the leaf in rice, which is positively relative to the concentration of chlorophyll. In addition, in order to improve the efficiency of the algorithm, a parallel computational strategy is implemented using a multicore graphics processing unit (GPU). Phantom experiments were carried out to