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● *Original Contribution*

TRACKING DYNAMIC TONGUE MOTION IN ULTRASOUND IMAGES FOR OBSTRUCTIVE SLEEP APNEA

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Abstract—Obstructive sleep apnea (OSA), a breathing disorder characterized by repetitive collapse of the pharyngeal airway during sleep, can cause intermittent hypoxemia and frequent arousal. The evaluation of dynamic tongue motion not only provides the biomechanics and pathophysiology for OSA diagnosis, but also helps doctors to determine treatment strategies for these patients with OSA. The purpose of this study was to develop and verify a dedicated tracking algorithm, called the modified optical flow (OF)-based method, for monitoring the dynamic motion of the tongue base in ultrasound image sequences derived from controls and patients with OSA. The performance of the proposed method was verified by phantom and synthetic data. A common tracking method, the normalized cross-correlation method, was included for comparison. The efficacy of the algorithms was evaluated by calculating the estimated displacement error. All results indicated that the modified OF-based method exhibited higher accuracy in verification experiments. In the human subject experiment, all participants performed the Müller maneuver (MM) to simulate the contour changes of the tongue base with a negative pharyngeal airway pressure in sleep apnea. Ultrasound image sequences of the tongue were obtained during 10 s of a transition from normal breathing to the MM, and these were measured using the modified OF-based method. The results indicated that the displacement of the tongue base during the MM was larger in the controls than in the patients with OSA ($p < 0.05$); the calculated areas of the tongue in the controls and patients with OSA were 24.9 ± 3.0 and 27.6 ± 3.3 cm^2, respectively, during normal breathing ($p < 0.05$), and 24.7 ± 3.6 and 27.3 ± 3.8 cm^2, respectively, at the end of the MM. The percentage changes in the tongue area were 2.2% and 1.3% in the controls and patients with OSA, respectively. We found that quantitative assessment of tongue motion by ultrasound imaging is suitable for evaluating pharyngeal airway behavior in OSA patients with minimal invasiveness and easy accessibility. (E-mail: cchuang@mail.ncku.edu.tw) © 2017 World Federation for Ultrasound in Medicine & Biology.

Key Words: **Obstructive sleep apnea, Modified optical flow-based method, Medical ultrasound, Tongue motion.**

INTRODUCTION

Obstructive sleep apnea (OSA) is characterized by recurring episodes of partial or complete obstruction of the pharyngeal airway during sleep, resulting in symptoms such as intermittent hypoxemia, frequent arousal and sleep fragmentation (Caples et al. 2005). The prevalence of OSA in the adult population is approximately 3%–7% for men and 2%–5% for women (Stuck and Maurer 2008). If left untreated, OSA may lead to serious medical consequences such as hypertension, stroke, ischemic heart disease, and even sudden death. Currently, polysomnography (PSG) is the most accurate diagnostic tool for OSA. Although PSG records several physiologic signals during sleep, it does not obtain information regarding upper airway (UA) anatomy. A previous study revealed that patients with severe OSA usually exhibited minimal tongue movement during breathing because of their difficulty in dilating the restricted UA, even during wakefulness (Brown et al. 2013). Defining static and dynamic UA anatomy provides not only the biomechanical and pathophysiologic basis in the development of OSA diagnoses, but also possible treatment strategies for patients with OSA (Faber and Grymer 2003; Hong et al. 2016; Togeiro et al. 2010).

Several imaging modalities have been used to detect UA anatomic characteristics in patients with OSA, including magnetic resonance imaging (MRI) (Barrera 2011; Schoenberg et al. 2000), computed

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tomography (CT) (Lam et al. 2004; Yucel et al. 2005), endoscopy and ultrasonography. Each technique has its own advantages and limitations. Schoenberg et al. (2000) used dynamic MRI to detect the complete pharyngeal collapse of a patient with OSA. However, the imaging frame rate was not sufficiently fast to monitor the dynamic variation of the UA, and the method also had a cost–efficiency problem. Yucel et al. (2005) used CT to compare the entire cross-sectional areas of the UAs of typical individuals and patients with OSA. The results revealed that patients with severe OSA had significantly narrower cross-sectional areas than did the typical individuals at the velopharyngeal level. However, the safety of ionized radiation is a major problem for CT scanning. Because its real-time, non-ionizing radiation, and portability advantages, ultrasound imaging has been used in several studies to investigate the tongue for OSA; the results also revealed that anatomic variations of the tongue and UA are the major factors contributing to OSA (Lahav et al. 2009; Liao et al. 2016; Liu et al. 2007; Hofauer et al. 2017; Remijn et al. 2015; Shu et al. 2013). In our previous study, we reported that measurement of tongue base thickness (TBT) with ultrasound imaging during the Müller maneuver (MM) is an effective index for differentiating between individuals with and without OSA (Chen et al. 2014). The MM is a simple examination that has been used to simulate the pathophysiologic conditions of OSA during wakefulness (Soares et al. 2009). Forty patients (20 patients with OSA and 20 control patients with an apnea–hypopnea index [AHI] <5) were recruited into the study. The patients with OSA had a significantly greater TBT during eupneic breathing and the MM than did the control group, and there was a significant difference between their TBTs with and without the MM. However, the maximum TBT during the MM was arbitrarily determined by the physician who performed the ultrasound in that study. Dynamic tongue deformation was not evaluated in real-time ultrasound image sequences.

An efficient algorithm for contour tracking of tongue motion would be invaluable in helping physicians understand UA behavior in patients with OSA. Several approaches have been proposed to quantify tongue deformation in ultrasound images. For example, Akgul et al. (1999) proposed a method that entails automatically extracting and tracking the contours from digital ultrasound images using a discrete formulation for the deformable contour model. In this method, some tracking problems may occur because of the external energy definition, which involves applying only gradient information because the tongue surface cannot be distinguished from other high-contrast edges in the images. In 2005, Li et al. introduced a contour tracking system, Edge Track, for ultrasound images of the human tongue. In this system, an active contour model that combines the edge gradient and intensity in the local region was developed, and the results exhibited robustness and accuracy. However, when a part of the tongue contour disappeared, the obtained contour became erroneous and required manual re-initialization because of poor acoustic coupling or a decrease in reflected energy. In 2012, Tang et al. developed a method for the extraction of tongue contours from ultrasound images; this method does not require re-initialization, training data, combination with other data modalities or electromagnetic sensors. However, automatically setting weights is still a problem. Xu et al. (2016a, 2016b) proposed an automatic contour tracking algorithm based on the active contour model for detecting tongue motion from ultrasound images. They used a contour-similarity constraint to solve the problem of a missing contour; the performance of this method is encouraging.

Although these studies have all produced reliable and valid results regarding tissue motion evaluation, they could not determine the motion of each pixel in the image during tongue deformation. Another method for determining the dynamic motion of tissue from ultrasound images, called speckle motion tracking, has been widely developed over the past two decades. Block matching (BM) is a commonly used method for speckle motion tracking. BM uses the similarity measure between reference and target windows to track tissue motion. Several approaches are available for estimating the similarity measure, such as the sum of absolute differences (SAD) (Vanne et al. 2006), the sum of squared differences (SSD) (Cohen 2002) and normalized cross-correlation (NCC) (Korstanje et al. 2010; Wei and Lai 2008). Among these, NCC applies the maximum correlation between a reference window and a target window to track tissue motion. Moreover, this approach is considered one of the most accurate and effective estimators. BM procedures with different similarity measure approaches have previously been proposed for tracking the dynamic motion of tissues such as tendons (Lai et al. 2016a, 2016b) and the carotid artery (Golemati et al. 2003, 2012). However, the accuracy of these procedures decreased as the speckles in the region of interest (ROI) were moved in many directions. This situation occurs during tongue movement, particularly for OSA during the MM or sleep. An alternative approach, called the optical flow (OF) method, has been used for tracking complex deformations of the heart and vessel motion in ultrasound images (Duan et al. 2009; Ledesma-Carbayo et al. 2005; Rajpoot et al. 2011; Veronesi et al. 2006). This method has led to promising results for some specific cases of tissue motion, such as rotation and distortion. Several techniques based

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