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Finite element modeling of haptic thermography: A novel approach for brain tumor detection during minimally invasive neurosurgery

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ABSTRACT

Intraoperative Thermal Imaging (ITI) is a novel neuroimaging method that can potentially locate tissue abnormalities and hence improves surgeon's diagnostic ability. In the present study, thermography technique coupled with artificial tactile sensing method called "haptic thermography" is utilized to investigate the presence of an abnormal object as a tumor with an elevated temperature relative to the normal tissue in the brain. The brain tissue is characterized as a hyper-viscoelastic material to be descriptive of mechanical behavior of the brain tissue during tactile palpation. Based on a finite element approach, Magnetic Resonance Imaging (MRI) data of a patient diagnosed to have a brain tumor is utilized to simulate and analyze the capability of haptic thermography in detection and localization of brain tumor. Steady-state thermal results prove that temperature distribution is an appropriate outcome of haptic thermography for the superficial tumors while heat flux distribution can be used as an extra thermal result for deeply located tumors.

1. Introduction

Despite significant advances in diagnosis and treatment, the survival rate of patients with central nervous system tumors has not considerably improved (Kateb et al., 2009). According to the American Cancer Society statistics in the United States for 2015 (American Cancer Society, 2015a), an estimated 22,850 malignant tumors of the brain or spinal cord (12,900 in males and 9950 in females) will be diagnosed including both adults and children while about 15,320 people (8940 males and 6380 females) will die from central nervous system tumors. Brain and spinal cord tumors are the second most common diagnosed cancers among children, with more than 4000 cases are diagnosed each year in children and teens (American Cancer Society, 2015b).

The brain tumors are classified into two general groups, primary and secondary. Both whole brain radiotherapy and local treatment (surgery or radiosurgery) are the cornerstones of treatment (Scoccianti and Ricardi, 2012). Determinant factors in therapeutic method selection are highly dependent on type, location and size of the brain tumor. However, surgery is a popular but invasive treatment of the brain tumors. In recent years, surgical operation has been revolutionized by introducing Minimally Invasive Surgery (MIS). MIS refers to surgeries performed through small incisions, in order to minimize trauma to body as well as decrease recovery time (Rosenfeld, 1996). Tumor detection and localization have long been the challenging tasks in the accuracy and applicability of MIS. Preoperative imaging techniques including Magnetic Resonance Imaging (MRI) and Computed Tomography (CT) scan are the most common methods which have been used for tumor detection and localization. However, the most important drawback of preoperative imaging falls into a well-known phenomenon which is referred as the "brain shift" (Kateb et al., 2009; Soza et al., 2005).

The opening of skull and of dura mater, the loss of cerebrospinal fluid and placing surgical apparatus during surgery can often contribute to a considerable deformation of the brain tissue. The surface of brain can be deformed up to 20 mm after the skull is opened during neurosurgery, also the resection of big lesions can increase the deformation of the brain structures even up to 50 mm (Hartkens et al., 2003; Nimsky et al., 2002). The brain shift causes a significant decrease in the accuracy of commercially available neuronavigation systems which register preoperative images to the intraoperative tumor localization (Soza et al., 2005).

The most common method to deal with the brain shift is use of intraoperative MRI (iMRI) in the operating room (Schulder and Carmel, 2003). This technology provides the high-quality intraoperative images during brain tumor resection and offers the surgeons an opportunity to obtain various surgically relevant parameters such as location and border of the tumor (Fahlbusch and Samii, 2007; Mittal and Black, 2006). Aside from iMRI, the intraoperative imaging techniques utilizing computer tomography

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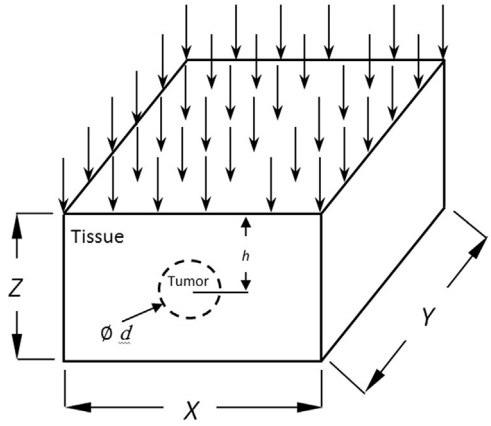

Fig. 1. Schematic simplified model of brain tissue (rectangular cube) including a spherical tumor.

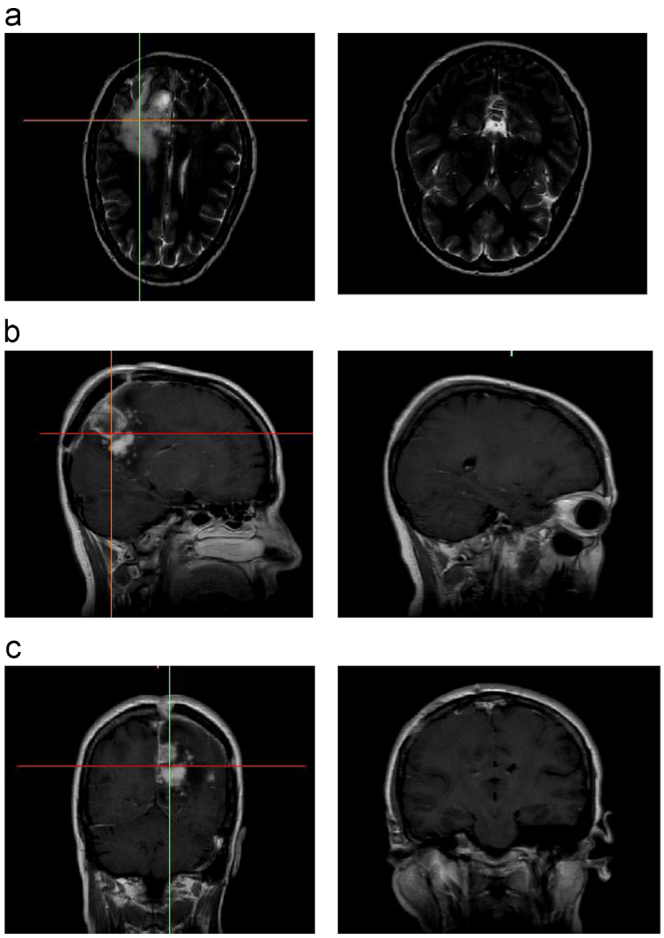

Fig. 2. (a) Coronal MRI; (b) sagittal MRI; and (c) axial MRI images of brain; please note the view of tumor in left pictures.

(Nakao et al., 2003) and ultrasound (Gobbi et al., 2000) were also reported to improve accuracy of the surgery. The use of intraoperative imaging techniques which can detect the brain shift would be a real improvement in minimizing unnecessary resection of the normal brain tissue (Kateb et al., 2009). Nevertheless, the intraoperative imaging techniques are still classified in the group of invasive methods, since the body is exposed to the harmful effects of using magnetic field and X-ray (Black et al., 1997). Moreover, intraoperative imaging techniques are really expensive and time-consuming as each scan prolongs about 20 min (Fahlbusch and Samii, 2007).

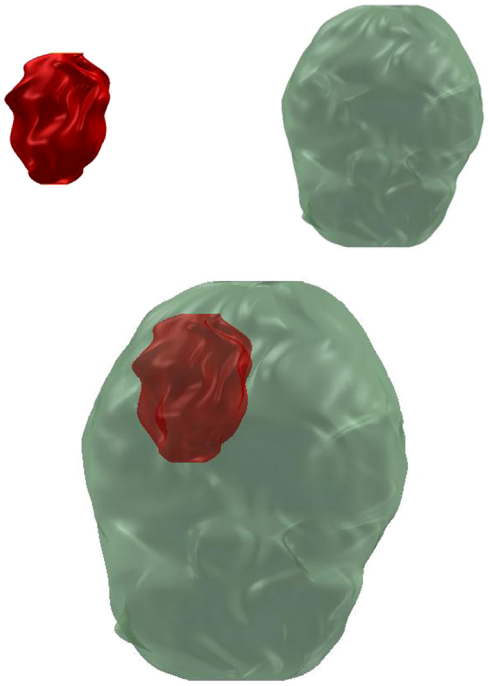

Fig. 3. 3D solid model of brain and tumor for finite element modeling.

Table 1
Viscoelastic properties of swine brain tissue (Miller, 1999).

Instantaneous response	Characteristic time t_1=0.5 (s)	Characteristic time t_1=50 (s)
$C_{100} = C_{010}$=263 (Pa) $C_{200} = C_{020}$491 (Pa) C_{10}=0	g_1=0.450	g_2=0.365

Table 2
Time parameters for computational cases, all values are in seconds.

Time period	Initial time increment	Minimum time increment	Maximum time increment	Maximum number of increments
1	0.05	0.0001	0.05	1000

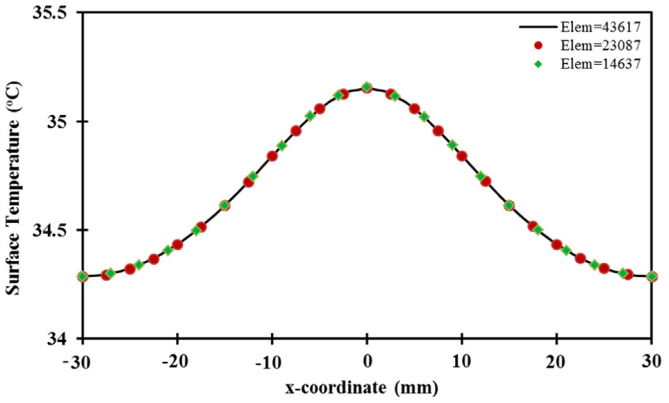

Fig. 4. Surface temperature measurements on a path passes through the center of the tissue's upper surface and parallel to the *X*-axis for three stages of mesh refinement.

Body temperature is a good indicator of human health condition. Therefore, an unexpected increase in temperature may be indicative of an internal abnormality. Cancerous cells generate