A Blood Vessel Deformation Model Based Virtual-reality Simulator for the Robotic Catheter Operating System

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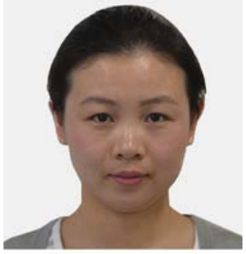

Yu Wang

Abstract: In endovascular interventional surgery, the virtual-reality (VR) simulator is critical for robotic catheter operating system since it offers physicians visual information between catheter and vessel. In spite of most VR systems using mass-spring to formulate vascular physical model, the uniform deformation doesn't satisfy the vascular characteristics. In order to simulate the vascular deformation more vividly, we introduce standard linear solid model to formulate its physical model and determine this model's parameters based on vascular wall elasticity analysis. In this way, the vascular physical model deforms according to vascular radius and material properties. In addition, so as to provide the vascular radius information for parameter identification process, we adopt discrete curvature estimation based on meshed triangle method in VR system. Finally, the VR simulator equipped with the parameters determined stand linear solid model is used to describe vascular deformation which is related to its radius and material characteristics.

Keywords: Blood vessel deformation, robotic catheter operating system, standard linear solid model, vessel wall elastic analysis, virtual-reality simulator.

1. INTRODUCTION

Recently, the prevalence of cardiovascular and cerebrovascular diseases increases as the fast pace of modern life. Based on World Health Organization statistic, about 17 million people annually worldwide died of these diseases. Thus, technology of vascular interventional surgery is expected to apply in medical fields. Robot assisted minimally invasive surgery, such as catheter manipulated system, which is able to deliver the drug to target position. Some commercial robotic catheter systems have been produced like Sensi [1] and Amigo [2] catheter systems. Sensi robot system works with Artisan guide catheter, which has steerable sheath with extended length, flexibility to control so as to reach hard-access area. Equipped remote console keeps physician from radiation source. Catheter Robotics Inc. developed remote catheter system Amigo allowing remote controller steering the catheter like Sensi. However, operating these products is far away from physicians' habits in surgery. In order to achieve good operability, our team developed catheter operating system [3-5] resembling to surgeon's hand inserting catheter actions shown in (Fig. **1** and Fig. **2**). In the physician's console part, through pushing or pulling handle, the surgeon's imposing force is measured by load-cell, which used fuzzy PID control algorithm to direct motor [6]. When motor works, the slide is programmed to drag catheter moving forward or backward. Meanwhile, the displacement of handle measure by encoder of step is transmitted to catheter manipulator side. Clamper 1 fixing on catheter as surgeon's hand drives the catheter move forward or backward. Besides translation, the catheter manipulator is capable of rotation by twisting the handle. Since the pulley wraps the handle and motor, the motor encoder will detect the rotation angle.

However, the blood vessel is fragile and the contact between the catheter and vessel wall is inevitable in surgery. To prevent catheter from piercing the vessel, the patient specific the virtual-reality simulator is high demanded. The VR system designed by our team is able to show the 3D of vessel network based on patients computed tomography. Besides, the mass-spring model is integrated in VR system which allows vessel deforms uniformly. Apart from our designed VR system, a number of studies in ref. [7, 8] have discussed to use mass-spring model describing deformation because of its small computation burden. In their work, the spring coefficient which is relevant to deformation is set manually to a constant. But in common sense, the vessels are impossible to deform uniformly. Several researchers [9-11] have explored to use FEM (finite element method) as reference to analyze parameter identification problem for soft tissue. According to the analysis of vascular mechanical properties in ref. [12], the elasticity is supposed to be relative to vascular radius. Thus, in order to describe the vascular deformation more appropriately, it is necessary to formulate vascular physical model based on mechanical properties.

In this paper, first we will introduce the standard linear solid model (SLSM) as physical model to describe the vascular deformation. To achieve accuracy, the parameters in

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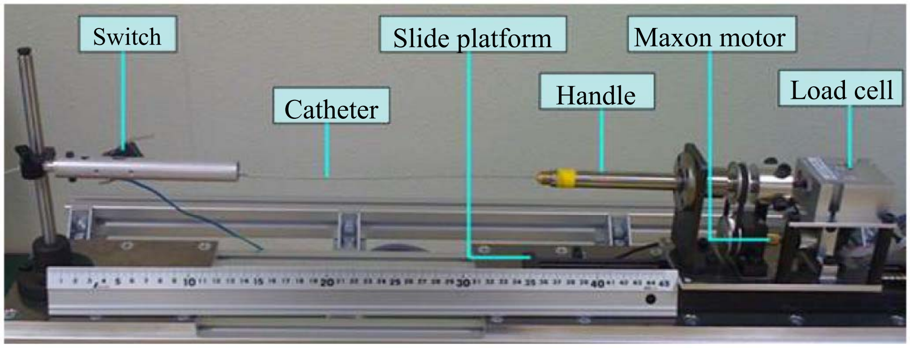

Fig. (1). The Structure of Physician Console.

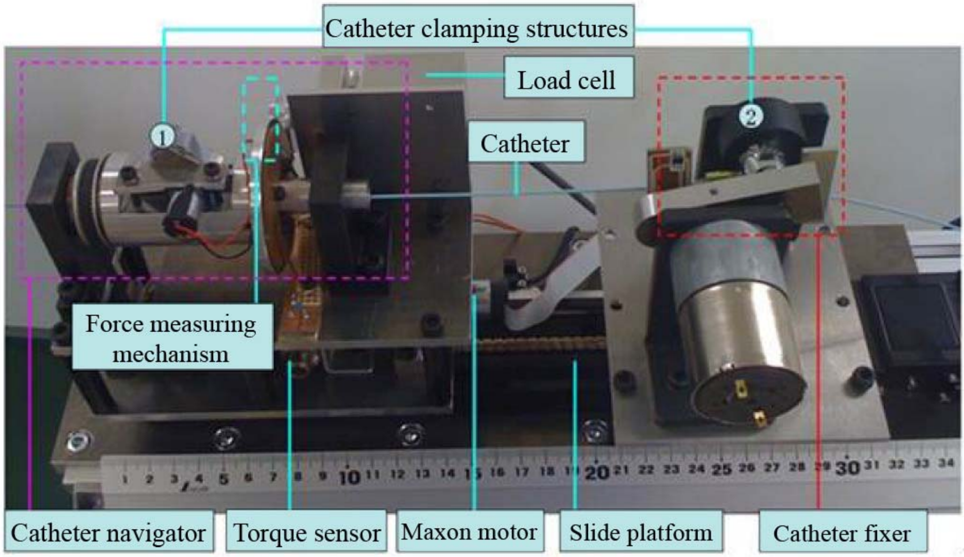

Fig. (2). The Catheter Manipulator.

SLSM are set based on vascular radii and its material properties. Second, since the vascular surface in VR system is dispersed into triangle mesh, acquiring radius corresponding to each node for parameters determination in vascular physical model is a tough task. Therefore, we adopt curvature estimation on meshed-surface method to obtain vascular radii. Through this method, parameters like spring and damper coefficients can be identified appropriately.

The paper is organized into the following sections. In section II, we present general formulation of standard linear solid model and derive the method to determine the parameters in physical model. Next in section III, we introduce a meshed-surface based curvature estimation to get vascular radii assisting SLSM parameters. The simulation results are shown in section IV. Finally, the conclusion and future work are discussed in section V.

2. SLSM PHYSICAL MODEL FORMULATION

In general, arteries are roughly divided into two kinds: elastic and muscular. Elastic vessels have large diameter and located close to the heart (like carotid), while muscular vessel are located at the periphery (such as femoral and cerebral vessel). From the mechanical view, the constituents of vascular wall catch researchers' eyes who are interested in analyzing vascular elasticity. The structure of vascular wall is made up of three layers, the intima, the media and adventitia according to reference [13]. The most inner layer intima is a single layer of endothelial cells. Its pathological condition may be related to atherosclerosis, the common arterial disease. But the intima layer contributes little to mechanical properties of vascular wall. The media is middle layer of vessel consisted of smooth muscle cells and elastin and collagen fibrils. According to the reference [13], the elastic laminae divided the media into multiple well-defined concentrically fiber-reinforced medial layers. Since the vascular size varied from elastic artery to muscular artery, the number of elastic laminae decreases to periphery. The close interconnection between elastic and collagen fibrils is called helix, which give medial high strength. The structure arrangement supports media strength to resist loads. The outmost adventitia contributes less to low pressure than media. Consequently, the media is most significant layer for wall stretch.

To simulate the vascular wall mechanical properties, spring and damper are assembled together like (Fig. **3**) to exhibit the viscous and elastic characteristics of vessel when it bears stress. Under a constant stress, the Maxwell model deforms immediately because of spring but it fails to predict creep. On the contrary, the Kelvin-Voigt model is good to model creep but with regards to relaxation it has less accurate. That is the reason these two models are not suitable.

Therefore, we choose standard linear solid model (SLSM) which combines the Kelvin-Voigt model and spring in series. The relation between stress σ and strain ε can be expressed as

$$\begin{cases} \varepsilon = \varepsilon_1 + \varepsilon_2 \\ \sigma = E_1\varepsilon_1 + \eta_1 \dfrac{d\varepsilon_1}{dt} \\ \sigma = E_2\varepsilon_2 \end{cases} \tag{1}$$

E_1, E_2 and η_1 denote spring and damper coefficients respectively and ε_1, ε_2 are strains of spring elastic part and Kelvin-Voigt. When SLSM is applied constant stress σ_0, the strain is derived as

$$\varepsilon(t) = \frac{\sigma_0}{E_2} + \frac{\sigma_0}{E_1}(1 - e^{-E_1 t/\eta_1}) \tag{2}$$

If SLSM is loaded constant stress for a time period Δt, the induced strain function of time following (2) is shown in (Fig. **4**)

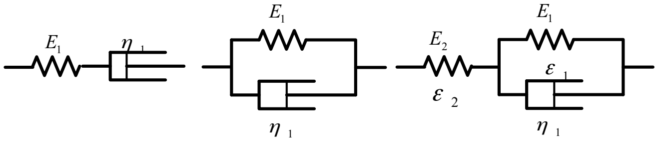

Fig. (3). Three kinds of viscoelasticity model.

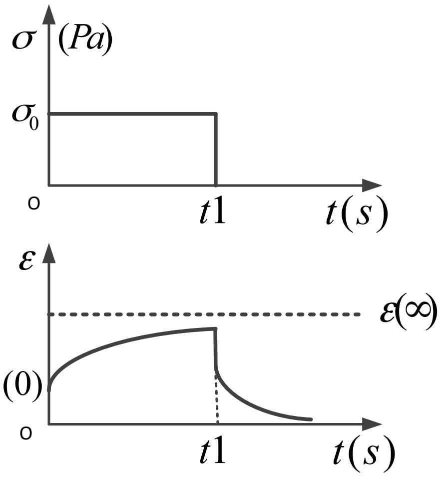

Fig. (4). Strain function when applied stress over a period of time.

As it is shown in (Fig. **4**), the SLSM will deform instantaneously because of spring part. Due to Kelvin-Voigt model, the strain will asymptotically approach to steady-state. Its strain is approximated like

$$\begin{cases} \varepsilon = \dfrac{\sigma_0}{E_1} \\ \varepsilon = \dfrac{E_1 + E_2}{E_1 E_2}\sigma_0 = \varepsilon_\theta \end{cases} \tag{3}$$

ε_θ is circumferential strain of vessel derived from reference [12]. According to reference [12], compared with circumferential strain, the strains in radial and axis direction are too small to neglect. Thus the vascular strain is represented by circumferential strain. In the period of constant stress, the SLSM strain is expected to reach to steady-state asymptotically. Thus, we set the asymptotically steady strain is p% of ε_θ and the initial strain is q%. Finally, the spring and damper coefficient is determined by following formula.

$$\begin{cases} E_1 = \dfrac{1-q}{q}E_2 = \dfrac{\sigma_\theta}{q\varepsilon_\theta} \\ \eta = \dfrac{-\Delta t E_1}{\ln(2-2p)} \end{cases} \tag{4}$$

Through (4), the parameters in SLSM are identified by circumferential stress and strain derived according to vascular mechanical properties.

$$\begin{cases} \varepsilon_\theta = \sqrt{\dfrac{C_1^2}{r^2} + 1} - 1 \\ \sigma_\theta = \dfrac{E}{1+v}\left(-\sqrt{\dfrac{C_1^2}{r^2} + 1} + C_2\right) \end{cases} \tag{5}$$

In (5) r, E and v are vascular radius, Young's modulus and Poisson's ratio respectively. And constants C_1 and C_2 are determined by boundary condition.

By formulating the standard linear solid model based on vascular mechanical properties, the important spring and damper coefficients are identified related to vascular radius and its material characteristics. Consequently, the SLSM ensures the vessel deforming more vividly in virtual-reality simulator.

3. VASCULAR RADIUS ESTIMATION IN VR SYSTEM

The virtual-reality system in ref. [14] is developed by our team according to patient-specific CT files. After segmenting the images, the three-dimensional visual of vessel is realized by Open Scene Graph (OSG). According to this geometry model, the surface meshed vascular is built in physics engine Bullet like (Fig. **5**).

However, the vascular surface is discrete into numerous nodes connected by triangle mesh in Bullet. In order to use above derived SLSM, we must have knowledge of vascular radii corresponding to each triangle mesh connected nodes.

Assuming the triangle mesh at node P_i is shown in (Fig. **6**). In the case that normal vector $\vec{n}$ at node P_i is known and arbitrary neighbor node P_j is for example, it is easy to yield the curvature k_{ij} in edge $\overrightarrow{P_i P_j}$ direction.

$$k_{ij} = 2\frac{(P_j - P_i)\bullet\vec{n}}{\left\|P_j - P\right\|^2} \tag{6}$$

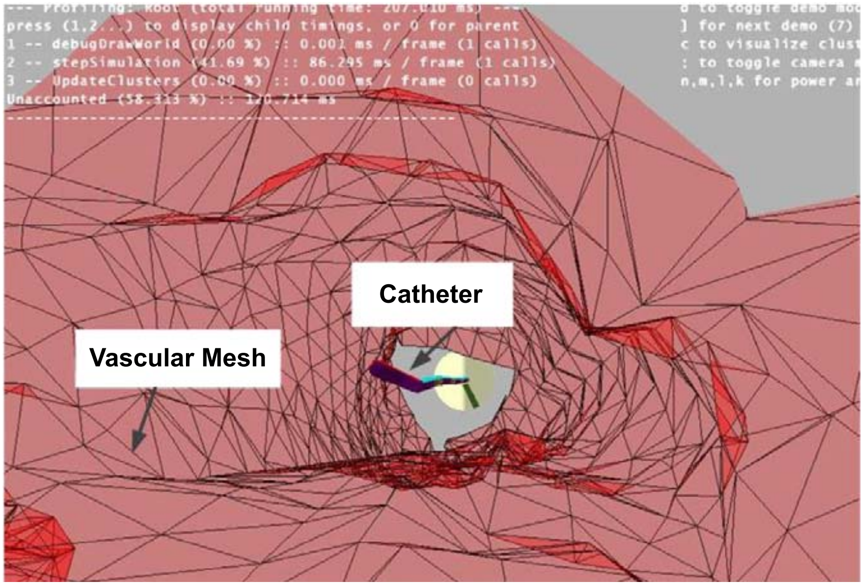

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Fig. (5). Triangle meshed vascular surface.

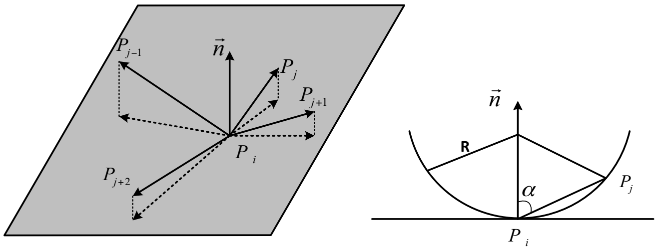

Fig. (6). Discrete surface curvature estimation at node P_i

As the blood vessels are approximate to be hollow tubes, the estimated radius at each node is supposed to be the maximum curvature of node's vicinity surface. We adopt Meyer's method in reference [15] to obtain the principal curvatures. Meyer applied the Gauss-Bonnet theorem to estimate the Gaussian curvature k_G, and introduced the Laplace-Beltrami operator to approximate the mean curvature k_H. Once the Gaussian curvature and mean curvature are got by Meyer's method, the maximum curvature is one of principal curvatures written as

$$k_{\max} = k_H + \sqrt{k_H^2 - k_G} \tag{7}$$

Once the curvature of surface around node is estimated, it is easy to determine the vascular radius corresponding to each surface node. Finally, combined with parameters identification of the standard linear solid model, the vascular physical deformation is related with vascular radii and material properties.

4. SIMULATION

In the simulation part, first we input the OSG generated vascular geometry model into physics engine Bullet. So far the vessel in Bullet is able to deform because the simplest spring is used as physical model. But vessels deform uniformly for all the springs are set to the same coefficients. The vascular surface is meshed into triangle as displayed in (Fig. **7**), where the red, green and blue scales represent X, Y and Z axes.

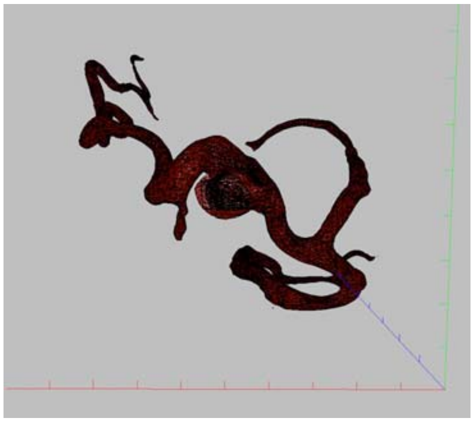

Fig. (7). The triangle meshed vascular physical model.

As exhibited in (Fig. **7**), the discrete surface is composed of 13316 nodes. Based on the curvature estimation method introduced in section III, we determined the cross section radius corresponding to each node. (Fig. **8**) shows the nodes corresponding radii distribution and the results imply that majority of nodes is in 0.4-1.0mm radius range.

Once the vascular radii are achieved, the SLSM is equipped in Bullet, which is used to simulate the vascular deformation. Since the spring and damper coefficients are determined by mechanical properties based on Eq.4, the vascular wall elastic analysis is based on following assumption. The vessel is treated as impressible material. Its Young's modulus and Poisson ratio are set to $E = 1.17 \times 10^7$ and $\nu = 0.495$ respectively. When vessel is subjected to inner pressure, the approximate steady strain of SLSM is capable to reach 95% of vascular strain ε_θ. The inner pressure lasts for one second and the initial strain q is set to 50% of steady strain. In above circumstance, two spring coefficients are equal and the relationship between spring and damper coefficients and vascular radius is showed in (Fig. **9**). Both spring and damper coefficients grow with vascular radius. Consequently, the results suggest that when VR simulator adopting standard linear solid model, the node corresponding to larger cross section radius is able to bear more stress. It explains the reason vessel with large radius deforms less dramatically than vessel with small radius.

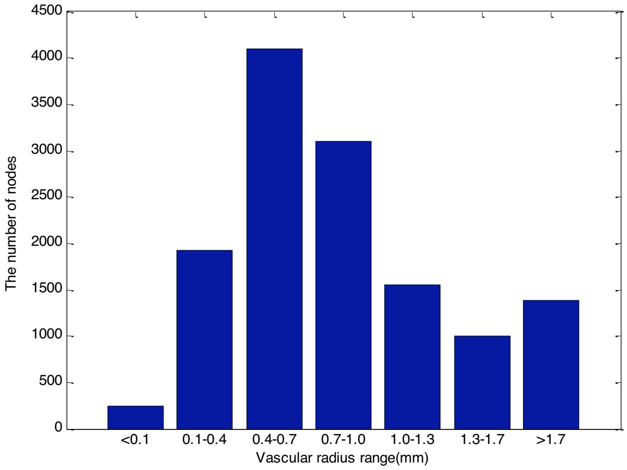

Fig. (8). The statistic of vascular radius range corresponding to each node.

The outcomes in (Fig. **10**) reveal the relationship between the SLSM strain and vascular radius. The SLSM model corresponding to small vascular radius in VR system is under larger strain. Therefore, SLSM equipped VR simulator is capable of imitating varying vascular deformation.

Compared with former uniform vascular deformation, it’s no double that newly derived SLSM and its parameters determination method are appropriate for describing the vascular physical model. According to SLSM in VR simulator, the vessels deforms based on their radii and material properites.

5. CONCLUSION AND FUTURE WORK

Simulating the vascular deformation in virtual-reality simulation is a significant task because it provides surgeon’s visual feedback. Therefore in this paper, we introduced spring and kelvin model serially combined standard linear solid model to formulate the vascular wall deformation. Since the spring and damper coefficients are critical to vascular deformation, we adopted previous elasticity analytical results to identify these important coefficients. In this way, the parameters in SLSM are relative with vascular radius and its material. In addition, the vascular surface is discrete in triangle mesh in VR system. To provide the vascular radius for parameters determination in VR simulator, we adopted curvature estimation based on surface meshed method for obtaining radius. Combined these two methods, the simulation results show that the spring and damper coefficients grow with vascular radius, which means that SLSM corresponding to large vascular radius can tolerate more stress. It explains why the vessel with small radius deforms more dramatically.

In the future work, firstly we will provide the VR system with collision detection mechanism. When the physician’s console device cooperates with VR system, it may work as a training system which is able to detect collision between catheter and vessel. Next, we will develop the haptic force feedback equipment on physician’s console device. Once the collision information in VR simulator delivers to console device, the haptic equipment is capable to offer a big force to alert surgeon the collision occasion.

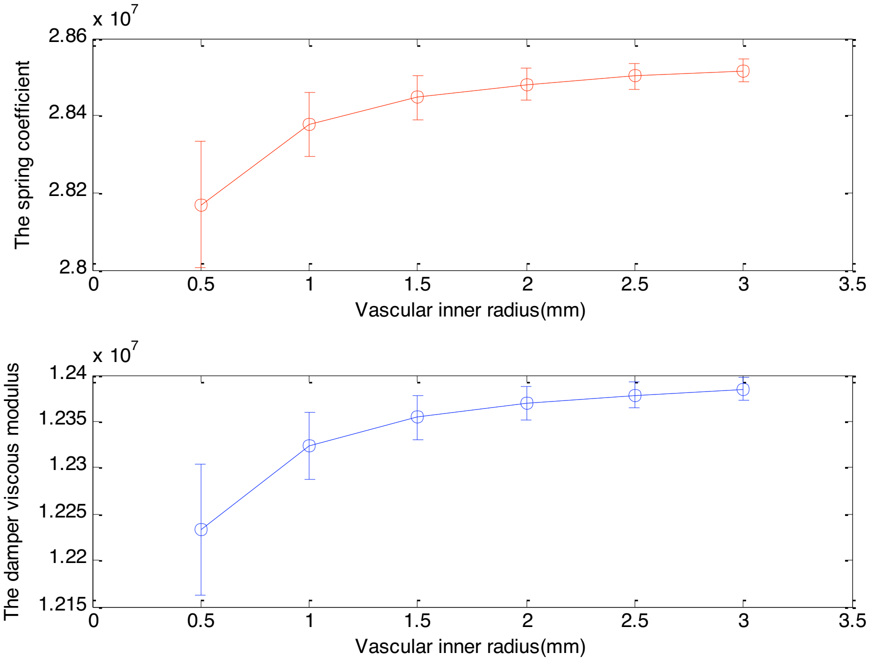

Fig. (9). The relationship between spring (and damper) coefficients and vascular radius.

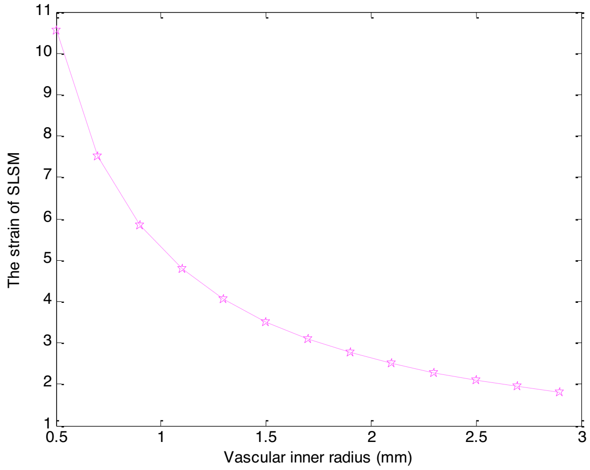

Fig. (10). The relationship between SLSM strain and vascular radius.

CONFLICT OF INTEREST

The author(s) confirm that this article content has no conflict of interest.

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