Modeling and Analysis of the Effects of Nephrolithiasis in Kidney Using a Computational Tactile Sensing Approach

Elnaz Afshari, and Siamak Najarian

***Abstract*—**Having considered tactile sensing and palpation of a surgeon in order to detect kidney stone during open surgery; we present the 2D model of nephrolithiasis (two dimensional model of kidney containing a simulated stone). The effects of stone existence that appear on the surface of kidney (because of exerting mechanical load) are determined. Using Finite element method, it is illustrated that the created stress patterns on the surface of kidney and stress graphs not only show existence of stone inside kidney, but also show its exact location.

***Keywords*—**Nephrolithiasis, Minimally Invasive Surgery, Artificial Tactile Sensing, Finite Element Method.

I. INTRODUCTION

NEPHROLITHIASIS defines as the condition of having Kidney stone or renal calculi, in medical terminology. it is one of the most painful and prevalent diseases of urinary tract that mankind has confronted since ancient times. Scientists have found evidence of kidney stones in a 7,000-year-old Egyptian mummy. Stones In fact are composed of the crystals of salts and other minerals present in the urine. These crystals can combine and grow to form the stones that vary in size and shape, and may be smooth or jagged.

There are different procedures to remove kidney stones from body, which include extracorporeal shock wave lithotripsy (ESWL), percutaneous nephrolithotomy (PNC), open surgery and different minimally invasive surgery approaches [1]–[3]. These methods have their own advantages and disadvantages, in other words not every method is suitable to remove any size of kidney stone and the doctor determines the best method according to the patient’s situation and the stone diameter.

Minimally invasive surgery (MIS) is a new method of surgery that has a lot of valuable advantages in comparison with the traditional open surgery approach [4]–[6]. The need to detect various tactile properties (such as stiffness, temperature and surface texture) justifies the key role of tactile sensing that is currently missing in MIS [7], [8]. At this moment, determination of the exact location of stone during MIS is one of the limitations of these methods that no scientific solution has been found for so far. According to the above discussion, design and fabrication of an intelligent surgical instrument based on artificial tactile sensing, capable of determining the exact location of stone during MIS seems necessary. This instrument can be also used in robotic surgery or telesurgery systems [9]–[11].

Artificial tactile sensing is a new method for obtaining the characteristics of a hard object embedded in a soft tissue. In this regard, artificial palpation is one of the important applications of artificial tactile sensing that can be used in different types of surgery operations [12]–[15].

The design and fabrication of such an instrument can be based on different parameters. In this paper, using 2D modeling of nephrolithiasis (two dimensional model of kidney containing a simulated stone) and analyzed by Finite Element Method, the effects of stone existence that appear on the surface of kidney were investigated. Also it is illustrated that the stiffness of stones can be a good criterion in design and fabrication of an intelligent surgical instrument.

II. MATERIALS AND METHODS

In the present study, the effects of nephrolithiasis is modeled and analyzed in order to find a suitable parameter to be used in design and fabrication of an intelligent surgical instrument. Having imitated surgeon’s palpation during open surgery and modeled it using a computer, changes appearing on the surface of kidney as a result of stone existence were studied.

III. ASSUMPTIONS

Considering the point that this instrument will be used during MIS, it is assumed that the instrument is able to acquire data about the exact location of stone only by contacting with the surface of kidney. It is interesting to know that during open surgery, the surgeon finds out the exact location of stone by palpating the surface of kidney, which confirms the above assumption.

The kidney tissue and kidney stone are assumed to be elastic and isotropic material in this work. The elastic modulus of kidney tissue and its Poisson ratio are assumed to be 2,500 Pa and 0.4, respectively [16]. The elastic modulus of stone and its

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Poisson ratio are also deemed to be 5 GPa and 0.3, respectively [17].

The load on kidney surface is applied as displacement. In fact it is assumed that by contacting the intelligent surgical instrument with the surface of kidney and exertion of a small pressure on it, the surface of kidney is displaced by 5 mm.

IV. Modeling and Simplifications

Considering the complicated nature of the 3D analysis and also the importance of the effects of mechanical loading on the surface of kidney, a 2D model of the transversal section of kidney and simulated stone in it will be presented (see Fig. 1). In this model, the section of kidney and the stone are assumed to be rectangular and circular, respectively. According to the anatomy of kidney, dimensions of the rectangle are selected to be 5 cm × 7 cm. Also a normal stone (which is 1.5 cm in diameter and 2.5 cm in depth) was modeled.

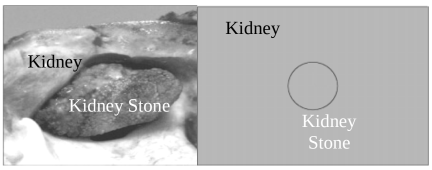

Fig. 1 Modeling of kidney section and kidney stone in it

V. Finite Element Model and Boundary Conditions

This problem was modeled and solved by the finite element software ABAQUS (Release 7-1, Version 6). The common edge between kidney and stone was glued together in order to keep continuous strain in consequence of deformation. The side edges did not have any constraints but the lower edge was fixed in the direction of upper edge compression. By doing this, it was possible to avoid rigid body motion and solve the problem statically. The meshed model is shown in Fig. 2.

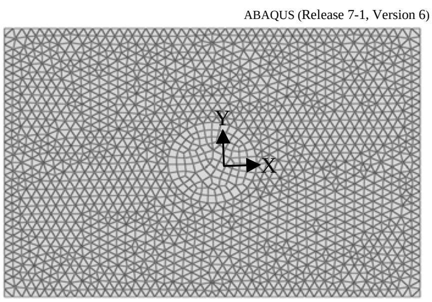

Fig. 2 The meshed model

VI. Results

In a stress analysis problem, the stress and strain distributions are usually important results. In this section, in addition to analyzing these results, using software's abilities we will extract graphs which can be useful in analyzing the effects of stone on the surface of kidney. In Figs. 3 and 4, stress and strain distribution contours are illustrated, respectively.

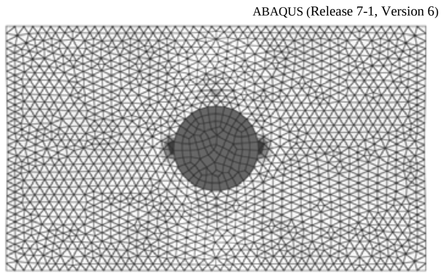

Fig. 3 Stress distribution contour in 2D model

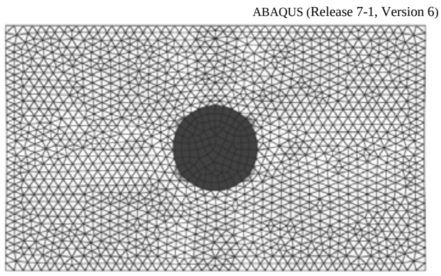

Fig. 4 Strain distribution contour in 2D model

According to Figs. 3 and 4, stress and strain contours have very similar distribution forms but they differ in magnitude. We expected this, for we had assumed the material to be linear elastic. Thus in the following only stress analysis will be presented.

Based on stress contours, moving from one side of the model to the other, we can see that the stress distribution in kidney surface varies and it reaches its maximum exactly in the point under which stone center is located. This is the basic conclusion we obtain from our analysis, which can be called briefly "the appearance of the signs of stone existence on the surface of kidney".

In order to analyze what exactly happens on the surface of kidney, we take a path along the rectangle's upper edge and using the ABAQUS software capabilities, we draw stress in this path in a graph. The stress graph on the surface of kidney is illustrated in Fig. 5.

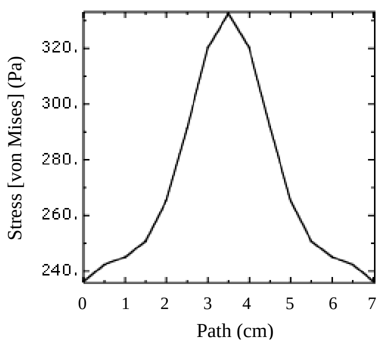

Fig. 5 Stress graph on the surface of kidney

It is important to note that the point in which stress graph has its maximum value shows the exact location of the stone. We will show in the following graphs that by moving the location of stone to the left or right of the model, the point that has maximum stress will also move to the left and right, respectively. Figs. 6 and 7, illustrate stress graphs for the cases in which stone is located in the left side and the right side of model, respectively.

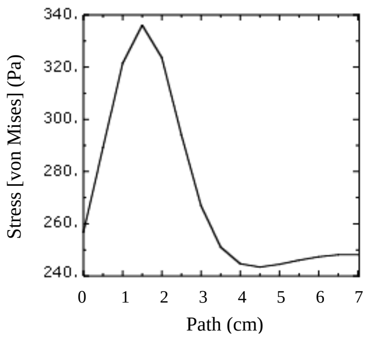

Fig. 6 Shifting the stress maximum value to the left, by shifting the kidney stone to the left of model

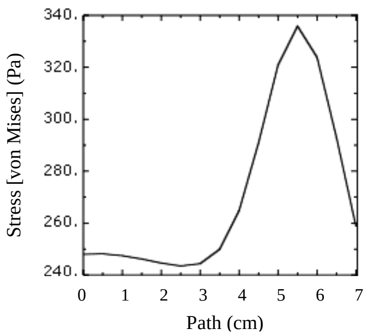

Fig. 7 Shifting the stress maximum value to the right, by shifting the kidney stone to the right of model

In continue we present the finite element analysis for a case in which the stone is embedded in a deeper location and it has smaller diameter. Therefore, we will model a stone which is 1cm in diameter and 4cm in depth. The meshed model is shown in Fig. 8.

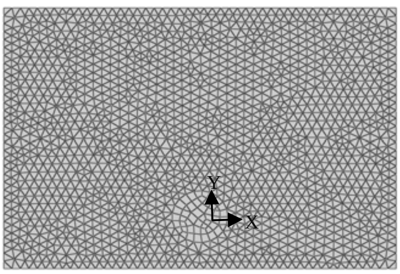

Fig. 8 The new meshed model

The result of this analysis is illustrated in Fig. 9.

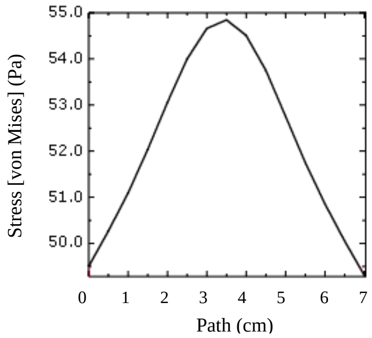

Fig. 9 Stress graph on the surface of kidney in a new model (a stone with a diameter of 1 cm and an embedding depth of 4 cm)

According to the graph of Fig. 9, it is clear that the maximum value of stress is smaller in comparison with the previous models, but it still corresponds with the exact location of stone.

VII. Simulation of Intelligent Surgical Instrument's Function

In order to obtain a more realistic model and complete our discussion, the "contact between intelligent surgical instrument and kidney surface" is modeled and analyzed in this section. This is done by adding another object representing intelligent surgical instrument to the model of kidney and stone. This object is assumed to be convex in shape.

In this new condition, the finite element models of kidney and stone as well as the boundary conditions of problem have not been varied. The only difference is loading. Contrasting to the previous model in which the load was applied as a displacement in rectangle's upper edge, the loading is the amount of concavity in kidney's tissue caused by intelligent surgical instrument. Considering the biocompatibility of intelligent laparoscopy instrument, mechanical characteristics of stainless steel was assume for it (E = 60 MPa).

In order to model contact between the instrument and kidney surface, the surface-surface contact method is used. This makes possible the analysis of contact between two elements and also allows for sliding of surfaces (the instrument and kidney). A sample stress distribution contour is illustrated in Fig. 10.

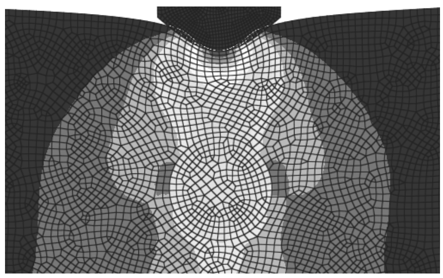

Fig. 10 Stress distribution contour in a sample model

It is important to note that in stress diagrams, the maximum value of the diagram neither shows existence of stone, nor its location. In fact, in these diagrams, the point of maximum stress always corresponds with the center of intelligent laparoscopy instrument. Due to the convexity in instrument's geometric shape, displacement in this point is always larger than that of other points affected by the contact, and thus this point always has the maximum stress. However, the value of maximum stress in these diagrams is the interesting and notable point. This value decreases as the intelligent laparoscopy instrument increases its distance from the location of stone. This is clearly visible in the diagram of Fig. 11.

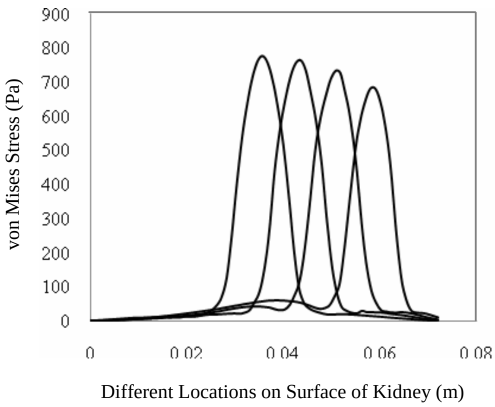

Fig. 11 Variations of stress values

VIII. Conclusion

Based on our analysis, using finite elements method, we illustrated that:

- Stress analysis is an appropriate method to verify the existence of kidney stone inside kidney (because of the alteration of stress distribution on kidney surface caused by existence of stone).
- Stress analysis depicts exact location of the stone. This concept can be used in the intelligent laparoscopy instrument design in order to determine the exact location of stone during laparoscopy and robotic surgery.

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