Development of an Ultrasonic Scalpel

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Abstract. This paper explains the development of an ultrasonic scalpel for soft tissue dissection. It is used in both open and laparoscopic surgery to coagulate and dissect the soft tissue. The ultrasonic scalpel has been designed, prototyped, and characterized. The development includes its power supply with ultrasonic-wave-signal generator, ultrasonic transducer, ultrasonic amplifier, a pair of end effectors, and a casing with trigger mechanism. Conceptual design was done by using SolidWorks, and the conceptual design was simulated and refined until optimum design is obtained. The prototype of the final design was done by using machining process for the metal components and rapid prototyping for the plastic parts which are finally assembled for characterization purpose, which includes the measurement of natural frequency, vibration stroke, and its capability to dissect soft tissue. The result shows that the natural frequency of the ultrasonic scalpel is 29.3 kHz, with peak to peak vibration stroke of $40\mu m$. The ultrasonic scalpel can dissect muscle tissue of chicken in 16.6 s at the maximum temperature along the dissection site of $81.7^\circ C$.

1. Introduction

As early as 1993, ultrasonic cautery was developed by Amaral, called ‘laparoscopic scalpel’ for laparoscopic surgery by allowing simultaneous coagulation and dissection of blood vessel [1]. Laparoscopic surgery is the first type of minimally invasive surgery where it is a surgery done through one or more small incisions, rather than a larger incision through abdominal wall. It is done by using small tubes, imaging system, and surgical instruments with extension rod [2]. Energy devices of laparoscopic instruments such as monopolar, bipolar, and ultrasonic scalpel are widely used during the operation [3]. As compared to the electrosurgery devices, ultrasonic scalpel reduces the operating time, difficulty, blood loss, and lateral thermal spread [4], [5].

Within the ultrasonic scalpel, alternating current is applied to electric generator which convert to direct current and into oscillated current at desired frequency. Piezoceramic acts as transducer to converts electrical energy into mechanical vibration energy at frequencies ranges from 20kHz to 60kHz. The vibration motion oscillates the active blade of the ultrasonic scalpel linearly and the active blades movement ranges from 50 to 100μm [6]. Tissue is held between the active and counter blade and heat is generated from the friction between active blade and the counter blade to denature the protein in the tissue resulting in coagulation. The advantages of ultrasonic scalpel include less instrument traffic as it can perform vessel sealing and tissue cutting simultaneously, and low smoke generation [7]. The temperature generated ranges from 50°C to 300°C, which reduces the lateral thermal spread and less charring [8]. In the case of lower density tissue with high water content, the intracellular water is vaporized by the heat generated causing
‘cavitation effect’ further assisting in the dissection by separating tissue layers [3]. The efficiency of dissection by ultrasonic scalpel is dependent on the nature of the tissue such as its water content, and the tissue strength which is directly related to the type of tissue, amount of collagen and its organization.

When applying ultrasonic scalpel to a tissue, there are three main effects on the tissue which are cavitation, coagulation, and cutting. Firstly, in the cavitation effect, oscillating pressure field is produced due to the linear stroke from the active blade and causing the expansion and contraction of intracellular fluid and the tissue around the dissected site at ultrasonic frequency. When it is in the expansion stage, the pressure of the intracellular fluid dropped below its vapor pressure, causing vapor bubbles to be generated within the tissue. In contraction stage, the pressure is then raised rapidly causing the vapor bubbles to collapse. Since this happened is at ultrasonic frequency, shock wave is produced, and jet-like ejections is generated into the intracellular fluid. These phenomena happened in micro-second scale and over a period, the tissue will be dissected [9]. Cavitation is essential because it causes the separation of tissue planes facilitating the dissection process later. Next, for the coagulation, it occurs when the frictional heat generated between tissue and active blade is transmitted into tissue, which might heat up to 60°C to 100°C. Denaturation of protein or collagen starts and result in occlusion of blood vessel. Denaturation of protein happened because the tertiary hydrogen bonds between collagen and protein is broken. The proteins denature and convert from colloidal proteins into an insoluble gel that helps on occlusion. Lastly, the cutting effect is achieved by the high frequency oscillation of the active blade applied to the tissue [10].

The project has two objectives highlighted below:

1. To develop an ultrasonic scalpel as it can be used for cutting and cauterizing tissue. The design of ultrasonic scalpel includes its ultrasonic transducer, ultrasonic horn, trigger mechanism, active and counter blades, and the casing.
2. To characterize the designed ultrasonic scalpel in terms of frequency, stroke, elevated temperature, and the ability to cut tissues.

2. Methodology

2.1. Conceptual Design of Ultrasonic Scalpel

The conceptual design of ultrasonic scalpel done in the SolidWorks includes two independent working systems, which is as shown in figure 1.

In the System 1, oscillated electric signal from the signal generator is amplified to actuate the piezoceramic. Through the inverse piezoelectric effect, the oscillated current is converted into vibration stroke. With the stroke amplifier, the active blade will vibrate at a desired range of stroke. In the System 2, the mechanism is functioned to transmit the load applied by the surgeon, to the counter blade. In ideal condition, there is no energy loss due to damping of the system.
within the mechanism, the amount of energy of surgeon applied should be all goes to the counter blade to hold the soft tissue firmly.

2.2. Finite Element Analysis
After the conceptual design is done, finite element analysis is carried out to simulate the natural frequency of the system. The result obtained from simulation is used to validate the result obtained from the measurement of natural frequency of the system. SolidWorks software is used to simulate the system.

2.3. Prototyping
In the prototyping stage, the rapid prototyping technology was be used for plastic parts while the machining process was used for metal parts. FDM 3D Printer, CNC, EDM Wire Cut, and some other machining processes have been applied to fabricate the prototype.

2.4. Characterization of Ultrasonic Scalpel
After the prototype of designed ultrasonic scalpel was created, it was characterized to describe about its key features in soft tissue dissection, which are natural frequency of the system, vibration stroke produced by ultrasonic scalpel, time taken for soft tissue dissection, and maximum temperature elevated during dissection.

2.5. Measurement of Natural Frequency of the Ultrasonic Scalpel
To measure the natural frequency of the system, signal generator, oscilloscope, and the ultrasonic transducer can be connected through electrical circuit, as shown in the figure 2.

![Figure 2. Circuit design for measurement of the natural frequency](image)

When the ultrasonic scalpel is excited at its natural frequency, the impedance of the EUA, $Z_{load}$ is at its lowest point as the ultrasonic scalpel vibrates at its maximum amplitude. The 47Ω resistor is connected in series to the ultrasonic scalpel, both loads share the same amount of current within the circuit. Since $Z_{load} \ll 47\Omega$, the voltage drops across the ultrasonic scalpel is at the least amount. Most of the voltage drops across the 47Ω resistor and it shows the maximum potential difference across the circuit. If ultrasonic scalpel vibrates at its natural frequency, the difference between the root mean square voltage, $V_{rms}$ should be at its minimum, and the two voltage signals across ultrasonic scalpel and resistor should be ideally in phase.

2.6. Measurement of Vibration Stroke of the Ultrasonic Scalpel
Next, to measure the vibration stroke produced by the ultrasonic scalpel, electrical circuit connection, as shown in the figure 3 will be followed.
Figure 3. Circuit for stroke measurement of the ultrasonic scalpel.

From the schematic diagram as shown in figure 3, it can be observed that the circuit on the left is open circuit, no current flows across the 68kΩ resistor and micrometre, hence there is no voltage drop across the two components. The oscilloscope that connected to measure the voltage signal of micrometre will show the 15V of power supply on screen with zero current. However, when the spindle of micrometre is in contact with the active blade of US, the micrometre is then grounded through the US. The DC power supply provide 15V of voltage and flow across the 68kΩ resistor and micrometre. Since micrometre and resistor are connected in series, the current across the two components is constant. By applying the Ohm’s Law, voltage drop is higher at the components with higher resistance. Since the spindle of micrometre is a good electrical conductor, it has negligible resistance as compared to 68kΩ resistor, thus voltage drops across the micrometre is approximately zero. The oscilloscope will show a zero-voltage signal when the spindle of micrometre and active blade of US is in contact.

2.7. Dissection of Soft Tissue by Ultrasonic Scalpel

In this section, the fabricated ultrasonic scalpel was used to test for soft tissue dissection. In this experiment, the time taken for soft tissue dissection and the maximum temperature variation at the dissection site were measured. In this experiment, ultrasonic scalpel will be handheld to dissect the soft tissue. The functionality of the trigger mechanism was tested on the ultrasonic scalpel. In the sample preparation, chicken breast was chosen as sample and sliced into small piece with its width is controlled within 5mm.

3. Results and discussions

3.1. Conceptual Design of Ultrasonic Scalpel

Figure 4 depicts the prototype of the ultrasonic scalpel with the labelled components. In the System 1, the oscillated electric current through power supply actuated the piezoceramics. The vibration stroke produced is then amplified through the horn and transmitted to the active blade to cut the soft tissue (the top blade as in figure 4). The active blade is driven by the ultrasonic motor which is cylindrical and located in the motor housing which is the bulky cylinder in the bottom half of the scalpel. For the System 2, the load applied using a scissor like mechanism. The counter blade is flat and together with the active blade, shear the soft tissue located in between the two blades for dissection.

Figure 4. The prototype ultrasonic scalpel.
3.2. Simulation and Measurement of Natural Frequency of Ultrasonic Scalpel

The results obtained from the simulation and measurement are listed in table 1.

**Table 1. Results of simulation and measurement.**

|                       | Measured Natural Frequency, \( f_{exp} (kHz) \) | Simulated Natural Frequency, \( f_s (kHz) \) | Percentage Difference, % |
|-----------------------|-----------------------------------------------|-----------------------------------------------|---------------------------|
| Without Active Blade  | 43.5                                          | 41.8                                          | 3.82                      |
| With Active Blade     | 29.3                                          | 28.2                                          | 3.53                      |

The result shows that the first natural frequency of the desired mode shape is, \( f_{1,2} = 28.2 \, kHz \). As observed, the natural frequency is dropped from 41.84 kHz to 28.245 kHz. The natural frequency of a system is inversely proportional to the mass. When active blade is added to the system, the active blade contributes additional mass to the system. With the increase in mass of system, the natural frequency of system is dropped.

3.3. Measurement of vibration stroke of the ultrasonic scalpel

The results obtained are listed in table 2. Figure 5 shows the example of voltage signal obtained when the spindle of micrometre is at the peak of vibration stroke.

**Figure 5. Voltage Signal Detected when Spindle of Micrometre at Peak Position.**

**Table 2. Vibration Stroke of Ultrasonic Scalpel.**

| Trial | Reading on Micrometer at Peak Position, mm | Reading on Micrometer at Rest Position, mm | Forward Stroke, \( \mu \text{m} \) | Peak to Peak Vibration Stroke, \( \mu \text{m} \) |
|-------|-------------------------------------------|----------------------------------------|----------------------------|---------------------------------|
| 1st   | 0.45                                      | 0.47                                   | 20                         | 40                             |
| 2nd   | 0.03                                      | 0.05                                   | 20                         | 40                             |
| 3rd   | 0.37                                      | 0.35                                   | 20                         | 40                             |

From the result obtained, it shows that the peak to peak vibration stroke of System 1 in ultrasonic scalpel is \( 40 \mu \text{m} \) throughout the 3 trials. The type of micrometre used is depth micrometre with resolution of \( \pm 0.01 \mu \text{m} \). Thus, the tolerance of for the peak to peak vibration stroke is \( \pm 0.005 \mu \text{m} \).

3.4. Dissection of Soft Tissue by Ultrasonic Scalpel

Figure 6 shows the sample tissue after dissection by using prototype of ultrasonic scalpel. The time taken for dissection and maximum temperature variation during the dissection process are plotted in figure 7 and figure 8 respectively.
In figure 7, the average time taken for the dissection by ultrasonic scalpel is 16.6s. In Fig.11, it shows that the average maximum temperature elevated at dissection site is 81.72°C.

One of the challenges in the development of energy scalpel is the collateral tissue damage. In this case because of the high internal temperature generated at the cut location there will also lateral thermal spread on the dissected tissue with the width of approximately 1mm from the dissection site on one side of dissection site. Thus, there is total lateral thread spread of less than 2mm on the sample of tissue. This is the proof where the frictional heat generated is enough to denature the protein within soft tissue. There is minimum amount of excessive heat generated to transmit into lateral thermal spread.
In the dissection process, tissue is held firmly with a certain amount of force on it. Once the ultrasonic transducer is excited, the active blade on the soft tissue will start to oscillate back and forth at ultrasonic frequency. This will create a sliding effect on the tissue, and friction due to the sliding is generated at the dissection site. Friction has been continuously occurring between the surface of active blade and the soft tissue. Thus, frictional heat is generated on the dissection site. As dissection process is carried on, more heat is generated and causes the heat zone increased. The heat zone can be observed with the colour changed on the soft tissue from light pink colour to the white colour. This is happened when the protein within the region undergo denaturation. In addition, mist is released from the dissection site during the dissection process. This has proven that the vapor bubble created during the expansion stage from the intracellular fluid is collapsed. The thin film on the vapor bubble is spread out as the mist when the bubble is collapsed.

4. Conclusion
The ultrasonic scalpel has been developed and characterized. The natural frequency of the system is 29.3 kHz and capable of stroke of 40μm. During the dissection, the time taken for dissection is as short as 16.6s while the maximum temperature elevated at the dissection site is 81.72°C.

5. References

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