Hindawi
Journal of Spectroscopy
Volume 2020, Article ID 7816969, 6 pages
https://doi.org/10.1155/2020/7816969

Research Article

Evaluation of Tensile Force in a Porcine Trachea Using a Reflective Optical Method

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Received 11 November 2019; Revised 21 January 2020; Accepted 11 February 2020; Published 21 March 2020

Academic Editor: Alessandra Durazzo

The trachea serves a variety of functions during breathing and swallowing. In cases requiring a partial resection, the treatment may involve anastomosis of the healthy ends of the trachea. The tension in the anastomosis should not exceed 1,000 g. Traditional methods for estimating tension in the trachea are very invasive. The aim of this work is to develop a noninvasive optical system devoted to estimate the tension of the trachea *in vivo*. An optical system was designed using a light source and a photosensor. To determine the most suitable wavelength for the light source, a photoacoustic spectroscopy study was performed. To test the system, a cadaveric pig trachea was mounted on a universal testing machine, and it was subjected to three tensile tests of up to 30 mm elongation. The optical response was measured at 0, 10, 20, and 30 mm elongation. An exponential response was observed so that the optical voltage-response curves were adjusted, and three exponential equations were derived to correlate the voltage with the optical response. We can conclude that the proposed optical system is able to noninvasively estimate the tension of a cadaveric porcine trachea.

1. Introduction

The trachea has an anatomical structure that allows it to carry out its functions. It has a cartilage ring structure joined by muscle and connective tissue, allowing it to remain open while breathing; its structure also provides elasticity for swallowing, neck mobility, and speech [1]. In surgeries in which it is required to remove a segment of the trachea affected by benign or malignant medical conditions, it is necessary to reestablish the airway and maintain the continuity of the tube. The simplest way to reconstruct the trachea involves resection of the affected segment, followed by anastomosis of the unaffected ends of the trachea. In adults with lesions affecting less than 50% of the length of the trachea, the two ends can be connected immediately after resection [2]. In the case of children, up to 40% can be removed safely [3]. Block resection with end-to-end anastomosis is the treatment of choice when there are no previous scars [4].

Postresection and reconstruction complications following anastomosis are uncommon but can be severe [5, 6]. Complications of anastomosis include the presence of granulation tissue at the site of attachment, stenosis, and separation, which may signify catastrophic failure of anastomosis. Other authors have identified reoperation, early age, diabetes, resections greater than 4 cm, and presence of tracheotomy before resection as risk factors for complications of anastomosis [7]. Tension on the suture line may cause stenosis at the anastomosis [3, 7]. In previous cadaveric studies, it was established that the maximum recommended resection is 4.5 cm, which corresponds to a tension of 1,000 g [8, 9]. The ability to determine acceptable tension at the anastomosis is learned with experience because there is no direct method to measure it *in vivo*. In the present work, an optical system is used to estimate tension in a porcine model *in vitro*. To determine the appropriate wavelength to be used in the optical system for a porcine trachea, a photoacoustic study was performed. Once the wavelength has been determined, a device was developed to emit light at the appropriate wavelength so that a photosensor can capture the intensity of the reflected light. The tension was estimated in a porcine trachea subjected to progressive elongation in a universal testing machine, while the optical device was simultaneously used to indirectly measure the tension on the trachea. This device could be used to measure the tension during an anastomosis procedure in an *in vivo* trachea.

2. Materials and Methods

2.1. Photoacoustic Spectroscopy. Photoacoustic spectroscopy allows us to determine the wavelength of incident light which has minimal optical absorption [10]. The sample to be studied is placed in a cylindrical closed metal cell, which is covered with a quartz window to minimize absorption of ultraviolet or infrared light. The incident light on the sample is modulated at a fixed frequency, f (17 Hz), by a rotating disk having a radial groove (chopper). Light enters the cell at the top, and a microphone is placed laterally, as shown in Figure 1. Figure 2 shows the experimental equipment used for the photoacoustic study.

A 1,000 W Xe lamp was used as the light source; its beam was focused onto the monochromator in order to obtain a monochromatic light beam. That light beam was applied to the sample via optical fiber. The optical absorption spectrum of the sample was obtained using a computer program which sweeps through a defined range of wavelengths by adjusting the monochromator. The photoacoustic signal was obtained as a function of the incident wavelength. Two samples of porcine trachea were tested. The acquired data were processed simultaneously, and the graph corresponding to the absorption spectrum is shown.

2.2. Development of the Optical System. The optical system must meet the following design requirements:

(i) Portable
(ii) Easy to use
(iii) Sensitive enough to measure small changes in the intensity of reflected light
(iv) Integrate transmission of light through bifurcated optical fiber
(v) Minimize noise generated by ambient light sources

The device contains a laser light source coupled to a bifurcated optical fiber. The laser light hits the sample and is reflected. The reflected light is led by the second path of the bifurcated optical fiber to a photosensor. An electronic coupling card communicates with an Arduino

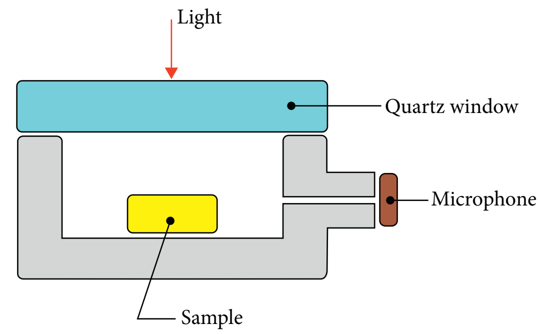

Figure 1: Photoacoustic cell.

microcontroller board to measure changes in the voltage of the photosensor and display the optical response measurement. Figure 3 shows a block diagram of the optical device.

2.3. Biomechanical Tension Testing and Measurement of Optical Response. A sample of a cadaveric trachea of a young adult pig without apparent disease was obtained. The sample was tested within four hours of obtaining the sample, during which time it was kept in physiological solution. The segments corresponding to the fibrocartilaginous tube were preserved; the lungs, carina, esophagus, cricoid, and thyroid cartilage were removed. The testing length, in this case the distance between supports, was 100 mm. A universal Instron testing machine model 4502 (Instron Corp, Norwood, MA, USA) was used at a constant speed of 20 mm/min from 0 to 30 mm elongation. Optical equipment was mounted next to the test machine, and the optical response of the sample was recorded at 0, 10, 20, and 30 mm elongation (Figure 4). Tensile tests and measurements of optical response were done three times using the same sample and the same experimental setup.

3. Results

Small tissue samples were taken from two cadaveric porcine tracheas and mounted in the photoacoustic cell. Their optical absorption spectra were determined as a function of wavelength using the photoacoustic spectrometer equipment described above. It was observed that the optical absorption is higher at lower wavelengths and decreases gradually and asymptotically (Figure 5). We observed that there are high peaks in the absorption measured after 700 nm, so we chose a wavelength of 650 nm, which corresponds to the red color.

Using this wavelength, it was possible to select the suitable photosensor for the optical system in order to measure trachea tension. We selected the TSL 257 phototransistor (ams AG, Premstaetten, Austria), which operates at wavelengths between 300 and 1,100 nm and temperatures between 0 to 70°C.

Tension tests were made three times on the same cadaveric porcine trachea sample from 0 to 30 mm. In the three

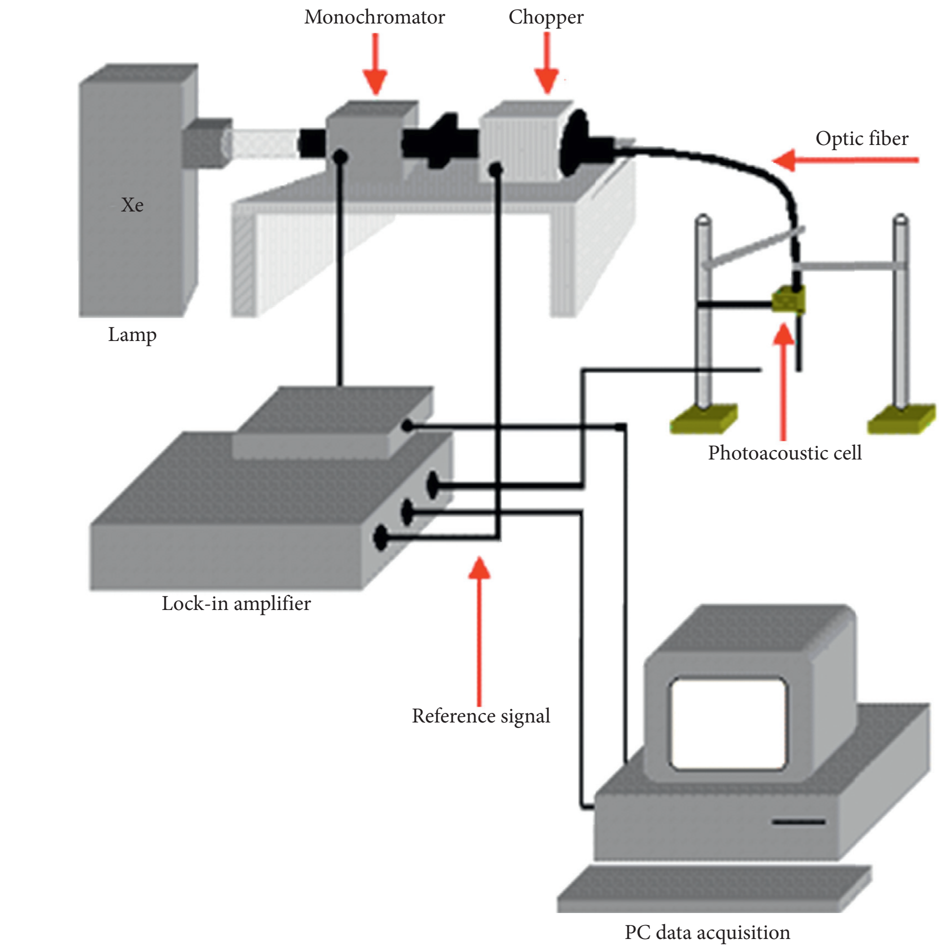

Figure 2: Experimental arrangement for photoacoustic spectroscopy.

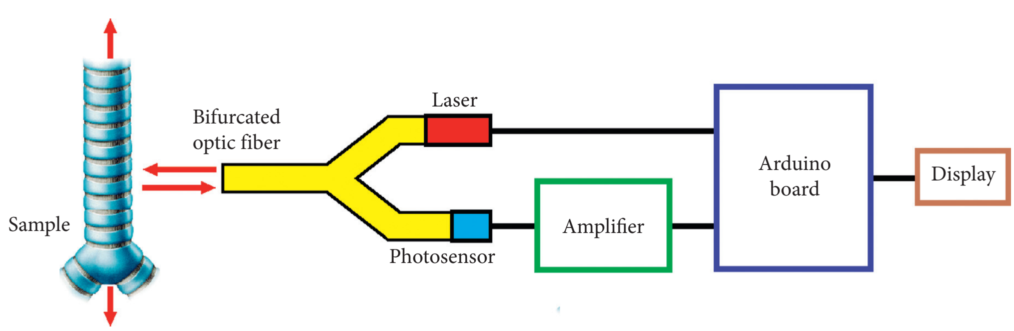

Figure 3: Block diagram of the prototype that measures optical response caused by tension in a porcine trachea model.

tests, it was observed that the graphs showed a similar, exponential trend; the first one (T1) showed a higher stiffness from the 7.5 mm of elongation, but tests T2 and T3 showed very similar behavior (Figure 6).

Table 1 shows the load results obtained from the tension test with the values measured by the optical system at 0, 10, 20, and 30 mm of elongation (equivalent to 0%, 10%, 20%, and 30%). Note that the curves have a nonlinear behavior. An exponential (allometric) nonlinear adjustment was made using Origin software version 8.0 (Origin Lab Corp., Northampton, MA, USA), as shown in Figure 7. The following equations were obtained:

$$\begin{aligned} Y &= 95.76 * X^{0.0481}, \quad \text{for } T1 \\ Y &= 96.24 * X^{0.0357}, \quad \text{for } T2, \\ Y &= 95.91 * X^{0.0356}, \quad \text{for } T3. \end{aligned} \tag{1}$$

4. Discussion

The trachea is an anatomical structure formed of cartilage rings that fulfill a variety of functions. If a segment is removed, the simplest way to reconstruct the trachea is the anastomosis of the healthy ends of the trachea. The extension

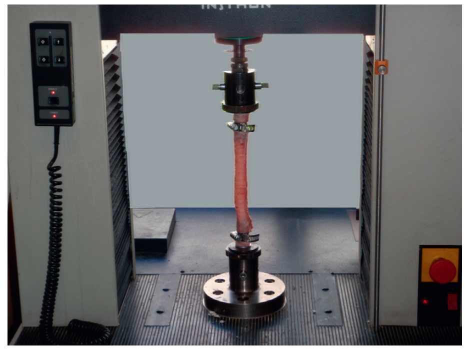

Figure 4: Testing arrangement of the trachea in a universal test machine.

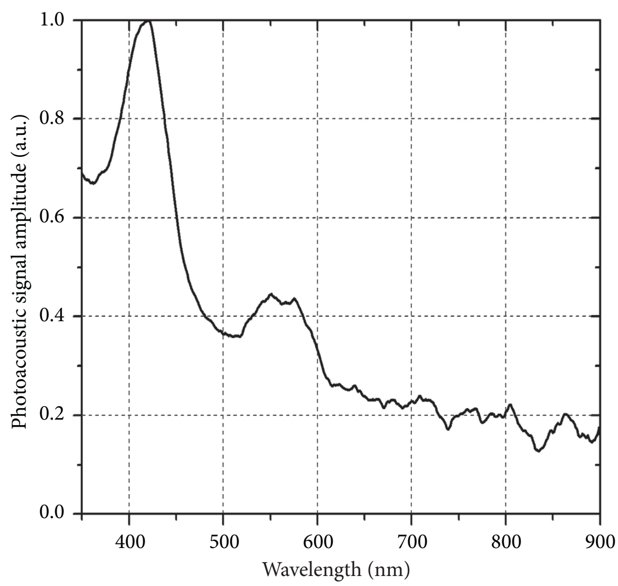

Figure 5: Absorbance measured in two cadaveric porcine trachea samples at different wavelengths.

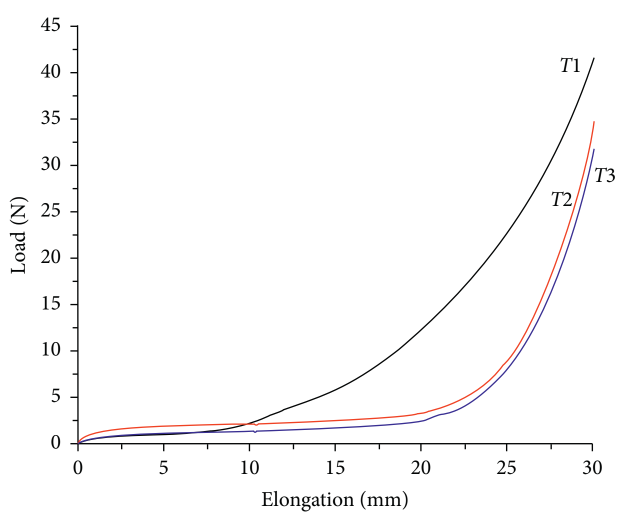

Figure 6: Load-elongation graph of the three tension tests of a porcine trachea sample.

of the trachea limits the use of this technique because excessive tension on the anastomosis can cause separation or stricture. It has been established that the tension should not exceed 1,000 g at the ends subjected to anastomosis. Estimating tension on the trachea is usually done by *in vitro* destructive tests with cadaveric specimens [11, 12]. In the

Table 1: Load and response of the photosensor for an elongation of 0%, 10%, 20%, and 30%.

Elongation (%)	Test 1		Test 2		Test 3	
	Load (N)	Photosensor (mV)	Load (N)	Photosensor (mV)	Load (N)	Photosensor (mV)
0	0	96.0	0	88.7	0	83.8
10	2.8	100.6	2.1	98.1	1.3	96.1
20	15.2	109.1	3.2	101.2	2.4	99.9
30	43.5	114.9	33.8	109.0	30.9	108.2

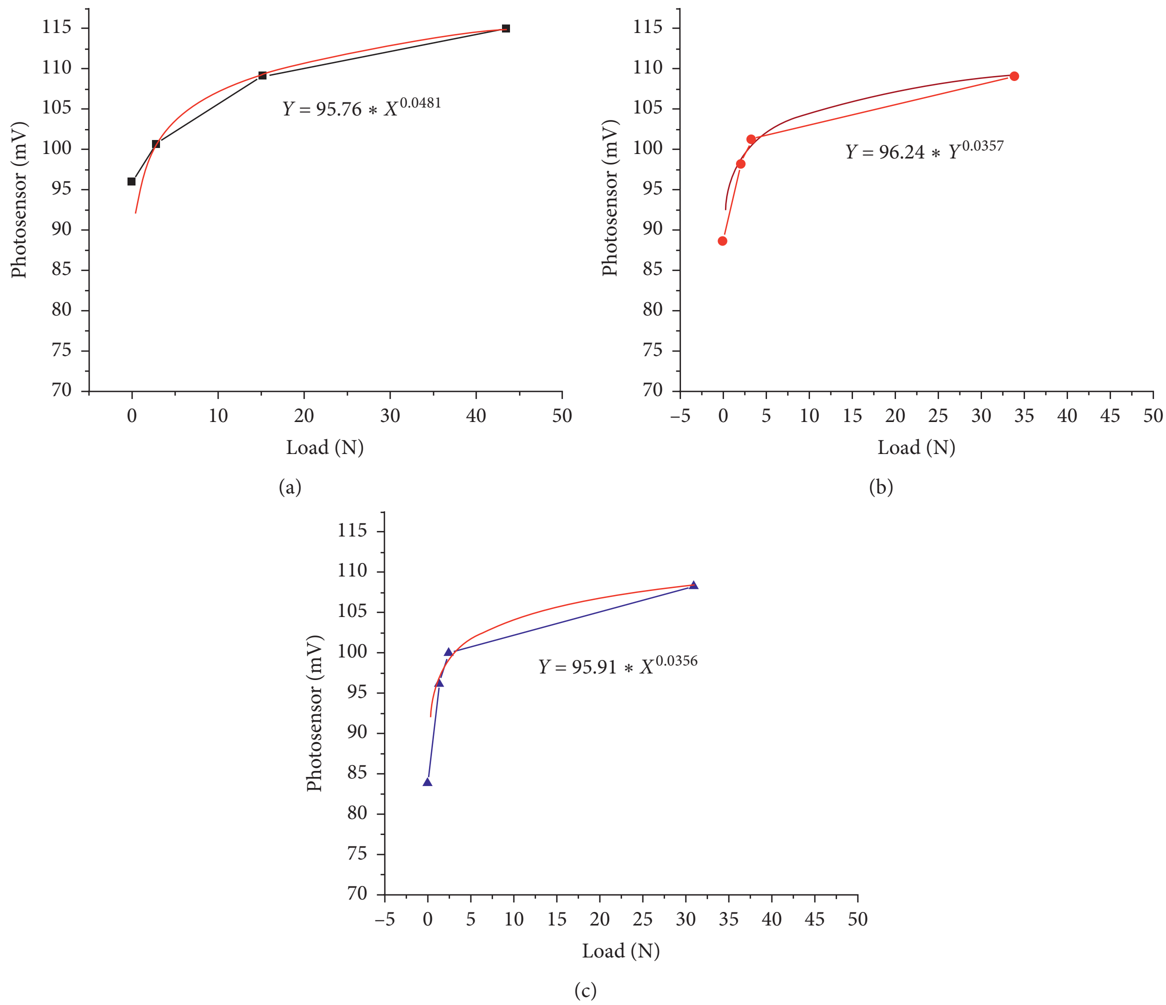

Figure 7: Load graphics vs. response of the photosensor with exponential adjustment for the tests T1 (a) (standard error = 0.1215), T2 (b) (standard error = 1.0912), and T3 (c) (standard error = 0.9940).

present work, an optical system was designed to noninvasively measure the tension in the trachea, allowing the proposed system to potentially be used in clinical settings.

First, a photoacoustic spectroscopy study was carried out to determine the optical absorption spectra of two porcine cadaveric trachea samples. Based on this information, a 650-nm red light source was selected. The developed system consists of a 650-nm light source, which is applied using a laser diode, and a photosensor that captures the reflected light. To calibrate the system, a cadaveric porcine trachea was obtained and subjected to tension while the optical system was used to measure the corresponding optical response.

These tests were done three times on the same sample of porcine trachea. The equations that correlate the tension with the optical response were obtained. The curves follow an exponential trend, and their equations have very similar values. If we assign load values from 0.05 N to 15 N to the equations described above, we would have the graph shown in Figure 8.

One limitation of this study is that a single porcine trachea sample was used. However, the intention of the present work is to demonstrate that the optical system can measure the tension of the trachea in a noninvasive way. To establish the calibration curves that would be required to use the system in human patients, several tests would have to be

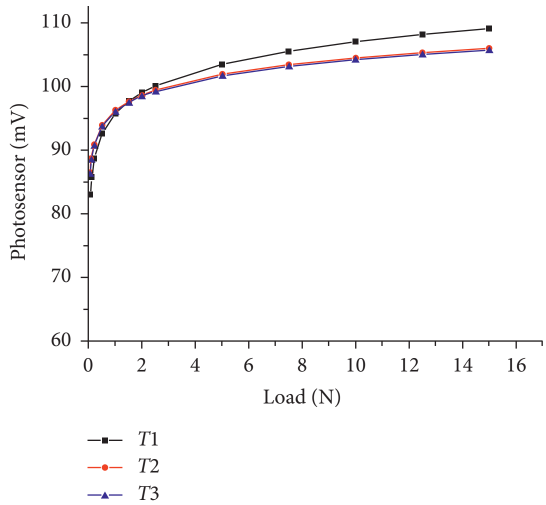

Figure 8: Response of the three proposed equations with load values from 0.05 N to 15 N.

done using fresh human cadaveric tracheas subjected to tension tests and measured using the optical system.

This system could be used in clinical practice to make decisions when reconstructing the trachea after a resection. The terminal-terminal anastomosis is the simplest form of reconstruction if there is not preexisting fibrosis [4]; this procedure requires the tension to not be excessive [8, 9]. Once this system has been properly calibrated, one could decide when to reconstruct using the terminal-terminal anastomosis and when to use other techniques [1].

5. Conclusions

The proposed optical system was able to estimate the tension of a cadaveric porcine trachea in a noninvasive way in an *in vitro* model.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare there are no conflicts of interest.

Acknowledgments

The authors want to express appreciation to Griselda Franco Sánchez, Head of Student Services at ESM-IPN, for editing the graphic material used in this paper.

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