Penerbit Akademia Baru

Journal of Advanced Research in Fluid Mechanics and Thermal Sciences

Journal homepage: www.akademiabaru.com/arfmts.html
ISSN: 2289-7879

Rapid Prototyping 3D Model for PIV: Application in Human Trachea Model Flow Analysis

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ARTICLE INFO

Article history:
Received 8 July 2020
Received in revised form 16 November 2020
Accepted 20 November 2020
Available online 13 January 2021

ABSTRACT

Experimental works for analysing flow behaviour inside human trachea has become continuous problem as the model used to study cannot imitate the real geometry of human trachea structure. As the technology develop, Rapid Prototyping (RP) become more useful in constructing the 3D model that has complexity in their geometries. RP not only offer several technologies in developing the 3D model, but also varies type of materials that can be used to manufacture the 3D model. In this study, RP technique was chosen to develop the 3D model of human trachea to do the Particle Image Velocimetry (PIV) experimental works. Material used was Vero Clear due to PIV need a model that transparent so that visualization on flow inside the model can be seen and the velocity magnitude can be capture. The geometry was adapted from 60 years old trachea patient where the images of trachea was taken by using CT-scan. MIMICS software was used to extracted the images before reconstruct the trachea into 3D model. Velocity distribution was visualized and the magnitude were taken at both left and right bronchi. From the analysis, it concluded that the distribution of airflow to the second generation of trachea was 60:40 to right and left bronchi. It follows the rules as the right bronchi need to supply more air to the right lung compared to left as the volume of right lung bigger that left lung.

Keywords:
CT-images; Particle Image Velocimetry; Rapid Prototyping; Trachea; 3D Printing

1. Introduction

For most emergency patient that has breathing difficulties, tracheal intubation was the first procedure that usually will be conducted. The process requires the insertion of an endotracheal tube (ETT) to form an artificial airway for the delivery of ventilation gases and aerosolized medications.

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https://doi.org/10.37934/arfmts.79.2.6573

Thus, information on flow behavior such as velocity and pressure distribution can increase the percentage of the successful treatment because it helps medical practitioner in deciding the best treatment for trachea patient. Various research using Computational Fluid Dynamic (CFD) were done in order see the flow behavior inside human trachea [1-11]. They summarized that flow inside human trachea did affected by the complexity of the trachea structure. The curvature and the angle at the bifurcation area play a significant role in distribution of flow rate to the lower generation of trachea branches. Beside simulation method, experimental study also has been made to study the flow inside the human trachea. Even the experimental works take much higher in cost and time, but it helps to validated the simulations results. Most researcher choose Particle Image Velocimetry (PIV) to conduct the experimental works in order to analyze and observe the flow behavior inside the human trachea.

To run the experimental work by using PIV method, 3D model of human trachea must be constructed in order to study the flow inside the windpipe. The model must embed the curvature of the complexity trachea structure and must be transparent as well. There are several techniques that has been used to produce the 3D model and one of the techniques is by using rapid prototyping technique (RP). This technique also called as 3D printing can create very complex physical models directly from 3D Computational Aided Design (CAD) model [12]. 3D printing also used various type of materials to suit with the analysis model. Most frequent material used are, Polylactic Acid (PLA), Acrylonitrile Butadiene Styrene (ABS), Polyethylene Terephthalate Glycol (PETG), Thermoplastic Elastomers (TPE), Vero Clear and Polyamide (PA) or commonly called Nylon (Figure 1) [13]. Each material has its own advantages and disadvantages based on each study. In PIV application, the experimental need transparent material, Vero Clear is one of the suitable materials that can be used. The material can create both; the complexity of the physical solid model and transparent through the model to observed the flow inside the 3D model [14].

(a) (b)

Fig. 1. Example of model created using (a) ABS plastic material and (b) VeroClear resin

In for experimental research using PIV in human trachea, previous researchers used simplified model to replicate the windpipe as the model was easier to be created. Thus, the results were less accurate as the curvature of the trachea structure were not included in the 3D model. They choose either thin wall tube or silicone rubber, Figure 2, to replicate their model [15,16]. As the technology rapidly developed and RP technique was introduced, researcher started to use this technique to created more accurate model [14,17]. This technique allow researcher to construct 3D model that embed the complexity of the structure and also flexibility of the wall.

(a) (b)

Fig. 2. 3D bifurcations model produced by (a) Theunissen and Riethmuller [16], (b) Walenga *et al.,* [17]

2. Experimental Works

2.1 Model Geometry and Manufacturing

In this paper, the geometry of human trachea model was taken from 60 years old male trachea stenosis patient. Using CT-scan, images/data scanned from the male patient then were extracted using MIMICS software. MIMICS is a 3D imaging software that generates and modifies 3D surface models from medical images [18]. The images were taken with resolution 512 x 512 and at position of axial angle. 3D model of human trachea started from main trachea until first generation of bifurcation then been constructed based on these images All refined works were done in MIMICS software to get the best quality of the 3D human trachea model. The human trachea model then has to be scaled up to ease the manufacturing procedures. Before transferring the human trachea model for 3D printing, the model saved into STL file format to match with the 3D printing standard file format.

Using Polyjet Technology, 3D model of human specific trachea model was manufactured. Using VeroClear as the material in the RP technique, the trachea model has rigid, transparent and colorless material featuring great dimensional stability characteristic. The reflection index for this material is 1.47. This characteristic complies the rules of PIV where the model should be transparent to capture the flow movement of the particle use in the experimental works. To cater enough space for blasting procedure, the 3D trachea model was scale to 1.3 and the thickness of the trachea wall also was set as 1.4mm. Blasting process is a procedure where the support material inside the model used during manufacturing procedure were removed.

2.2 Experimental Setup for PIV

Particle Image Velocimetry (PIV) is one of the experimental methods that has been choose to study the internal flow behavior (Figure 3). This non-invasive optical method of flow visualization used to obtain direct velocity measurement. Using PIV, researchers can gain both extraction of measurement data and the visualization of flow structures. A standard setup for PIV consists of high-speed camera, a high power multi pulsed laser, and an optical arrangement to convert laser output light to a light sheet and a synchronizer, which controls the synchronization between the laser and the camera. A small tracer particle (sediment) will be added in most PIV cases.

In this study, highly sensitive digital speed camera (HAS-D71) with 1/1.8-inch format sensor, resolution of 640 x 480 (VGA) was used. Together with green laser 1 W output, the small tracer particle flow movement were captured using 500fps. By using two-point method to calibrate the measurements and correlation coefficient map as a preview function, the calculations of the velocity inside the models were done by the software and the velocity outputs were saved in excel format. The software used in this study is Flownizer2D. As for the particle tracer, sediment with silver coated was used to enhance the visualization of flow movement and to capture the lighting perfectly.

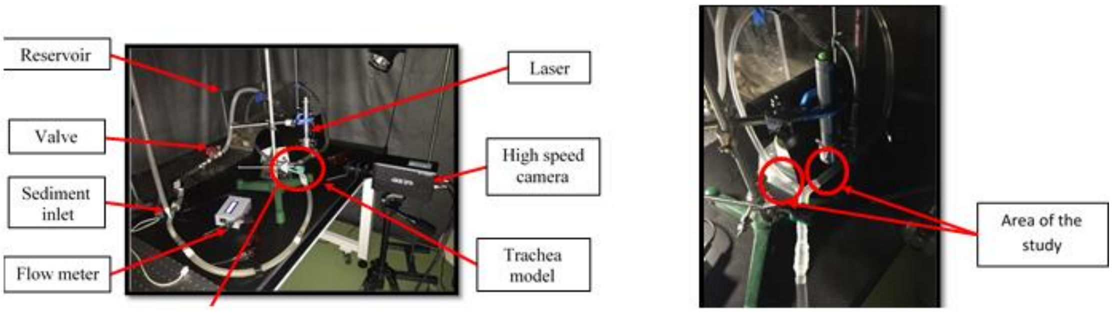

Fig. 3. Experiment set-up for PIV works and the location of case studies

For working fluid used in this experimental works, glycerin-water mixture was used to replace air due to limitation of PIV facilities. The mixture ratio between the glycerin and water is 30:70. Table 1 summarized details on the properties of working fluid.

Table 1
Properties of working fluid

Glycerin-Water Mixture (30:70) properties	
Density	1089.6 kg/m3
Dynamic viscosity	0.025748 Ns/m2
Kinematic viscosity	0.0000023631 m2/s

As the properties of working fluid (glycerine-water mixture) and air have different value, Reynolds number for each case studied in PIV experimental works were kept as the real Reynold numbers for airflow inside human trachea. The purpose is to get the equivalent velocity inlet for experimental boundary condition that imitate the real flow inside human trachea.

$$Re = \frac{\rho u^2}{\frac{\mu u}{L}} = \frac{\rho u L}{\mu} = \frac{uL}{v}$$

where,
ρ = density (kg/m^3)
u = velocity (based on actual cross section area) (m/s)
μ = dynamic viscosity (Ns/m^2)
L = length (m)
v = kinematics viscosity (m^2/s)

In this study, three different activities represent condition during human breath were studied which are resting, normal and exercise activities. All Reynolds number datas were refer to previous studies by former researchers [19-21]. These Reynolds numbers then been converted to velocity and flow rate inlet that used in the experimental works. Table 2 shown the summary for boundary condition used in the PIV experimental works.

Table 2
Summary of boundary condition used in PIV experimental works

Parameter	Sleeping (Zheng Li *et al.*, [19])	Normal (Luo *et al.*, [21])	Exercise (Calay *et al.*, [20])
Reynolds number, *Re*	1.201×10^3	3.012×10^3	4.66×10^3
Flow rate, Q (l/min)	0.3	0.8	1.2
Velocity inlet, u (m/s)	0.02	0.05	0.08
Outlet pressure, P (pa)	101325		

Due to limitation and constraint in experiment facilities, only velocity data was extracted during the PIV experimental works. Magnitude for velocity along centre plane of trachea branches were taken and the velocity streamline at the centre plane for both bronchi were visualized. Flowrate output at left and right bronchus were calculated. To summarized all works done for preparation and analysis in PIV experimental works, Figure 4 illustrated the overall process.

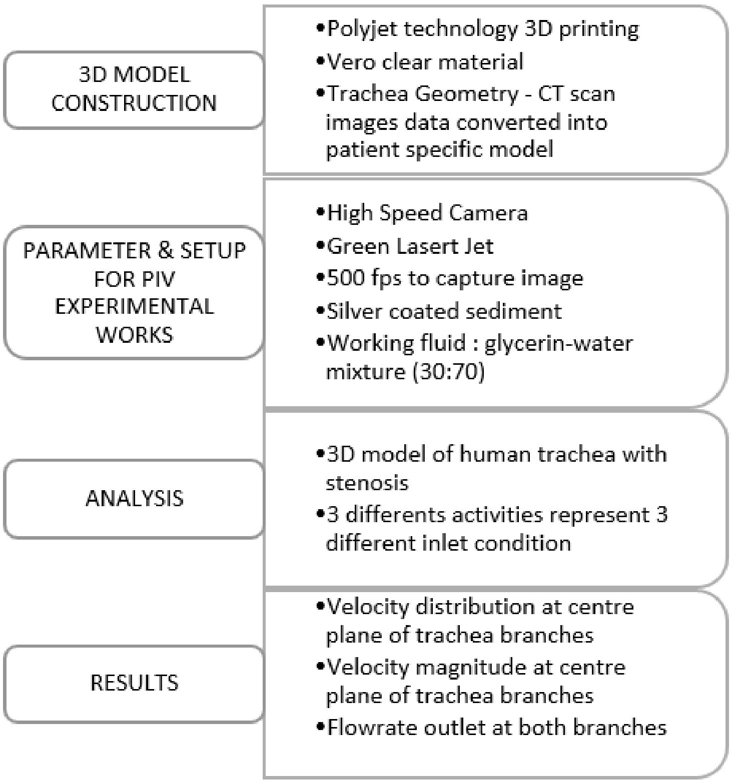

Fig. 4. Summary of experimental works

3. Results and Discussion

In each bronchus, results for velocity data were investigated at the centre plane. Effect from different flowrates inlet to velocity distributions was discussed. The percentage of flowrate distribution to both left and right bronchus were analysed to see the effect from stenosis presence.

3.1 Velocity Distribution Along Both Left and Right Bronchus

Normally, velocity distribution at the right bronchi will show higher magnitude compared to the left bronchi. The reason is due to the location of heart that located at left side of lung that makes the size of right lung bigger than left. So, the right side need more air compared to the left side. Figure 5 shown distribution of airflow velocity for both branches in three different flowrate inlets. Generally, distribution of velocity magnitude will increase when the velocity inlet increase. Similar to airflow velocity inside human airway, when the flowrate inlet increase, distribution of velocity for both branches show higher magnitude number. The flow demonstrated almost uniform flow along the bronchus as the stenosis was located at main trachea. The flow effect due to the obstruction were stabilize as the location of the branches is far enough. But for sleeping case, slightly disturbance shown in velocity distribution for both left and right bronchi as the velocity inlet was to slow to begin with.

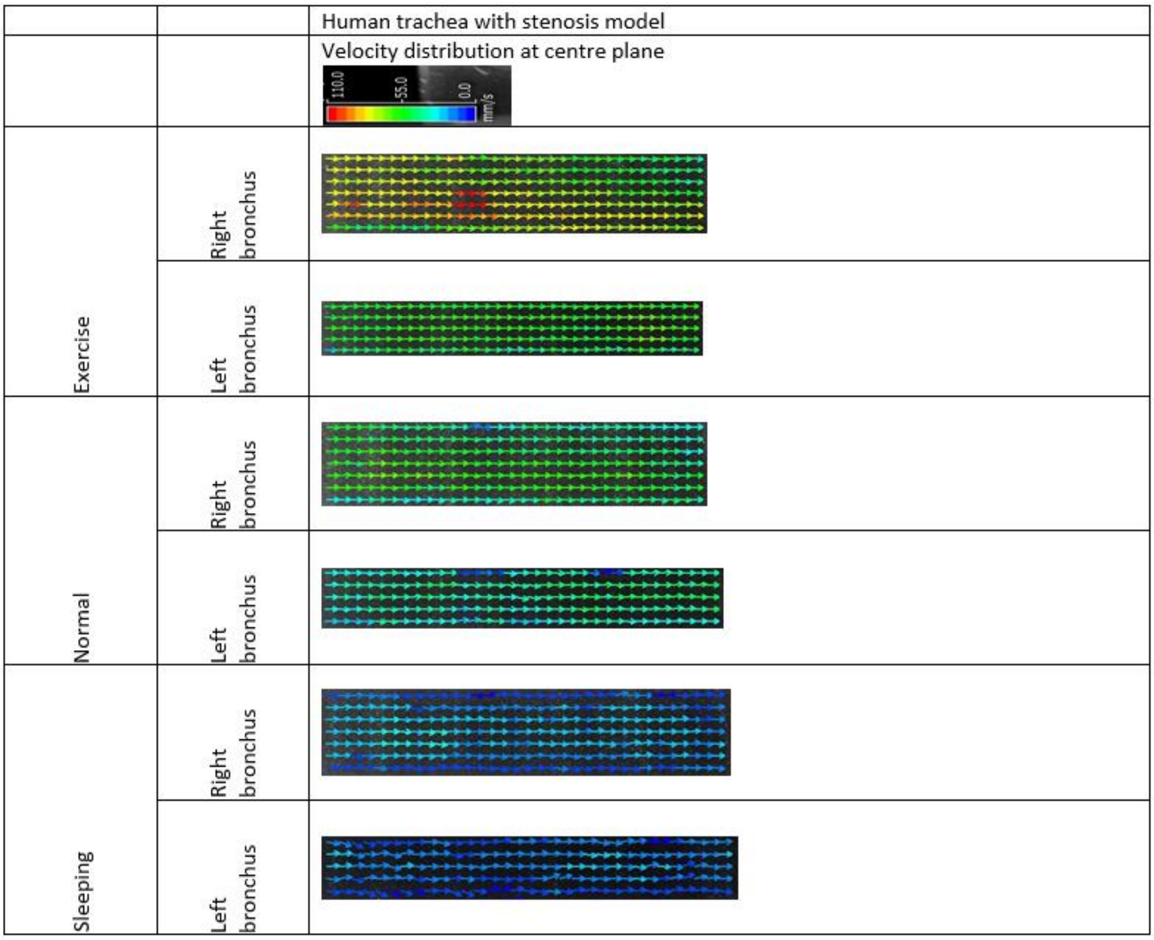

Fig. 5. Velocity distribution at centre plane for both left and right bronchus of human trachea with stenosis model

Several researchers in their study set the percentage distribution to right and left bronchi to 45:55 so that right bronchi received more airflow rate compared to the left bronchi [7,9,11]. In this study, the actual distribution was analysed to see the real percentage distribution to the second generation of human trachea.

In Figure 6, average velocity distribution along the centre plane for right bronchi were plotted for all three cases: exercise, normal and sleeping condition. The purpose is to study the percentage of inlet flowrate that reach at the beginning of bronchus compare to flowrate reach at bifurcation area. In this study, velocity that reach at bifurcation area for sleeping, normal and exercise activities were recorded at 33m/s, 84.2 m/s and 130.33 m/s. Using these values and the velocity extracted at the beginning of each bronchus, the percentage of air-flowrate distribution were calculated. For all cases, approximately 60% of airflow were going to the right bronchi so that other 40% go to the left bronchi. It slightly higher compared to the other parameter that have been used by previous study. But the right bronchus still gets more flowrate compared to the left bronchus. Thus, this result is doable as it served purpose to transfer air to each lung according to it volume.

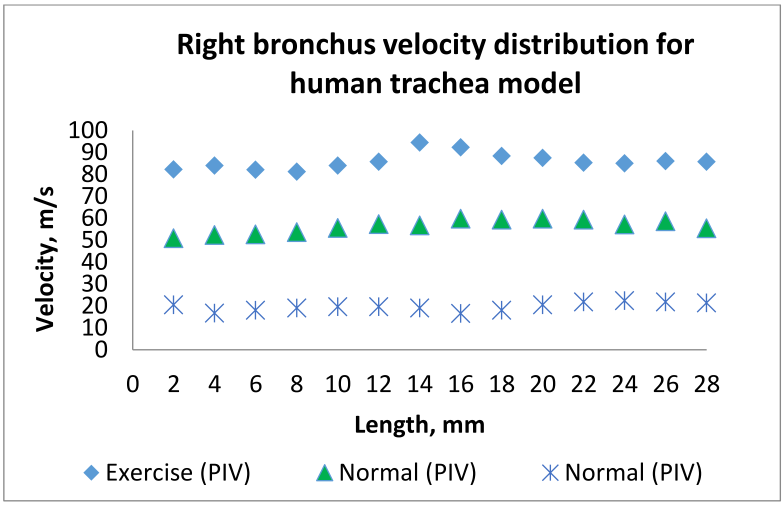

Fig. 6. Velocity magnitude distributed along the right bronchus

4. Conclusion

The opportunities to conduct experimental studies for human trachea now is higher as the technologies in rapid prototyping (RP) is develop rapidly. Using RP, the complexity of the human trachea structure can be embedding together during the manufacturing of the 3D model. Together with several CAD software, the real patient specific model was no longer impossible to be recreated. For investigating the internal flow inside the trachea, PIV experimental works is enough to get acceptable results. Thus, all works can be used to conclude and validate any simulation works that related to analysis of flow inside the patient specific of human trachea model.

Acknowledgement

This research was supported by grants from Malaysia Ministry of Education registered under Universiti Tun Hussein Onn Malaysia, Malaysia (K156) and experimental collaboration with Gifu National College of Technology, Japan.

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