Research Article

Standardization of Malaysian Adult Female Nasal Cavity

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This research focuses on creating a standardized nasal cavity model of adult Malaysian females. The methodology implemented in this research is a new approach compared to other methods used by previous researchers. This study involves 26 females who represent the test subjects for this preliminary study. Computational fluid dynamic (CFD) analysis was carried out to better understand the characteristics of the standardized model and to compare it to the available standardized Caucasian model. This comparison includes cross-sectional areas for both half-models as well as velocity contours along the nasal cavities. The Malaysian female standardized model is larger in cross-sectional area compared to the standardized Caucasian model thus leading to lower average velocity magnitudes. The standardized model was further evaluated with four more Malaysian female test subjects based on its cross-sectional areas and average velocity magnitudes along the nasal cavities. This evaluation shows that the generated model represents an averaged and standardized model of adult Malaysian females.

1. Introduction

The human nasal cavity consists of two symmetrically complex three-dimensional nasal passages that are separated in the middle by the nasal septum. During inspiration, air flows into the nasal cavity from the nostrils and then reaches the smallest cross-sectional area, the nasal valve, before reaching the tortuous turbinates region that forms large cross-sectional areas covered with mucous layers and cilia. These moist regions play an important role for the humidification, warming, and cleaning of the inspired air by entrapping the air-borne particles as well as moistening the air by evaporation [1]. Then, the turbinates region will guide the airflow towards the posterior region of the nasal cavity which is the nasopharynx.

Objective measurement methods are also very common in studies related to nasal geometry where it is used to determine cross-sectional area nasal airway resistance, and also visualization of the human nose. Shelton and Eiser carried out an evaluation of active anterior and posterior rhinomanometry in normal subjects [2]. Suzina et al. used active anterior rhinomanometry (AAR) for the objective assessment of the nasal airway resistance in normal adult Malays [3]. However, these methods have their limitations in measuring the precise velocity of the airflow as well as in evaluating the local nasal resistance in every portion of the nasal cavities [4]. In addition to that, the complex nasal anatomy consists of numerous thin airway channels that prevent direct experimental measurements of the flow patterns inside the nose [5].

In recent years, with the rapid development in computer resources, there have been increasingly wide and deep applications of the CFD technique to studying the airflow characteristics in the human nasal cavity and hence its correlation with the symptoms and functions of the human nose [6–11]. Majority of these studies used a combination of different softwares (e.g., Mimics, Amira, and ICEM-CFD) to produce numerical nasal cavity models. In addition to that, there are a few review papers in this area, such as Bailie et al. [12], Leong et al. [13], and Zubair [14]. A better understanding of the nose
The objective of this research is to create a standardized adult Malaysian female nasal cavity using a new approach that is simpler and applicable to a larger population. This standardized model was compared to existing standardized models from past researches to review the differences.
duetothedifferenttypesofpopulationbasedongeographical
differences. Large differences especially in cross-sectional
areas were observed from the Malaysian standardized model
when compared to the Caucasian model. Thus, this proves
that the standardized model is a good addition to the existing
nasal models used in past researches.

2. Materials and Methods

This paper discusses the new methods in generating the stan-
dardized model in details. This method is a new approach as it
is different compared to the method implemented by Liu et al.
[30]. A complete set of average images used to generate the
standardized model can be created in less than a few hours,
saving time and cost as well as human labour. Developing the
CT scans into three-dimensional model requires extra detail
especially in determining the boundary layer of the nasal
cavity and strict guidance from a rhinologist. Generation of
the standardized nasal geometry involves several important
steps that can be divided into three major parts. The first
part is construction of geometry, followed by meshing of
grouped together, and

The first part of methodology involved generation of the
standardized nasal cavity from two-dimensional CT scans
of 26 sets of normal healthy Malaysian females’ cavities that
were obtained from the Advanced Medical Department of
Universiti Sains Malaysia. The CT scans were transferred into
MIMICS (Materialise, USA) to generate a three-dimensional
model of the nasal cavity. Axial, coronal, and sagittal views of
the nasal cavity were obtained from MIMICS, but only sets of
axial images (captured from the anterior to the posterior of
nasal cavity) were used in generating the averaged standard-
ized nasal cavity. Axial images are able to show the complex
geometry such as turbinates more clearly compared to other
orientations. In order to generate the standardized model,
an image processing program was executed to calculate the
average pixel values in every axial image. The first axial images
of all the 26 sets of CT scans were grouped together, and
Figure 2: (a) Cropping image, (b) rotating image, and (c) average image obtained.

average values were calculated to generate the first axial image
for the standardized model. These methods were repeated
for all the 37 images per test subject. This is a slightly
tedious process, but only a few minutes are required to
complete an average axial image. This study used CT images
of both left and right nasal cavities to produce the averaged
images. Several important precautions need to be taken such
as cropping of the images. Since the size of the human
head varies from individual to individual, the dimension,
resolution, and position of the nasal cavity were maintained.
The dimensions were measured from the septum with a crop
ratio of 4:3 using the automatic cropping function of image
cropper as shown in Figure 2(a). Another important detail
that requires attention is the orientation of the nasal cavity
during the CT scan as the subjects tend to position their
heads in different directions. The entire image was rotated to
a certain angle as shown in Figure 2(b) which ensures that
the straight nasal septum can be viewed to obtain accurate
average pixel values. The nasal septum plays an important role
as it acts as a reference line for cropping as well as rotation
of the images. Therefore, subjects with septum deviations are
omitted from this research with the help of a rhinologist. Only
healthy female subjects were used in this study. Figure 2(c)
shows one of the final averaged images located in the middle
of the nasal cavity from axial view. The different lines were
created from all 26 images of different subjects.

A total of 37 new axial averaged images obtained from
averaging of 26 test subjects were then imported to MIMICS
to create a three-dimensional model as shown in Figure 3.
Some functions like thresholding and editing the masks in
MIMICS were used to facilitate the generation of the model.
These functions were used to eliminate unwanted areas and to
distinguish soft tissues and bone structures as well as empty
spaces. The threshold in MIMICS neglected the soft tissues
along nasal cavity as the nasal cavity was assumed to be
decongested. The first draft of the standardized model can be
seen in Figure 3 with some minor rough surfaces, but overall
the structure seems to be well constructed.

The three dimensional polylines data from MIMICS
were then imported to CATIA V5 (Dassault Systèmes) for
smoothening the rough surfaces and to delete unwanted
This study represents the general equations for three-dimensional simulation was based on the Navier-Stokes equations by better understanding of the new standardized model. The provided by FLUENT 6.3.26 (Fluent, Lebanon, USA) for cal simulation was performed using finite volume method ning the analysis and analyzing the results. The numeri-

resting breathing with a flow rate of 7.5Lmin

focused only on laminar airflow simulation for normal, shown in Figure 5.

obtained from Kim and Son [31] and We ne et al. [15, 17] as
theresults are validated with the pressuredrop

resulted in an optimized meshing of 1,109,123 elements, and

areas. The results showed that the grid dependency study

will cause failure in capturing nasal airflow in the crucial

especially at the thin turbinates region inside the nasal cavity

500,000 to 3,000,000 elements. Lack of meshing elements

mesh using unstructured tetrahedral meshing ranging from

independence study was carried out to determine the best

perform volume meshing as shown in Figure 4(c). The grid

CATIA V5 was then imported to Gambit as a volume to

of the geometry. The standardized model generated from

GAMBIT 2.3.16 (Fluent Inc., Lebanon, USA).

as it is proven that it has no significant effect on the flow

imposed in FLUENT [1]. Nasal hair was also not considered

was assumed to be 32.6°C and 100% relative humidity as

imposed in FLUENT [1]. Nasal hair was also not considered

as it is proven that it has no significant effect on the flow

within the nasal cavity [35]. Paranasal sinuses were excluded

in the creation of the standardized model as most researches

(both computational and experimental as well as disease and

nondisease cases) only focus on the study of nasal airflow and
do not consider paranasal sinuses in analyses [1, 4, 6–8, 11, 15,
17, 21, 22, 24, 29, 30, 33, 34, 36–40]. The sinuses were deemed
to have negligible impact on the gross airflow patterns due to
the small openings (ostia) with minimal cross-sectional area
[11, 24].

The same methodology was repeated for the generation
and analysis of two half-models and four more female
nasal cavities. One of the half-models was cut from the
standardized model while the other was obtained from Liu
et al. (generated from 30 sets of Caucasian nasal cavities).
Both models were compared in order to view the differences
between the standardized model of different populations
based on geographical differences as well as the methods
applied in their generation. Meanwhile, the four Malaysian
female subjects were carefully chosen from the 26 test subjects
based on their ages and races. These four models were used
for comparison with the standardized model to prove that the
generated standardized model represents an average model of
a Malaysian female nasal cavity. The information for all the 26
subjects is presented in Table 1. It was previously mentioned
that the methodology for the current study is suitable for a
large population. However, only 26 subjects were asked to
participate in this study as it is only a preliminary study.
Another reason which limits the number of subjects for this
study is the lack of data as most patients with nasal pain or
diseases are only willing to do the CT scans. Therefore, it
is harder to obtain samples of healthy cases for the current
study.

3. Results and Discussion

Results obtained from the standardized model generated
from 26 female subjects were presented and discussed in
two major parts. The first part is the comparison of two
half-models; one is from the generated standardized model
(labelled as Model A), and the other half-model is obtained
from the research of Liu et al. [30] (labelled as Model B) for
discussions of various results obtained from the CFD analysis.
Comparisons were carried out by studying the cross-sectional
areas, average velocity magnitudes, and contours coloured by
velocities at four main cross-sections along the nasal cavities
for both models. Based on the comparisons, variations among
the standardized model of both geographically different nasal
cavities can be obtained thus proving the requirement for a
standardized model of different populations. The second part
was only focused on the generated standardized model and
the four nasal cavities chosen from the group of test subjects.
Evaluation was carried out on all five complete models by
comparing its cross-sectional areas and average velocity
magnitudes at four cross-sections along the nasal cavities.
The results obtained prove that the generated standardized model
is able to represent the averaged adult Malaysian female nasal
cavity.

3.1. Comparison of the Half-Models. The generated stan-
dardized model, Model A, is 99.312 mm in length which is
relatively close to the average value presented in Table 1 while
the half-model obtained from Liu et al., Model B, is 109.73 mm in length. Both models are shown in Figure 6 with obvious differences in the structures, both horizontally and vertically. Model B shows obvious existence of superior meatus, longer middle region of all turbinates, shorter nasopharynx, and an imprecise vestibule shape. On the other hand, Model A shows only inferior and middle meatuses, longer nasopharynx region, and a more accurate representation of the nasal vestibule. Longer nasopharynx region is more relevant to ensure proper outlet condition during CFD analysis [20]. Based on the observation made on all the 26 subjects, the inconsistent visibility of the superior meatuses caused Model A to consist only of superior and middle meatuses. Cutting planes as shown in Figure 6 were implemented to obtain the required information because of the variation of lengths among the models. These cutting planes allowed comparison to be carried out at certain locations along the nasal cavities. There are a total of 8 cutting planes with the first one being A, located at the vestibule which is slightly upward from the inlet. The second cutting plane B is located at the nasal valve, which is the smallest cross-section of the nasal cavity. The third cutting plane, plane 1, C is located at the starting of the inferior meatus while the middle plane E is located at the middle of all the meatuses and plane 4 G is located at the end of the inferior meatus. Both planes 2, D, and 3, E, are located in between of C–E and E–G, respectively. Finally, the nasopharynx H is located at the end of the nasal cavity near the outlet.

Cross-sectional areas along the nasal cavities are presented in Figure 7 for a more thorough comparison of both models. It is noticeable that Model B has a smaller cross-sectional area compared to Model A as shown in Figures 6 and 7. This is due to the more slender shape of Model B. The cross-sectional area of Model A is higher except for the outlet due to the longer nasopharynx region of the model. Model A shows the lowest cross-sectional area located at the nasal valve and the highest cross-sectional area located at the middle plane of the meatuses. The sudden decline on plane 4 was caused by the ending of the meatuses. Both models were obtained from different populations at different geographical locations thus causing the variation in the cross-sectional areas. From a visual observation, it seems that the Malaysian nose is comparatively smaller in size and length when compared to the Caucasian nose. However, the result indicated in Figure 7 clearly shows otherwise. This shows that the outer nose appearance cannot be used to estimate the cross-sectional areas of the inner nasal cavity.

Figure 4: (a) Polylines from MIMICS, (b) smooth 3D nasal cavity from CATIA, and (c) meshing of geometry.

Figure 5: (a) Mesh dependency study at mass flow rate of 125 mL/s and (b) pressure drop versus mass flow rate.
Table 1: Table of information for 26 female subjects in current study.

| Subject | Age | Race  | Length, mm | Distance between slices, mm | Used for comparison |
|---------|-----|-------|------------|----------------------------|--------------------|
| 1       | 37  | Indian| 98.44      | 2.5                        | Yes                |
| 2       | 35  | Indian| 98.58      | 2.5                        | No                 |
| 3       | 34  | Chinese| 104.92     | 2.5                        | No                 |
| 4       | 38  | Indian| 103.48     | 2.5                        | No                 |
| 5       | 39  | Chinese| 96.82      | 2.5                        | No                 |
| 6       | 24  | Chinese| 107.93     | 2.5                        | No                 |
| 7       | 43  | Chinese| 99.63      | 2.5                        | No                 |
| 8       | 37  | Chinese| 97.61      | 2.5                        | No                 |
| 9       | 40  | Chinese| 103.31     | 2.5                        | No                 |
| 10      | 34  | Indian| 99.55      | 2.5                        | No                 |
| 11      | 23  | Chinese| 101.80     | 2.5                        | No                 |
| 12      | 38  | Chinese| 102.31     | 2.5                        | No                 |
| 13      | 31  | Chinese| 98.52      | 2.5                        | No                 |
| 14      | 20  | Malay  | 96.05      | 2.5                        | No                 |
| 15      | 24  | Malay  | 94.28      | 2.5                        | Yes                |
| 16      | 36  | Malay  | 94.66      | 2.5                        | No                 |
| 17      | 40  | Malay  | 90.86      | 2.5                        | No                 |
| 18      | 39  | Indian| 99.08      | 2.5                        | No                 |
| 19      | 32  | Indian| 97.92      | 2.5                        | No                 |
| 20      | 43  | Indian| 100.69     | 2.5                        | Yes                |
| 21      | 21  | Chinese| 87.08      | 2.5                        | No                 |
| 22      | 34  | Malay  | 95.34      | 2.5                        | No                 |
| 23      | 34  | Malay  | 105.81     | 2.5                        | No                 |
| 24      | 31  | Chinese| 94.72      | 2.5                        | Yes                |
| 25      | 45  | Malay  | 87.72      | 2.5                        | No                 |
| 26      | 40  | Malay  | 102.06     | 2.5                        | No                 |
| Min     | 20  | —      | 87.08      | —                          | —                  |
| Max     | 45  | —      | 107.93     | —                          | —                  |
| Median  | 36  | —      | 98.55      | —                          | —                  |
| Average | 34  | —      | 98.43      | —                          | —                  |

Figure 6: Half-models: (a) model from current study, Model A, and (b) model obtained from Liu et al. [30], Model B. Cutting planes: A = vestibule, B = nasal valve, C = plane 1, D = plane 2, E = middle plane, F = plane 3, G = plane 4, and H = nasopharynx.

The capabilities of CFD to present useful information on nasal cavities are undeniable, as it has been presented by various researches for over a decade [21, 41–43]. For this paper, CFD analysis was carried out to further investigate the differences between both standardized models. Figure 8 shows the graphs of average velocity magnitudes while the contours of velocities are illustrated in Table 2. Contours of velocities were chosen for discussion as they clearly show the physical differences of both models as well as the airflow analysis in the nasal cavities. Obvious differences
Table 2: Contours of velocities for both models.

| Planes     | Model A                  | Model B                  |
|------------|--------------------------|--------------------------|
| Vestibule  |                          |                          |
|            | 1.34e+00                 | 2.79e+00                 |
|            | 1.27e+00                 | 2.65e+00                 |
|            | 1.21e+00                 | 2.51e+00                 |
|            | 1.14e+00                 | 2.37e+00                 |
|            | 1.07e+00                 | 2.23e+00                 |
|            | 1.00e+00                 | 2.09e+00                 |
|            | 9.38e−01                 | 1.95e+00                 |
|            | 8.71e−01                 | 1.81e+00                 |
|            | 8.04e−01                 | 1.67e+00                 |
|            | 7.37e−01                 | 1.53e+00                 |
|            | 6.70e−01                 | 1.39e+00                 |
|            | 6.03e−01                 | 1.26e+00                 |
|            | 5.36e−01                 | 1.12e+00                 |
|            | 4.69e−01                 | 9.76e−01                 |
|            | 4.02e−01                 | 8.37e−01                 |
|            | 3.35e−01                 | 6.97e−01                 |
|            | 2.68e−01                 | 5.58e−01                 |
|            | 2.01e−01                 | 4.18e−01                 |
|            | 1.34e−01                 | 2.79e−01                 |
|            | 6.70e−02                 | 1.39e−01                 |
|            | 0.00e+00                 | 0.00e+00                 |

Nasal valve

Middle plane
were observed from both models as indicated in Figure 8 and Table 2. All this information was obtained from four main cross-sections along the nasal cavity, which are the vestibule, nasal valve, middle plane, and nasopharynx. Model A shows a vestibule and nasal valve that is more oval in shape while Model B shows an inconsistent shape. Thinner middle plane was observed for Model B compared to Model A, which showed a rounder shape of meatuses. Higher average velocity magnitudes were obtained for Model B for all cross-sections due to the smaller cross-sectional areas as indicated in Figure 6. On the other hand, lower average velocity magnitudes were obtained for Model A due to the generalized averaged model having a larger airway channel compared to Model B. Model B was created based on both female and male models while Model A only focused on Malaysian females. Similar patterns can be examined from both models as the highest velocity resulted from the nasal valve, which is the airflow restrictor before entering the meatus region.

Increment in average velocity was observed from vestibule to nasal valve, which decreased at the middle plane and finally increased again at the nasopharynx as its cross-sections become smaller. Lower velocities were obtained from the middle plane regions as the meatuses function to enlarge the surface area exposed to the air. This increases the heat and moisture exchange inside the nasal cavity. The percentages of differences of velocity magnitudes between both models were relatively high, which are 30% for vestibule, 40% for nasal valve and middle plane, and 25% for nasopharynx. These big differences strongly support the importance of having a standardized model that represents different populations and to generate a standardized model based on a larger group of test subjects.

3.2. Comparisons of Model A with 4 Other Female Models. Comparisons made with Model B from the research of Liu et al. [30] are not sufficient to prove that Model A can be used
to represent an averaged adult Malaysian female nasal cavity. Thus, further investigations were carried out by analysing four female models chosen from the group of 26 subjects by taking into consideration their races and age range. Only four models were chosen for the comparison. Figure 9 shows the cross-sectional areas of all the five models and the average value calculated from the models. Model 1 and Model 4 seem to be smaller in size compared to Model A while Model 2 and Model 3 are slightly larger. The difference between Model A and the calculated average values is less than 20% for all cross-sections. Hence, this methodology was able to create a standardized model that is a very close approximation to the ideal average model. Based on the graphs, all the models possess similar patterns of cross-sectional areas. It was also noticed that an adult Malaysian female has relatively large vestibule and meatuses but a smaller nasopharynx.

Additional analysis was performed to enhance the understanding of this standardized Model A. It is noticed from Figure 10 that Model 1 and Model 4 possess higher average velocity magnitudes while Model 2 and Model 3 show lower average velocity magnitudes compared to Model A. This is due to the cross-sectional areas as indicated in Figure 9. Average velocity magnitudes obtained from Model A were very close to the average values from all the models. Similar patterns of all the models also proved that the models give consistent results of a characterized Malaysian female nasal airflow. Therefore, it was concluded that Model A represents the averaged Malaysian female nasal cavity.

4. Conclusions

A standardized model is required for studies involving human nasal cavities to avoid interindividual differences during comparison of results. The methodology mentioned in this research is applicable for a large group of subjects. Therefore, this is a good novelty approach to create a standardized model to represent certain populations. In addition, it is found from this research that there are clear differences between two standardized models from different geographical locations. Future work should be carried out for a larger number of test subjects to obtain a more accurate model. As a conclusion, the model generated from this study was proven to be a good and accurate representation of the adult Malaysian female nasal cavity. This new standardized model is available via corresponding author for various fields of researches.

Conflict of Interests

The authors have no conflict of interests to report.

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