An Evaluation of Exhaled Flow Measuring Mouthpieces for Breath Sampling Devices

Geethanga de Silva and Fred R. Beyette Jr.

Abstract— **A study is conducted to determine the dimensions of an exhaled flow measuring mouthpiece for a breath-sampling device that requires breathing for an extended period of time. Fleisch, Pitot and Venturi type differential pressure based flow measuring mouthpieces of various dimensions are evaluated. Inner diameters (IDs) of the cylinder shaped Fleisch, Pitot and Venturi mouthpieces are varied from 5mm to 25mm. Based on the study, we conclude IDs ranging from 8.75mm to 12.5mm for Fleisch type, IDs ranging from 10mm to 12.5mm for Pitot type and ID of 10mm for Venturi type are the most suitable dimensions for a breath sampling device.**

I. INTRODUCTION

Breath analysis of Volatile Organic Compounds (VOCs) is an extremely noninvasive method of disease diagnosis and evaluation of metabolic conditions. Breath biomarkers are known to be associated with lipid peroxidation, liver diseases, renal failure, allograft rejection, cancer, glucose metabolism, cholesterol metabolism and many other health conditions [1], [2]. In spite of its potential, breath analysis of VOCs is underutilized as a standard clinical diagnostic method, partly due to inadequacy of medical devices for breath sampling and analysis [3].

Breath sampling is a critical step in breath analysis and there is a clinical need for a breath sampling device that reliably produce a standard sample. Due to extremely low VOC concentrations in exhaled breath, samples are usually pre-concentrated before analysis [4]. It is also important to collect multiple breath samples to obtain a sample that best represents the VOC levels in blood. Therefore, sample preparation requires collecting breath samples over multiple breathing cycles. During the process of sample collection, deviation from normal breathing over an extended period of time may cause user discomfort and produce a faulty sample. Exhaled flow rate profile gives valuable information in preparing a standard breath sample [5]. Usually, a flow meter is integrated into the breath-sampling device. To the best of our knowledge there is no standard exhaled flow measuring mouthpiece used for breath sampling devices. This paper presents a study conducted to identify the most suitable dimensions for a cylinder shaped exhaled flow measuring mouthpiece that can be integrated into a breath sampling device. Commonly used differential pressure based exhaled flow measuring techniques are evaluated.

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II. TYPES OF FLOW MEASURING MOUTHPIECES USED IN THE STUDY

Differential pressure approach is a common flow rate measuring technique [6]. Various types of structures are implemented to create the pressure difference necessary to derive the flow rate. Fleisch, Pitot and Venturi are frequently used methods in respiratory flow measuring devices. Mouthpieces are fabricated in five different sizes with inner diameters (IDs) of 5mm, 10mm, 15mm, 20mm and 25mm for each method. A schematic diagram of the mouthpieces is shown in Fig. 1. The smaller end of the mouthpiece comes in contact with the mouth. The thickness of the smaller end is maintained at 1mm for all sizes while varying the IDs. The larger end contains the resistance structure and the ports to connect the pressure sensor. The outer diameter of the larger end of a mouthpiece is maintained 6mm higher than its ID. The study is extended to a second phase to further investigate the Fleisch and Pitot type mouthpieces. Five Fleisch type mouthpieces and five Pitot type mouthpieces with IDs of 7.5mm, 8.75mm, 10mm, 11.25mm and 12.5mm are evaluated in the second phase. Mouthpieces are modeled using 3D modeling software SolidWorks and fabricated using a desktop 3D printer (Replicator 2x, Makerbot Industries).

A. Fleisch

Fleisch type flow meters typically consists of a bundle of capillary tube like structures. According to Hagen-Poiseuille law, flow rate (Q) can be expressed as shown in (1) as a function of differential pressure (Δp)

$$Q = (r^4/8\eta l)\Delta p \tag{1}$$

where l is the length of the tube, r is the radius and η is a viscosity constant [6]. The Fleisch type flow meter shown in Fig. 1 (a) has a simplified stack of slots like structure instead of the capillary tubes, for ease of fabrication using the desktop 3D printer. The purpose of the capillary tubes is to generate laminar flow and similar results are expected using the slots.

B. Pitot tubes

Pitot tubes measure the impact pressure (P_T) using the pressure port facing the flow and static pressure (P) using the pressure port facing the opposite direction [7]. (2) Expresses point velocity (V_p) using impact and static pressures

$$V_p=C(P_T-P)^{1/2}/D \tag{2}$$

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where C is a dimensional constant and D is density. Flow rate is obtained by multiplying the point velocity by cross-sectional area of the flow tube. A Pitot type mouthpiece is shown in Fig. 1(b).

C. Venturi tubes

The two channels in the Venturi type mouthpiece shown in Fig. 1 (c) have two different cross sectional areas. When the air goes from the wider channel to the narrower channel, the velocity of the flow is increased and a positive pressure drop (Δp) is generated across the two channels. Flow rate (Q) inside the tube is given by (3)

$$Q = C_d A_2\{2(\Delta p)/\rho[1-(A_1/A_2)]\}^{1/2} \quad (3)$$

where C_d is the coefficient of dispersion, ρ is density and A_1, A_2 are cross sectional areas. Pressure drop also depends on the ratio of the diameter of the two channels. Maximum pressure drop is observed when the diameter of the narrower channel is one half the diameter of the wider channel and this ratio is maintained for all five sizes [8].

III. Evaluation Method

A. Hardware setup

The pressure across the resistance structure is measured using a differential pressure sensor (MPXV7025, Freescale Semiconductor Inc.) connected to the pressure ports in the mouthpiece. A 16-bit Digital Signal Controller (DSC) (dsPIC33FJ256GP710, Microchip Technology Inc.) is used to read the output of the pressure sensor via its on-chip 12-bit Analog-to-Digital Converter (ADC). The DSC transfers the pressure values to a SD card via the SPI interface for further analysis.

B. Test Protocol

Seven healthy students (2 females, 5 males) from University of Cincinnati volunteered for phase 1. The average age was 23.86, with a minimum age of 22 and maximum age of 27. Average weight was 164.71lb with a minimum of 100lb and maximum of 280lb. Average height was 68.43in with a minimum of 60in and a maximum of 75in. Six healthy students (1 female, 5 males) from University of Cincinnati volunteered for phase 2. The average age was 24.5, with a minimum age of 22 and maximum age of 27. Average weight was 165.83lb with a minimum of 125lb and maximum of 200lb. Average height was 70.5in with a minimum of 68in and a maximum of 75in.

During the evaluation subjects are instructed to sit straight on a chair and breath through the mouthpiece at a comfortable rate for 30 seconds. Subjects are asked to compare the comfort level of breathing through the mouthpiece to normal breathing and assign a comfort level of 1 to 5 for each mouthpiece. Mouthpieces are randomly introduced without repetition. Pressure profile of each test is stored in the SD card. Mouthpieces are rinsed with water, sterilized using Sterisol®, rinsed again and dried at room temperature before each test.

IV. Results

The summary of the statistical analysis performed on the study data is presented in this section. Fig. 2 shows the average comfort levels given to the fifteen different mouthpieces by seven subjects in phase 1. Mouthpieces with 10mm ID show the highest comfort level across all three flow measuring techniques. For all three types of mouthpieces comfort level decreases as the diameter increases from 10mm to 25mm and comfort level of the 5mm mouthpiece slightly less than that of 10mm. There is no statistical difference between the comfort levels given to mouthpieces with an ID of 10mm among the different flow measuring techniques. The variance of the comfort levels given by different subjects is statistically insignificant.

Averaged maximum pressure value is determined by averaging peak pressure value of each exhaled breath over the duration of the test. Averaged maximum pressure values for the fifteen mouthpieces are normalized by dividing by the maximum averaged peak pressure value of each subject. These results are plotted in Fig. 3. The purpose of

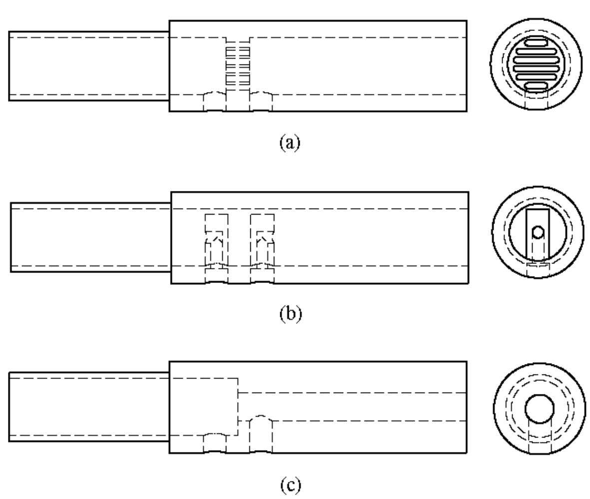

Figure 1. (a) Fleisch type mouthpiece, (b) Pitot type mouthpiece, (c) Venturi type mouthpiece

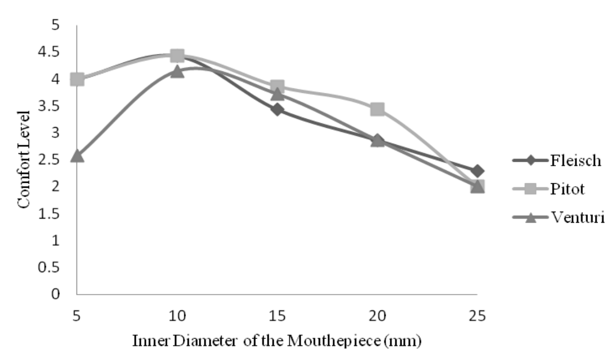

Figure 2. Average comfort level given to each mouthpiece in phase 1 is plotted. Mouthpieces with an inner diameter of 10mm show the highest comfort level for all three flow measuring types.

normalization is to eliminate the inter-subject variation in evaluating the mouthpieces. The highest maximum pressure values are observed at 5mm and pressure values gradually decrease as the inner diameters increase for Flesch and Pitot type mouthpieces. There is no statistical difference between the maximum pressure values of Venturi type mouthpieces. Similar maximum pressure values across all five sizes in Venturi type mouthpieces can be explained by the constant ratio between diameters of the two channels maintained in all five sizes. There is no statistically significant difference between the maximum pressure values of Fleisch and Pitot type mouthpieces, however there is a significant variance among subjects. Higher-pressure values can increase the sensitivity of the flow meter when coupled with a proper pressure sensor.

Variance in total exhaled volume can be used as an indicator for deviation from the normal breathing pattern. Total exhaled volume for each exhaled cycle is obtained and variance of exhaled volume for each mouthpiece for each test is calculated. Exhaled volume variance is normalized by dividing the pressure values by the maximum pressure value of each test and then dividing the sum of pressure values by maximum sum of pressure values. Exhaled volume variances of different mouthpieces are plotted in Fig. 4. There is no statistical difference among the variance of Fleisch type mouthpieces; however there is significant variation among the subjects. Variance is lowest for 10mm Pitot type mouthpieces. There is no statistical difference among the exhaled volume variance for Venturi type mouthpieces. Mouthpieces with a 10mm ID have the lowest average exhaled volume variance and there is no significant difference among the flow measuring techniques. It is important to note that the lowest exhaled volume variance and the highest comfort level have the same ID of 10mm across the three flow measuring techniques.

There is no correlation between age, height or weight of the subjects and comfort level. Fleisch type mouthpiece with ID of 15mm is the only mouthpiece that received a gender bias comfort level. Average comfort level given by the male subjects for this particular mouthpiece is lower than the comfort level given by the female subjects. There is no gender based difference for any other size.

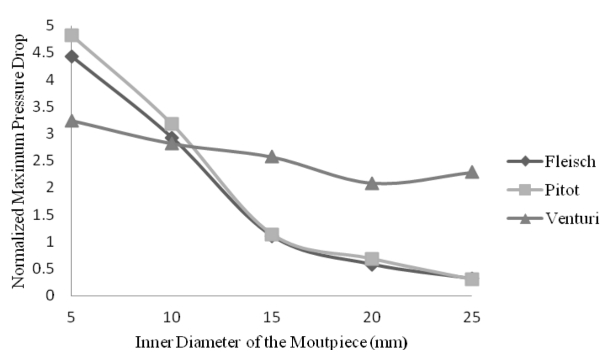

Figure 3. Maximum pressure drop of each exhaled cycle is averaged over the multiple exhaled cycles for the duration of the test for each subject for each flow measuring technique. Averaged maximum pressure drop is normalized and scaled to 0-5 by dividing by the averaged maximum pressure drop for each subject and multiplying by 5.

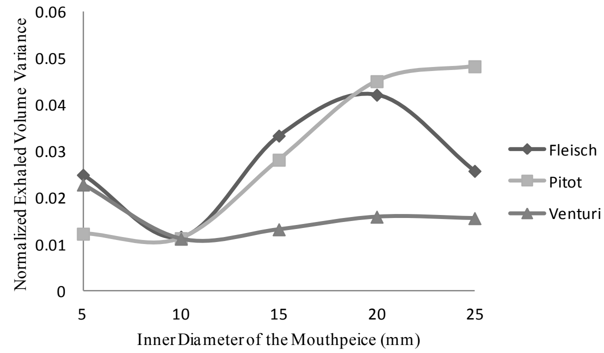

Figure 4. Total volume exhaled for a single exhaled cycle is calculated and variance of exhaled volume for different exhaled cycle for each mouthpiece is determined. Variance is normalized by dividing the pressure values by the maximum pressure value of each test then dividing the sum of pressure values by maximum sum of pressure value.

Based on phase 1 results mouthpieces with 10mm IDs performed the best across all three flow measuring techniques in comfort level and exhaled volume variance. The study is extended to a phase 2 where Fleisch and Pitot type mouthpieces with IDs of 7.5mm, 8.75mm, 10mm, 11.25mm and 12.5mm are further investigated. Purpose of phase 2 is to investigate the range of IDs centered around 10mm that maintains the highest comfort level, lowest exhaled volume variance and an optimum maximum pressure drop. Since there is no significant difference among the Venturi type mouthpieces in maximum pressure drop and exhaled volume variance in phase 1, Venturi type mouthpieces are excluded from phase 2.

Fig. 5 shows the comfort level given by six subjects for five Fleisch and Pitot type mouthpieces in phase 2. Averaged highest comfort level is given to mouthpieces with 11.25mm ID and there is no significant difference between the two types. There is no significant difference in comfort level among Fleisch type mouthpieces with IDs of 8.75mm, 10mm, 11.25mm and 12.5mm. There is no significant difference in comfort level among Pitot type mouthpieces with IDs of 10mm, 11.25 and 12.5mm. According to Fig. 6 Fleisch and Pitot type mouthpieces with IDs of 7.5mm have

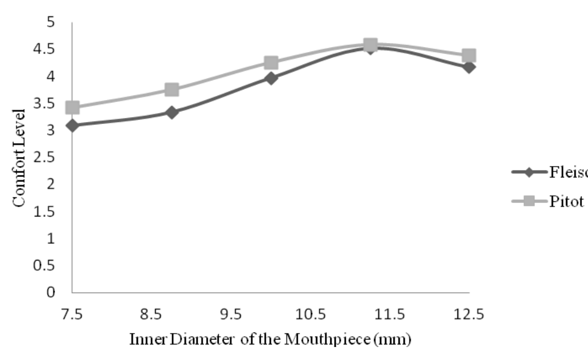

Figure 5. Average comfort level given in phase 2 of the study to each mouthpiece is averaged and plotted. 11.5mm Fleisch and Pitpt shows the highest comfort levels.

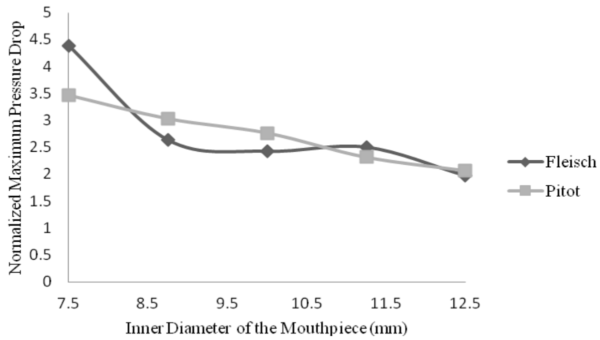

Figure 6. Normalized averaged pressure drop for each mouthpiece in phase 2 of the study.

the highest pressure drop but there is no significant difference among the remaining sizes. Deviation from normal breathing pattern is expressed using the difference in breathing rate when breathing through the mouthpiece and normal breathing. There is no significant difference in deviation from normal breathing among the mouthpieces as shown in Fig. 7.

V. Conclusion

Increase in maximum pressure value can be achieved only with the cost of reduced comfort level for Fleisch and Pitot type mouthpieces with IDs below 8.75mm. Since the loss of pressure resolution can be compensated by using a high resolution pressure sensor, we consider maximum pressure as a secondary performance matrix and comfort level as a primary performance matrix. Based on phase 1 results, deviation from normal breathing expressed using the exhaled volume variance is inversely related to comfort level. Finally, we conclude IDs ranging from 8.75mm to 12.5mm for Fleisch type, IDs ranging from 10mm to 12.5mm for Pitot type and ID of 10mm for Venturi type are the most suitable dimensions for a breath sampling device that requires breathing for an extended period of time. Type of flow measuring technique should be determined based on the range of flow rate and the accuracy required by the device.

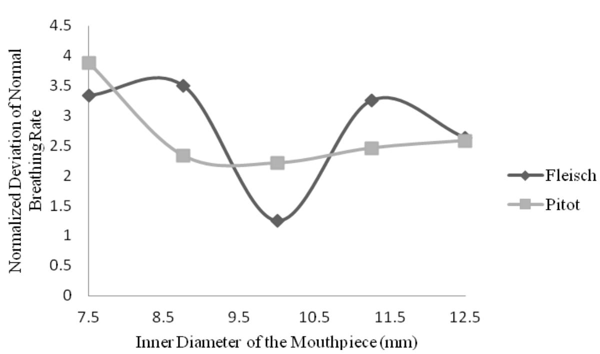

Figure 7. Difference of breathing rate using the mouthpiece and normal breathing is plotted.

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