Use of a Vortex Whistle for Measures of Respiratory Capacity

[*]**Shaheen N. Awan, and** [†]**Jordan A. Awan,** **Bloomsburg, and †West Lafayette, USA*

Summary: Objectives: A vortex whistle produces a tone which has a frequency proportional to the inlet air flow rate. The objectives of this study were to replicate previous studies demonstrating the use of a vortex whistle as an accurate flow meter, and to assess the degree of relationship between measures of vital capacity (VC) obtained using low-cost methods (vortex whistle and hand-held spirometry) vs. pneumotach-based spirometry.

Methodology: A vortex whistle was designed using 3D modeling software and manufactured using a 3D printer with non-toxic, biodegradable polylactic acid (PLA). The digitized vortex whistle tone was analyzed using custom software to produce a frequency vs. time contour. As the frequency is proportional to flow, the integral of this curve corresponds to the overall volume by a linear relationship. The accuracy of vortex whistle volume estimates were assessed using (1) controlled flow rates from a consistent volume calibration syringe, and (2) with 66 subjects between the ages of 18−30 yrs. in comparison to hand-held spirometry and two pneumotach systems.

Results: Observations from the calibration syringe experiment confirmed that the vortex whistle and software are able to effectively track the flow rate, with a correlation coefficient between the average flow and the average frequency of $r^2 = 0.9965$. Results from the human VC testing showed that measures obtained using both vortex whistles and hand-held spirometry correlated very strongly ($r > 0.94$) with computerized pneumotach systems, and the strength of correlations obtained via vortex whistles vs. hand-held spirometry were highly comparable.

Discussion & Conclusions: When coupled with the analysis software described herein, valid and reliable frequency/flow curves and volume estimates may be obtained using a vortex whistle that are highly comparable to the hand-held spirometer. The use of the vortex whistle has the potential to bring measures of basic respiratory function to clinicians and patients alike at a fraction of the cost of currently used spirometric methods.

Key Words: Vortex whistle−Vital capacity−Respiration−Spirometry−Airflow.

INTRODUCTION

The human voice is generated by a combination of respiratory forces and laryngeal mechanics. While the assessment of the typical vs. disordered voice often focuses on the laryngeal structures, vocal fold vibration, and the acoustic and perceptual byproduct of that vibration, it has been frequently reported that deficiencies in respiratory capacity and control may result in reductions in the efficiency and effectiveness of voice production.[1−4] One of the most important and effective respiratory measures is vital capacity (VC). VC is defined as the maximum volume of air that can be exhaled following maximum inhalation. While only a fraction of the total VC is used in most typical speaking situations, increased respiratory capacities are used in professional voice use that may require louder, more extended, or more controlled voice production (eg, public speaking; singing). Not only does VC provide information regarding available capacity, the measure can also provide information regarding the function of different contributing subsystems to phonation (e.g, respiratory vs. laryngeal subsystems), and may be combined with measures of maximum phonation time (MPT) to provide an estimate of airflow during voice production referred to as the Phonation Quotient (PQ) .[5−7]

SPIROMETRY

VC is typically measured using a spirometer. Spirometry is used in various health-related professions and is central to the diagnosis and management of chronic lung diseases (eg, the ratio of the forced expiratory volume in the first second (FEV1) and the VC may be used to determine the presence of restrictive vs. obstructive ventilatory defects). In spirometry, flow rate (L/s; mL/s) of air is measured as it passes through a mouthpiece. There are several types of spirometers: eg, flow-based spirometers such as pneumotachographs, turbines, anemometers, and ultrasounds; volume displacement spirometers such as wet spirometers. In flow-based spirometers, flow (ie, volume/time) can be integrated to produce a measure of volume.

Most hand-held and electronic spirometers require a power source (eg, AC source; batteries) and many spirometers require regular calibration and associated equipment (eg, calibrated syringe). In addition, the mechanical and/or electrical components of the spirometer may require regular cleaning (eg, the mesh within a pneumotach flowhead) and/or replacement due to the moisture contained within the expiratory airflow. Finally, the costs for spirometers can range from hundreds of dollars for handheld models to thousands of dollars for high end pneumotach systems, presenting a prohibitive cost for some groups (eg, voice professionals or for use in developing countries).

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From the *Department of Communication Sciences & Disorders, Bloomsburg University, Bloomsburg, Pennsylvania, USA; and the †Department of Statistics, Purdue University, West Lafayette, Indiana, USA.

Address correspondence and reprint requests to sawan@bloomu.edu

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Use of a Vortex Whistle

The initial description of a vortex whistle that could be used as a low-cost but extremely accurate flow meter was proposed by Vonnegut in 1954.[8] In a vortex whistle (see Figure 1), air is blown into an inlet tube (IT), flows into a cylindrical cavity (CC), and begins to whirl around in a vortex that eventually exits through an outlet tube (OT). As air exits the outlet tube, a tone is produced which has a frequency proportional to the inlet air flow rate.[9,10] The frequency can then be mapped to the inlet airflow rate, and the area under the frequency/flow curve obtained from the vortex whistle can be used as an estimate of volume. Vonnegut's[8] description of the vortex whistle was further supported by Michelson[11] and Chanaud[12], and a study by Sato and colleagues[13] reported on the potential use of a vortex whistle as a spirometer. In the Sato et al study, the acoustic output of the whistle was captured via microphone and the variable frequency of the output was detected via algorithms incorporating Fourier transformation. Pulmonary function tests using a vortex whistle and an electronic spirometer were performed with 74 male and female subjects between 30 and 70 years of age. Results from 56 usable signals showed $r^2 = 0.87$ between measures of forced vital capacity (FVC) measured using the vortex whistle vs. FVC's measured using the electronic spirometer.

Recent studies using the vortex whistle by Goel et al[14], Kaiser at al[15], and Mikalsen et al[10] have focused on measures of FEV1 and peak expiratory flow rate (PEFR), perhaps since irregularities in the periodicity (and thus frequency extraction) of the vortex whistle acoustic signal at low flow rates (eg, in the concluding portion of an extended expiration) may result in inaccuracies in resulting flow and volume calculations. While Kaiser at al[15] report that "personalization" of the vortex whistle (ie, creating and having available different whistle configurations for different flow expectations) in combination with additional side aerodynamic whistles that are initiated at low flow rates may aid to address this issue, these variations complicate the notion of a simple, non-moving part vortex whistle that may be used for spirometric estimates. In addition, as Sato et al[13] reported a very strong r^2 value with electronic spirometry using a simple vortex whistle design, there is prior evidence that a simple design can provide suitable estimates of VC.

Purpose

As a potential method of low-cost spirometry, the vortex whistle provides obvious benefits, including (1) no moving or electronic parts, (2) no calibration once the characteristics of the device are known, (3) potential to provide an accurate flow rate from which an estimate of respiratory volume may be determined, and (4) potential for low cost manufacture as compared to current hand-held and electronic spirometry methods. The purpose of this study was to replicate previous proof of concept studies demonstrating the use of a vortex whistle as an accurate flow meter, and to assess the degree of relationship between measures of VC obtained using a vortex whistle and currently available pneumotach-based standards. In addition, a key goal of this study was to compare the performance of the vortex whistle to hand-held spirometry, which is currently the lower cost alternative to computerized pneumotach-based systems.

METHODOLOGY

Vortex Whistle Characteristics

A vortex whistle design similar to that reported by Sato et al[13] was designed in OpenSCAD, a free software application for creating solid 3-D CAD objects.[16] The whistles were manufactured using a Flashforge Creator Pro 3-D printer (Flashforge USA, City of Industry, CA) via the open-source slicing software FlashPrint[17] with a non-toxic, biodegradable polylactic acid (PLA) plastic under default settings. Figure 1 provides a scale diagram of the vortex whistle including the diameter and length dimensions of the inlet tube (IT), cylindrical cavity (CC), and the outlet tube (OT). Whistles with dimensions that are too large do not effectively produce a vortex and output tone, resulting in a weaker relationship between the generated sound and the flow rate. In contrast, whistle dimensions that are too small will produce a strong back pressure during expiration that often results in substantial lip seal leaks around the input tube. The dimensions in Figure 1 were chosen to optimize the accuracy of the frequency-tracking in subsequent computer analyses.

A novel modification of the vortex whistle used in this study is the inclusion of an *output reflector* (OR; see Figures 1 and 2), placed perpendicular to the output tube at a distance of 3 mm. Preliminary investigations observed that the inclusion of the OR improved the signal to noise ratio of the whistle tone, which led to improved frequency tracking, and ultimately better flow and volume estimates.

Acoustic Analyses

A custom program was written in Java[18] to record the output tone of the vortex whistle for each trial. The recorded signal was center-clipped and then analyzed in a series of 1000 pt. frames with 50% overlap using autocorrelation (expected frequency range approx. 200−7000 Hz). Initial frequency estimates were corrected when necessary via frame-by-frame comparison and interpolation to account for potential octave jumps. Due to the nature of the procedure, the results are dependent on the periodicity of the initial selected bin. In the event that excessive octave correction is required throughout the initial analysis procedure, it is inferred that the results from the initial bin were spurious, and additional error-correction heuristics are applied to re-analyze the beginning of the sample. The output of this algorithm is a frequency vs. time contour. Previous studies have demonstrated that the frequency of the vortex whistle tone is proportional to flow; hence, the integral of this curve corresponds to the overall volume by a linear relationship. Figure 3 illustrates the vortex whistle

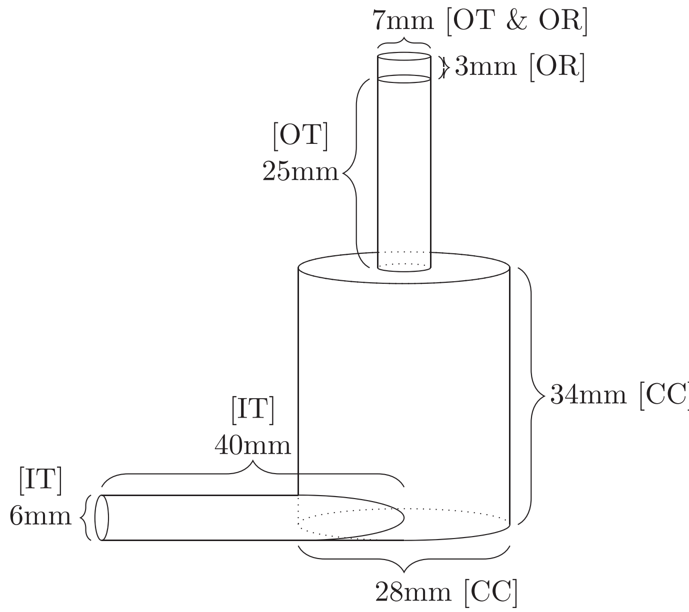

FIGURE 1. Scale diagram and internal dimensions of the vortex whistle used in this study.

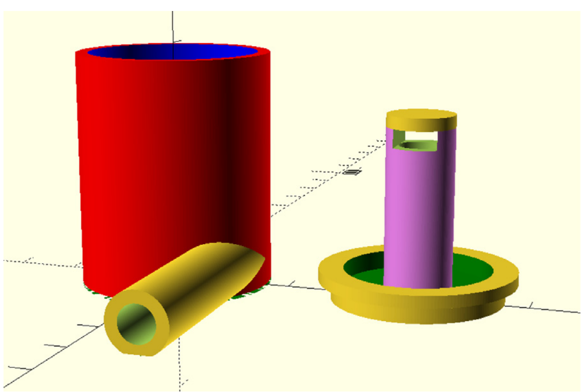

FIGURE 2. Image of the 3-D model of the vortex whistle designed in OpenScad.[16] The 3-D model realizes the internal dimensions provided in Figure 1. The walls of the model are 2mm thick, with the exception of the roof of the CC, which is 3mm thick. The model is designed in two parts to facilitate 3-D printing as well as cleaning between uses.

signal as recorded in the Java program as well as the frequency curves with and without error correction.

Vortex Whistle Validation via Known Volume Calibration Syringe

To evaluate the validity of the vortex whistle tone as an accurate predictor of flow, the vortex whistle was sealed to the outlet of a 3 L Calibration Syringe (Series 5530, Hans Rudolph Inc., Kansas City, MO), by which a known and consistent volume could be inserted into the vortex whistle at varying flow rates. Because the vortex whistle software computations are determined from an acoustic waveform, and are sensitive to noise interference, a foam pad was added to the end of the syringe handle to reduce impact noise from the handle hitting the syringe body. This reduced the total volume from 3 L to approximately 2.9075 L. The syringe volume was input into the vortex whistle at various rates (see Figure 4). Audio recordings and analysis were conducted using the aforementioned custom Java software running on a Dell Inspiron 11−3153 laptop computer running Windows 10. Vortex whistle signals were recorded at a distance of 15 cm, using an AKG Perception 200 microphone and Yamaha Audiogram 5 digital interface (Sampling rate = 44.1 kHz, 16-bits).

Flow Estimate Results: The average flow was computed as (2.9075*L*/Duration). The correlation coefficient between the average flow and the average frequency (produced by the vortex whistle, as measured by the Java program) is $r = 0.9983$ ($r^2 = 0.9965$) with 95% confidence interval (0.9955, 0.9993). The corresponding regression line is the following:

$$\text{AvgFlow}(L/s) = (0.04859) + (0.0002406)\text{AvgFreq} \quad (1)$$

Volume Estimate Results: The linear equation (1) was integrated to arrive at equation (2) which predicts the volume in terms of the area under the frequency curve and the duration of the sample.

$$\text{Volume}(L) = (0.04859)\text{Duration} + (0.0002406)\text{Area} \quad (2)$$

The mean volume over 20 trials = 2.906 L (sd =.044); Coefficient of variation = 1.5%.

Vortex Whistle Validation via Human VC Testing

Measures of VC were collected for 66 subjects (41 females; 25 males) between the ages of 18−30 yrs. using a methodology approved by the Bloomsburg University Institutional Review Board (IRB No. 2018−118). Subjects reported no significant history of untreated respiratory disorder, no

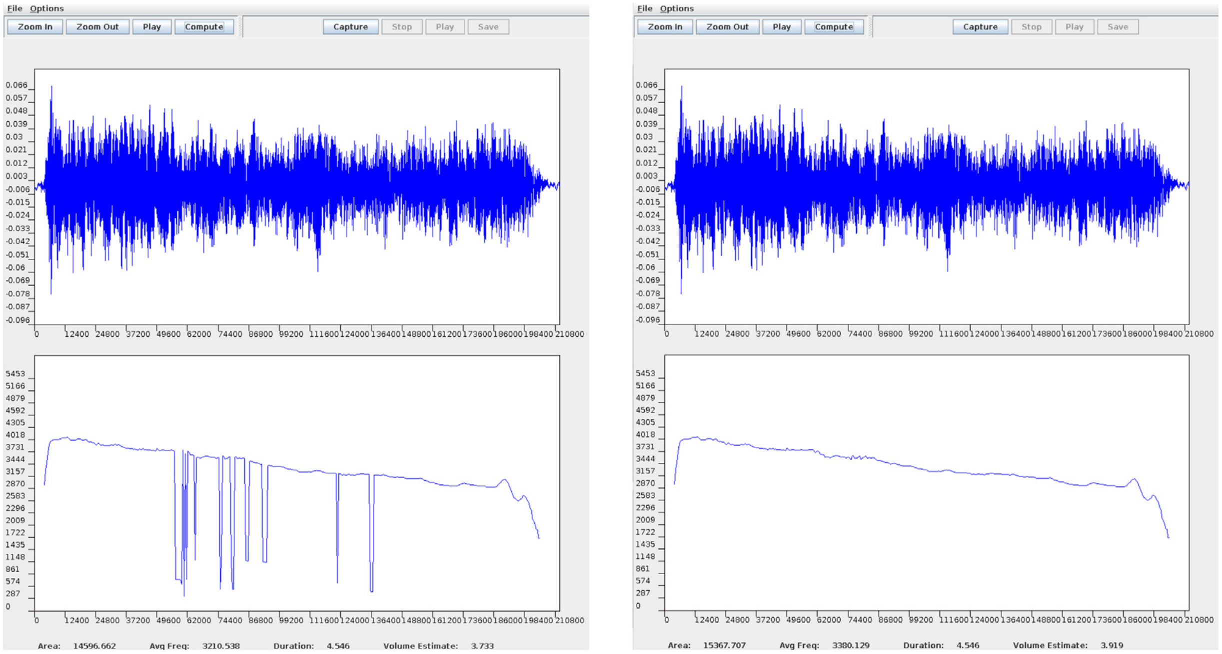

FIGURE 3. Two screenshots of the custom Java program, where the upper plot is the acoustic waveform and the lower plot is the frequency vs time contour. The left screenshot demonstrates the raw frequency estimate, whereas the right screenshot shows the refined estimate after error correction.

report of cough/cold or seasonal allergies that may have effected breathing on the day of testing, and reported no significant history of known neurological disorder. All subjects were nonsmokers, defined similarly to Awan[19] as someone who currently did not smoke and who had not smoked for at least 5 years prior to their inclusion in the study (this applied to both tobacco cigarettes and e-cigarettes).

Respiratory capacity was measured using: (1) hand-held spirometry, (Micro Spirometer, Microdirect), (2) two pneumotach systems (KoKo Spirometer, nSpire Health; Phonatory Aerodynamic System (PAS), Pentax Medical Inc.), and (3) 3-D printed vortex whistles created using the previously described design (see Figures 1 and 2). The vortex whistle signal was recorded and analysed using the aforementioned custom Java software running on a Dell PC and Ubuntu 18.04 LTS. Signals were recorded at 44.1 kHz, 16 bits using a Shure Beta-54 headset microphone (approx. mic-to-whistle distance of 25 mm) and a Yamaha Audiogram 5 digital interface.

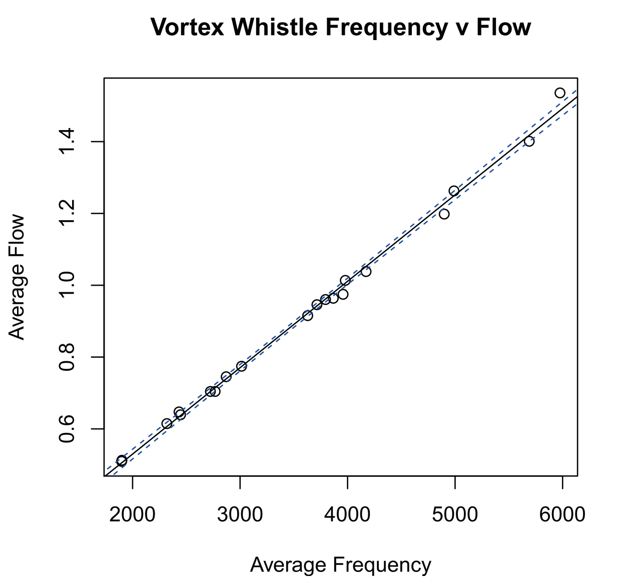

FIGURE 4. Plot of flow (L/s) versus whistle frequency (Hz). Included is the regression line and 95% confidence bands..

Subjects were asked to perform the following two forms of VC tasks: forced vital capacity (FVC - exhale with maximal force after deepest possible inhalation), and expiratory vital capacity (EVC - a.k.a. slow vital capacity; a slow maximal exhalation is produced after the deepest possible inspiration). While FVC and EVC tend to be similar in typical subjects, FVC may underestimate the respiratory capacity in subjects with severe respiratory disorders with EVC being the preferable measure in such cases.[20,21] In addition, FVC may be invalid in some subjects using the PAS since increased flow rates such as those elicited in FVC will often exceed the flow value limits that may be obtained using the small flowhead provided with the system. It was also of interest as to whether the vortex whistle used in this study could provide acceptable measures of VC when the task was elicited using lower flow rates as in the EVC task.

Three trials of FVC were obtained using each method of spirometry considered in this study: the Koko Spirometer, the hand-held Micro Spirometer, and the vortex whistle. In addition, three trials of EVC were measured using the PAS, the hand-held Micro Spirometer, and the vortex whistle. All VC elicitations were produced with the subject wearing a nose-clip. To prevent intersubject contamination, VC elicitations were obtained via a disposable cardboard tube into the hand-held spirometer and the pneumotach systems. Vortex whistles were sterilized externally and internally using Cavicide prior to subject use. Subjects were provided with a 60 second rest period between trials, as well as further rest between systems. The elicitation of FVC vs. EVC was counterbalanced across subjects. In addition, the presentation order of the levels of instrumentation (hand held spirometer; pneumotach systems; vortex whistle) was also counterbalanced across subjects to ensure an equal distribution of instrumentation order. As per standard procedure when eliciting maximum performance tasks, the greatest VC measure from the three elicited trials from each system and each condition (FVC vs. EVC) were used for data analyses.

RESULTS

The Koko system was considered to be the state of the art for FVC and the PAS to be the state of the art for EVC. The Koko system was chosen as the comparative standard for FVC since it meets American Thoracic Society (ATS) and European Respiratory Society (ERS) spirometry standards and has been used in other studies which have assessed the clinical utility of alternative methods of obtaining basic respiratory measures.[14,22,23] The PAS was selected as the comparative standard for EVC since this system has been frequently used for aerodynamic and basic respiratory measures in the voice research community.[24−26]

A series of Pearson's correlation coefficients were computed to ascertain the strength of correlation between the various measures. The following results were observed:

- For FVC, the vortex whistle correlated with Koko with $r = 0.941$ (95% CI: (0.906, 0.964); $r^2 = 0.886$). In comparison, the hand-held spirometer correlated with Koko with $r = 0.959$ (95% CI: (0.934, 0.975); $r^2 = 0.920$). The confidence intervals for these respective correlation coefficients significantly overlap, indicating that the difference between these correlation coefficients is not statistically significant.
  The linear regression formula which estimates the FVC value of Koko given the measured value by the vortex whistle is as follows:
  $$Koko_{FVC} = 0.5960 + (1.014)Vortex_{FVC} \quad (3)$$
  Koko FVC estimates computed from this formula have a standard error of 0.3199 for the vortex whistle vs. 0.2647 for the hand-held spirometer. The regression line of Equation (3) as well as a 95% confidence band are plotted against the observed data points in Figure 5.
- For EVC, the vortex whistle correlated with PAS with $r = 0.945$ (95% CI: (0.911, 0.966); $r^2 = 0.893$). In comparison, the hand-held spirometer correlated with PAS with $r = 0.949$ (95% CI: (0.918, 0.969); $r^2 = 0.901$). As with FVC, the confidence intervals for these respective correlation coefficients significantly overlap, indicating that the difference between these correlation coefficients is not statistically significant. In addition, the nearly identical confidence intervals indicate that there is essentially no loss in accuracy by using the vortex whistle in place of the hand-held spirometer.
  The linear regression formula which estimates the EVC value of the PAS given the measured value by the vortex whistle is as follows:
  $$PAS_{EVC} = 0.3206 + (1.071)Vortex_{EVC} \quad (4)$$

PAS EVC estimates computed from this formula have a standard error of 0.336 for the vortex whistle vs. 0.3199 for the hand-held spirometer. The regression line of Equation (4) as

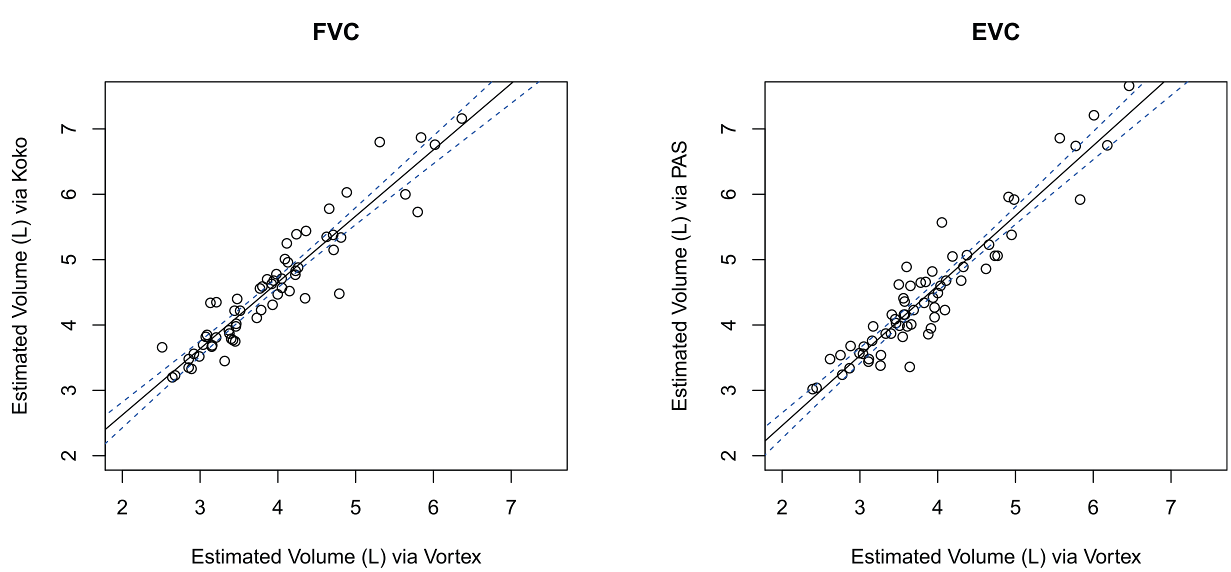

FIGURE 5. Plot of Vortex Whistle versus Koko for measures of FVC (Left) and Vortex Whistle versus PAS for measures of EVC (Right). Regression lines and 95% confidence bands are also provided.

well as a 95% confidence band are plotted against the observed data points in Figure 5.

DISCUSSION

The results from Section 2.3 confirm that a vortex whistle can produce valid and reliable measures of airflow in a simple low cost device, as demonstrated in previous studies. In fact, when using a consistent volume via the calibration syringe, equation (2) produced accurate estimates of the volume across a large range of flow rates with very little error (coefficient of variation: 1.5%).

In human subject VC testing, the results from Section 2.4 show that estimates based on the vortex whistle correlate very strongly ($r > 0.94$) with accepted state-of-the-art pneumotach-based spirometry systems. The r^2 (index of determination) values reported in this study are comparable and slightly greater than those previously reported by Sato et al.[13] Of particular importance is that the vortex whistle correlations are highly comparable to correlations observed between hand-held spirometry and the state-of-the-art systems. In terms of predictive error, the results of this study show that hand-held spirometry (± 0.26−0.32 L standard error) and the vortex whistle (± 0.32−0.34 L standard error) have very comparable performance relative to the standard pneumotach systems for FVC and EVC (Koko and PAS). These results indicate that the vortex whistle may be used as an acceptable substitute for hand-held spirometry. Since the vortex whistle and accompanying software are able to achieve this with a simple, disposable device that can potentially be made available at a small fraction of the cost of a hand-held spirometer, the vortex whistle and software package can enable measures of VC in settings where respiratory measurement is currently unavailable or prohibitively expensive.

Note that the initial volume estimates based on equation (2), which were calibrated using the syringe data, underestimate the VC when used in human subject testing. This may be due to the nature of the sound wave produced by a human subject through the vortex whistle. At the end of each VC elicitation the flow of air drops dramatically, resulting in whistle signals which do not produce a consistently periodic sound wave. Because of this, the analysis algorithms used in this study were unable to effectively track the frequency in this portion of the expiratory signal. However, the regression formulas (3) and (4) illustrate that the bias in the estimated volume produced by the vortex whistle software is a systematic and predictable underestimation of the true volume by approximately 0.3−0.6 L (depending upon the method of eliciting VC). Therefore, the bias can be corrected using the reported regression equations (3) and (4) to improve the initial volume estimates produced via the vortex whistle software.

Further Investigation

This study focused on typical young adult subjects in order to establish the validity of the vortex whistle as a tool for the measurement of VC. It would be valuable and necessary to study disordered subjects as well as other age groups to better understand the ability of the vortex whistle and software to provide valid and reliable estimates of FVC and EVC in other populations. For instance, if a subject can only produce very low flows, the vortex whistle signal may not be able to be accurately analyzed with the methods reported in this study.

Besides FVC and EVC, there are many other spirometry measures in the literature, which may be estimable with the vortex whistle. For instance, estimates of peak expiratory flow (PEF) and forced expiratory volume in the first second (FEV1) may also be calculated using the frequency-time contour. Future studies may compare these estimates to state-of-the-art measures.

Caveats and Conclusions

Any maximum performance test, such as VC, requires careful training of both subject and clinician. For instance, any measure of VC is susceptible to user error such as less than maximal performance, air flow leaks, or other misuse of the equipment/measurement apparatus. On the side of the clinician, factors such as training and monitoring of the subject, as well as maintenance and calibration of the equipment are crucial for obtaining accurate measurements. These issues would be common to any form of VC testing.

Specific to the vortex whistle and accompanying software, the clinician must monitor the characteristics of the acoustic wave being captured. Microphone placement too far away from the whistle outlet will result in weak amplitude signals that may result in invalid frequency computations. In addition, if the microphone is too close to the outlet of the whistle, signal distortion and clipping may occur, again resulting in erroneous analyses. In this study, a brief training period was provided to each examiner which focused on optimal use of the vortex whistle, techniques to train subjects on the VC tasks, use of the accompanying software, microphone placement, and examples of acceptable vs. unacceptable vortex whistle signals. This training was important for obtaining accurate measurements from the vortex whistle procedure and resulted in highly reliable testing with the subjects included in this study.

The results presented here are from an initial study to demonstrate the effectiveness of a vortex whistle and accompanying analysis software as a low-cost "flow-meter" as well as a suitable measure of FVC and EVC. While the design of the vortex whistle and frequency-tracking software have the potential to be further optimized and refined, these initial results are very promising. In particular, as the manufacture of a vortex whistle may be achieved for only a few dollars (or less) vs. hand-held spirometry or other methods that cost hundreds or thousands of dollars to obtain, this method provides the potential for valuable measures of basic respiratory capacity to be obtained where currently available methods are either unavailable or unaffordable.

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