Measurement Reliability of Phonation Quotient Derived From Three Aerodynamic Instruments

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Summary: Objective. The purpose of this study was to examine parallel forms reliability between two hand-held spirometers and a pneumotachograph-based system for vital capacity and derived phonation quotient measurements.
Study design. This is a prospective, repeated measures design.
Methods. A total of 20 adult males were tested using three aerodynamic instruments—Baseline windmill-type spirometer, Contec SP10 digital spirometer and the Pentax Medical Phonatory Aerodynamic System (PAS), Model 6600 for measures of vital capacity. Phonation quotient was calculated using vital capacity from each instrument along with maximum phonation time. Repeated measures analyses of covariance (ANCOVAs) were performed to test for main effects of the instruments on vital capacity and phonation quotient, with age as a covariate. Pearson Product Moment correlation was performed to assess measurement reliability between the instruments.
Results. Statistically significant differences on ANCOVA were seen in vital capacity measures for the digital spirometer compared with the windmill spirometer and PAS. No differences were found between any of the instruments for phonation quotient. Large and positive correlations were present between all three instruments for both vital capacity and phonation quotient measurements.
Conclusions. Strong parallel forms reliability in measures of vital capacity and derived phonation quotient was seen among the three instrument systems, although measurement precision was different when comparing the digital spirometer to two other instrument types.
Key Words: Measurement reliability–Spirometer–Aerodynamics–Vital capacity–Phonation quotient.

INTRODUCTION

Phonation is the result of aerodynamic and muscular activity acting on vocal-fold tissue to generate audible acoustic energy called "voice."[1] Changes in aerodynamic pressure and flow typically follow laryngeal pathology and/or physiological imbalances in the subsystems responsible for voice production.[1–3] The measurement of these aerodynamic influences provides valuable clinical evidence to the speech-language pathologist for the purposes of impairment detection, characterization, and differential diagnosis. It is thus not surprising that the clinical measurement of laryngeal aerodynamics underlying phonation is considered a standard modality in the evaluation of voice impairments.[4,5] In theory, quantifying measures of flow and/or pressure will provide the clinician with information that can improve diagnostic precision, inform treatment planning, provide a means of biofeedback during treatment, and enable objective measurement of clinical benefit.[4]

Aerodynamic assessments, often conducted as part of the clinical procedure "Laryngeal Function Studies" (current procedural terminology code 92520) in the United States, can measure parameters of volume, flow, pressure, and vocal efficiency.[6] Applied clinically, volume has been measured using calculations of vital capacity (VC), phonation volume, and forced expiratory volume, while airflow has been measured as average and peak flow rates, among other measurements.[4,7–10] Clinical measurement of vocal efficiency has included maximum phonation time (MPT), s/z ratios, aerodynamic efficiency, and the ratio of VC to MPT, called phonation quotient (PQ).[3,7–11] PQ, measured in milliliters per second (mL/s), has been used as an indicator of the efficiency of the valving function of the vocal folds for phonatory airflow. As a measure of vocal efficiency, PQ has been used to differentiate normal from impaired phonation and as a means to document treatment outcome.[4,12–15] The calculations of PQ require a measurement of VC derived from a spirometry system, and measurement of MPT, typically derived by measuring audible vocalizations with a timing device such as a stopwatch. Previous studies have found that PQ is sensitive to changes and imbalances in the subsystems of voice due to aging, pathology, or the impact of voice rehabilitation.[8,9,12,13,15,16]

Hirano et al[7] coined the term phonation quotient as a measure of air consumption during phonation and examined its reliability in the absence of expensive equipment such as a pneumotachograph. Because the total volume of air used during MPT (used to calculate mean flow rate when using a pneumotachograph) is less than VC, PQ is usually higher than mean flow rate (MFR).[13,17,18] Although measurement precision of airflow and volume is likely greater when using a pneumotachograph-based instrument, Hirano et al[7] found a high correlation between their measures of MFR and PQ both for males and for females, indicating that PQ can substitute MFR as a parameter of aerodynamic evaluation in the absence of pneumotachograph-derived airflow measurements. Rau and Beckett[9] measured PQ across three different spirometers, including low-cost hand-held devices, in healthy adults to assess feasibility of the equipment. Their data were consistent with the Hirano et al[7] study, with higher PQ values obtained for males than for females as a result of the comparable difference in VC between genders.

Accepted for publication November 19, 2015.
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Journal of Voice, Vol. 30, No. 6, pp. 773.e13–773.e19
0892-1997

http://dx.doi.org/10.1016/j.jvoice.2015.11.015

During normal development and with aging, lower MFR, MPT, and VC values have been reported in children and older adults (>65 years) compared with young adults (18–40 years).[19,20] However, a significant difference in PQ was not observed in a study by Awan[12] among 50 women divided into 5 age groups between 18 and 79 years, even though significant differences were found for VC and MPT. A strong correlation was found between VC and MPT which might explain the consistent ratio, ie, PQ, across age groups. Morsomme et al[21] saw similar results in their examination of PQ in 30 women with the age of 70–90 years. There was no significant difference in PQ means for these women when compared with young adult females. On the other hand, in their comparison of 10 older men with young adult men, they found 25% lower values in older men as compared with the young adult men. Morsomme et al[21] used normative data for young adults from previous studies performed by different researchers using different test procedures. The logistical variations make the comparison in PQ values for men and women more difficult. The difference in sample size between elderly men (n = 10) and women (n = 30) could also attribute to the discrepancy in the resultant data. A greater standard deviation from the mean was seen for women (mean = 154 mL/s, SD = 87) than men (mean = 153 ml/s, SD = 48) with similar means. The large variability in the older women data could have washed out some of the differences between age groups.

The early studies that looked at PQ in persons with laryngeal pathologies were performed by Hirano et al[7] in 1968 and, Iwata and von Leden in 1970.[8] Both studies measured PQ using a pneumotachograph in patients with vocal-fold inflammation, benign and malignant tumors, and unilateral and bilateral vocal-fold paralysis. The Hirano et al[7] study also tested patients with spasmodic dysphonia and functional voice disorders. PQ values were significantly greater than normative values in both studies, and Hirano et al. concluded that PQ was sensitive enough to identify laryngeal dysfunction but not for differential diagnosis between laryngeal pathologies. In a study on patients with unilateral vocal-fold paralysis undergoing treatment with hyaluronic acid injections, Wang et al[16] used PQ as a parameter to track progress at 1 week, 3 months, and 6 months postinjection. PQ values showed significant change at each time point, consistent with results on MPT, MFR, perceptual, and patient self-rating measures. Over the years, there have been other studies that have used PQ to measure change with treatment in patients with vocal-fold paralysis,[22–24] Parkinson disease,[25] and early glottic cancer.[26,27] Variations in PQ for spoken and sung tones in asymptomatic singers have also been reported.[28]

Although PQ has been used as a measure of vocal efficiency in the research literature and in clinical practice for many decades, spirometric equipment used in the acquisition of this measurement has been variable. Additionally, the use of pneumotachograph-based systems for measurement of aerodynamics remains somewhat prohibitive in many speech and voice clinics due to their high cost (eg, well above $1000). Although high-cost and low-cost options have been utilized in the literature and are currently available for measuring VC, PQ, and other quantitative measures of voicing efficiency, there is a paucity of data reporting the clinical reliability of measurements between different aerodynamic instrumental options. Clinicians who acquire these measures during the process of Laryngeal Function Studies must have evidence for the measurement reliability of instrumental choices for their valid application to the processes of impairment detection, characterization, and differential diagnosis.

Parallel forms or alternative forms reliability is the measurement of the same variable using different forms or versions of an instrument.[29] Its purpose is to determine if two instruments produce equivalent results when measuring the same variable or construct under identical measurement conditions. When measurements are very similar, parallel forms reliability is interpreted as being strong and suggests that either instrument is reliably capable of measuring the variable of interest. The purpose of this study was to investigate the parallel forms measurement reliability between three commercially available instrument systems. We used a pneumotachograph-based instrument and two hand-held spirometers for measuring VC, from which subsequent measurements of PQ were derived. If strong parallel forms measurement reliability is found, the results of this study might inform clinical practice by providing evidence for instrument choices used in the acquisition of certain aerodynamic measurements.

METHODS

Participants

A total of 20 adult men between the ages of 25–69 years were recruited in this study. We chose to control for sex as this factor influences measurements of VC and derived measurements of PQ.[9,30] All participants were self-reported nonsmokers with no history of hearing impairment, pulmonary, neurological, and previous or current voice disorder. The study was approved by the Committee for Protection of Human Subjects at the University of Houston.

Instruments

Three instruments were used to compare VC and derived PQ values. Two of the three instruments were low-cost (eg <$300) hand-held spirometers—an analog windmill type (Baseline Measurement Instruments, Fabrication Enterprises, Inc., White Plains, NY) (Figure 1) and a digital spirometer (SP10, Contec Medical, China) (Figure 2). The Phonatory Aerodynamic System (PAS) Model 6600 (KayPENTAX Corp, Lincoln Park, NJ) (Figure 3) was used as the pneumotachograph-based system and was also considered a high-cost (eg >$1000) comparative. Windmill spirometer consists of a lightweight hand-held plastic body with an internal resistance screen. Airflow through a mouthpiece moves an analog dial around a measurement window on the face piece of the spirometer. The digital spirometer consists of a hand-held frame with internal metal blades, which provide resistance to airflow. A small internal circuit board provides analog-to-digital conversion of the airflow signal and displays digital measurements on the LCD screen of the device. The PAS consists of a pneumotachograph with line input to a desktop personal computer. Custom software is used to digitize and process the aerodynamic signal for recording, playback, and analysis.

FIGURE 1. Baseline windmill-type spirometer. Baseline Measurement Instruments FE, Inc., White Plains, NY.

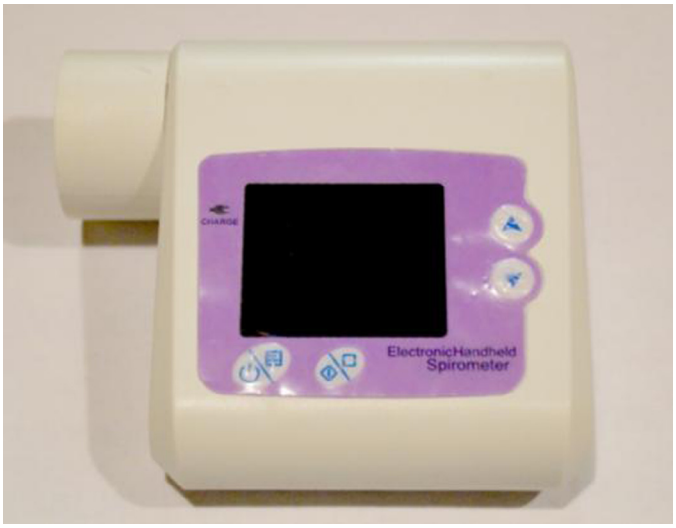

FIGURE 2. SP10 Digital Spirometer, Contec Medical, China.

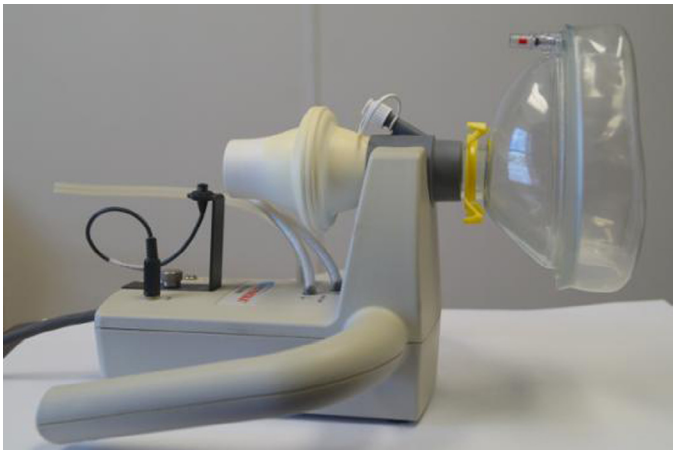

FIGURE 3. Phonatory Aerodynamic System (PAS), Model 6600, KayPENTAX Corp LP, NJ.

Calibration protocol

The calibration of the PAS airflow head was performed after launching the software program. The calibration procedure was completed as described in the PAS Instruction Manual.[31] The facemask was removed from the airflow head, and one end of a cardboard tube was attached to the airflow head while the other end was attached to the 1.0-L calibration syringe. The PAS external module with the attached cardboard tube and syringe were placed on a table for stability. The plunger of the syringe was fully withdrawn and then depressed while monitoring the calibration progress monitor on the computer screen. When an acceptable value as described by the manual was obtained (within 1% of 1.0 L), the calibration was completed.

The windmill and digital spirometer were calibrated with the same 1-L syringe by attaching the mouthpiece of the spirometer to the syringe with a suitable adaptor. The plunger was fully withdrawn and then completely depressed. The measured volume was displayed on the screen of the spirometer and was accepted if it was within 1% of the 1.0-L volume.

Procedure

Three trials of MPT were obtained as the first step of the testing protocol. Each participant was given instructions to take a breath, then sustain the vowel /a/ for as long as possible until he completely runs out of air. The principal investigator manually operated a digital timer to calculate MPT. The participants were given a 1-minute rest period between trials. After completing the MPT task, the participants were tested on the three aerodynamic instruments. The order of instruments was counterbalanced among participants.

When using the hand-held spirometers, participants were required to wear a nose clip on their nares to prevent nasal air escape. The participants were given the same instructions to complete VC measures on all three instruments. They were asked to breathe in maximally when ready, place their mouth around the mouthpiece of the spirometer or in the facemask of the PAS (and, for the PAS, to also press the mask against the face firmly), and blow out all their air until they have nothing left to expire. Three trials of VC were completed on each instrument, with 1-minute rest periods between trials. VC was obtained from the position of the dial on the analog windmill-type spirometer, from the LCD display of the digital spirometer, and from the computer screen *via* software calculation from the VC protocol of the PAS.

Analyses

For calculation of PQ, the VC trial with the largest volume (in milliliters) on each instrument was divided by the longest MPT trial (in seconds) taken at the start of the testing session. Statistical analyses were performed using SPSS 22.0.[32] Two separate one-way analyses of covariance (ANCOVAs) with repeated measures were performed to investigate the main effect of the instruments on VC and PQ, controlling for age as a covariate in the statistical model. *Post hoc* analyses using Fisher least significant difference (LSD) were performed for further investigation of significant differences on the ANCOVA. To investigate the measurement reliability between instruments, a Pearson Product

Moment Correlation was applied to the VC and PQ data from the three different instruments.

RESULTS

The mean age and standard deviation of the recruited participants was 38.40 years and 14.30 years, respectively, with a range of 44 years. Inspection of the data set revealed a positive skew (skewness = 1.07). As this was a substantial skewness, we applied a Kolmogorov-Smirnov test to the age data to test for distribution normality. This test was nonsignificant ($P = 0.077$), indicating that the age distribution of the sample was not significantly different from a normal distribution, and interpreted the skewness as related to the lower sample size of n = 20. Based on these results, we utilized age as a covariate in statistical models.

Mean and standard deviation for the longest MPT trial were 24.75 seconds and 7.87 seconds, respectively, with a range of 16–49 seconds. Mean and standard deviation for VC and PQ across instruments are provided in Table 1. Because age is known to influence both MPT and VC,[12,19–21] an *ad hoc* analysis was applied to assess these respective relationships using bivariate correlations. The relationship between age and MPT was negative and low, with r = –0.24 suggesting that age explained less than 6% of the variability ($R^2 = 0.058$) in MPT measurements. The relationship between age and VC was negative and low-to-moderate with r = –0.41, but indicated that age explained only 17% of the variability ($R^2 = 0.17$) in VC measurements.

Figures 4A–C illustrate scatterplots of VC data comparing the three instruments, along with coefficients of determination (r^2) and regression equations. Inspection of these graphs indicates strong positive relationships among the three instruments, with the windmill spirometer slightly overestimating VC from the PAS, and the digital spirometer underestimating VC from the PAS. The measurements obtained from the pneumotachograph-based PAS were considered highly precise based on calibration values, and with this in mind, Figure 4A–B shows that absolute error associated with both low-cost hand-held spirometers must be taken into account when interpreting measurements. The regression equations in Figure 4A–B can be used as a means of correcting measurements obtained from the hand-held spirometers used in this study.

A one-way ANCOVA applied to the VC data indicated a significant main effect for instrument (F = 3.89, df = 2, 56, $P = 0.008$). As predicted, age also significantly affected the VC measurements (F = 21.82, df = 1,56, $P < 0.001$) supporting its control as a covariate in the analysis. Fisher LSD indicated a significant difference between the windmill spirometer and digital spirometer instruments ($P = 0.011$) and, digital spirometer and PAS ($P = 0.004$). Difference between windmill spirometer and PAS was not significant for VC ($P = 0.745$). A one-way ANCOVA applied to the PQ data was nonsignificant (F = 1.86, df = 2, 56, $P = 0.164$), and the effect of the age covariate was also nonsignificant (F = 0.325, df = 1,56, $P = 0.325$). Thus, results from the ANCOVAs indicated statistically significant differences in VC measures as a function of spirometry instrumentation, but not a significant difference based on subsequent PQ measures.

The primary research question (measurement reliability) was addressed using a Pearson correlation. From this analysis, the correlation coefficient was used as an indicator of parallel forms reliability between the instrument types. Results of this analysis are provided in Table 2. All correlations were significant at the $P < 0.01$ level (two tailed), with strong positive correlations observed both for VC and for PQ between all three instruments (correlation coefficients ranged from r = 0.863 to 0.935). The strong relationships in measurements of VC obtained from the different instruments approached values found by Rau and Beckett, as did the strong relationships found in measures of PQ derived from the different systems.[9]

Collectively, the results from the ANCOVAs and Pearson correlations suggested that while measurement sensitivity for VC was influenced by instrument type (specifically, measures obtained from the hand-held digital spirometer were significantly lower than the windmill spirometer and PAS instruments), the derived measures of PQ were not. Additionally, the relationships between VC and PQ measures derived from the hand-held windmill spirometer and digital spirometer were highly reliable (as indicated by the strong relationships assessed *via* correlational analyses) in comparison with the pneumotachograph-based system. Although the VC measures were lower when obtained from the digital spirometer, the correlational analyses revealed that those measurements were highly reliable compared with the other two instruments (eg, a change in measures from the windmill spirometer or PAS instrument would be reflected in a similar change in the digital spirometer).

TABLE 1.
Means, Standard Deviations (SD), Ranges, and Standard Errors (SE) for VC (mL) and PQ (mL/second)

Measure		Baseline Windmill	SP10	PAS
Vital capacity (mL)	Mean	4968	4252	4759
	SD	1063.5	881.0	1048.9
	Range	3450	2930	3740
	SE	0.23	0.20	0.23
Phonation quotient (mL/second)	Mean	214.38	183.76	220.05
	SD	64.21	54.07	71.94
	Range	243.11	203.58	260.9
	SE	14.36	12.09	16.08

TABLE 2.
Intercorrelation Matrix for VC and PQ

		Baseline Windmill	SP10	PAS
Vital capacity	Baseline Windmill	1.00	0.872	0.863
	SP10		1.00	0.887
	PAS			1.00
Phonation quotient	Baseline Windmill	1.00	0.909	0.935
	SP10		1.00	0.955
	PAS			1.00

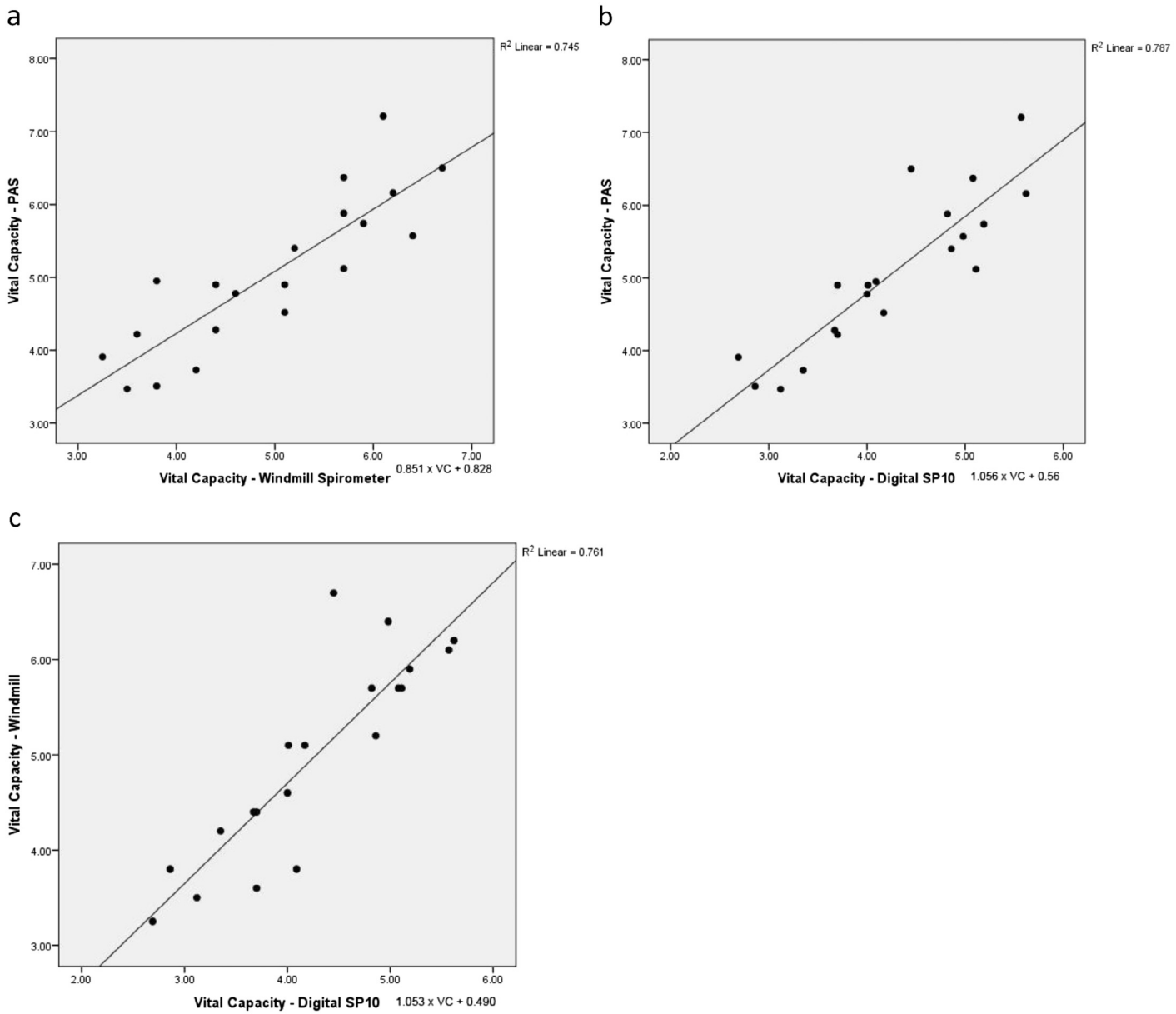

FIGURE 4. Scatterplots, coefficients of determination (r^2), and regression equations for VC measurements illustrating relationships between each instrument type.

DISCUSSION

The purpose of this study was to investigate the measurement reliability between three instrument systems (parallel forms reliability) used to measure VC and derived measures of PQ. An analog hand-held windmill spirometer, a digital hand-held spirometer, and a pneumotachograph-based instrument (PAS) were the instruments of choice. The findings revealed very strong and statistically significant relationships between measures of VC, and even stronger and significant relationships between derived measures of PQ. Although measurement precision of VC was influenced by instrument type (significantly lower measures of VC obtained from the digital spirometer), the direction of measurement change from each instrument was strongly related, as indicated by the large correlation coefficients, suggesting very good parallel forms reliability among the three aerodynamic instruments. Instrument type did not have an effect on derived measures of PQ, providing evidence to support the use of the windmill spirometer, digital spirometer, or PAS for measurements of VC and PQ.

The covariate effect of age on VC measures but not PQ was due to MPT trends, which are also part of the formula from which PQ calculations are derived. We suspected that age did not significantly influence MPT in the tested sample. As noted in the Results, the correlation of determination (R^2) for the age × MPT analysis was very low at 0.058. Although the distribution of age in the sample was positively skewed, it did not significantly differ from a normal distribution. However, our sample size was low (n = 20), which likely reduced the statistically sensitivity to age. Previous studies have found that MPT from elderly speakers (eg, >65 years) is different from that of younger speakers,[33] and it

is likely that the sample size in our current study was not large enough for age to influence the measures of MPT. Future studies will need to further test how age impacts the measures of PQ derived from different instruments as the elderly represent a significant percentage of treatment-seeking individuals.

Pneumotachograph-based aerodynamic systems hold some advantages over hand-held spirometers, which use flow tubes placed in the mouth. These include linearity in the output within the testing range, easy calibration methods, relatively sturdy construction, and greater sensitivity to direction of airflow.[30,34,35] Speech pathologists working in outpatient clinics, hospitals, nursing homes, home health, or schools may not have access to these systems or have the resources to purchase them. They are thus limited in their ability to assess the interaction of the respiratory and phonatory mechanisms during voice evaluations. The results of this study suggest that alternative and inexpensive hand-held spirometers provide reliable measures from which PQ calculations are derived when compared with PQ derived from measures obtained *via* a pneumotachograph system. These results are also supported by the earlier research of Rau and Beckett, and indicate that lower cost reliable options are available for the measurement of PQ as part of laryngeal function analysis during diagnostic evaluations.[9]

Limitations

A number of methodological limitations require caution in generalizing the results of this study. As noted earlier, the study sample included only men who ranged between young adult and middle age. Our next step is to investigate similar research questions among women across age groups. This study did not include a disordered population, but based on results, it can be hypothesized that a decrease in VC and hence PQ would be consistent across instruments. However, this will need to be tested in future studies that include speakers with dysphonia. The results obtained on laryngeal function tests are subject to the instructions provided for the task. Although instructions were controlled in this investigation, future studies should test the reliability of measures across instruments and examiners. Only two hand-held spirometers currently available in the market have been compared with one commonly used pneumotachograph-based system in this study. As such, results of this study are specific to the instrumentation utilized, and at this point, we cannot extrapolate to other aerodynamic systems. It should also be noted that for aerodynamic assessments that include measures of subglottal pressure and laryngeal resistance, a pneumotachograph cannot be replaced by a spirometer.

CONCLUSIONS

This study compared measures of PQ, and VC from which PQ was derived, across three aerodynamic instruments. The results revealed strong parallel forms reliability in measures of PQ and VC among the three instrument systems, although measurement precision was different when comparing a hand-held digital spirometer to two other instrument types. The portability and economy of using a hand-held spirometer with good accuracy and reliability for gross aerodynamic measurements holds clinical utility for speech pathologists who do not have the resources for expensive pneumotachograph-based instruments. Although hand-held spirometers do not allow for measurements related to air pressure, and measurement precision is likely greater with the pneumotachograph-based system used in this study, the strong relationships found in this study between PQ and VC among the three instrument types support the use of hand-held spirometers for acquiring measurements of PQ as part of laryngeal function analysis. Additional studies are needed to further test the measurement reliability and accuracy of these instruments while controlling for additional factors that could potentially influence PQ calculations.

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