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A Rapid, Handheld Device to Assess Respiratory Resistance: Clinical and Normative Evidence

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A Rapid, Handheld Device to Assess Respiratory Resistance: Clinical and Normative Evidence

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ABSTRACT Introduction: Following reports of respiratory symptoms among service members returning from deployment to South West Asia (SWA), an expert panel recommended pre-deployment spirometry be used to assess disease burden. Unfortunately, testing with spirometry is high cost and time-consuming. The airflow perturbation device (APD) is a handheld monitor that rapidly measures respiratory resistance (APD-R_r) and has promising but limited clinical data. Its speed and portability make it ideally suited for large volume pre-deployment screening. We conducted a pilot study to assess APD performance characteristics and develop normative values. Materials and Methods: We prospectively enrolled subjects and derived reference equations for the APD from those without respiratory symptoms, pulmonary disease, or tobacco exposure. APD testing was conducted by medical technicians who received a 10-min in-service on its use. A subset of subjects performed spirometry and impulse oscillometry (iOS), administered by trained respiratory therapists. APD measures were compared with spirometry and iOS. Results: The total study population included 199 subjects (55.8% males, body mass index 27.7 ± 6.0 kg/m^2, age 49.9 ± 18.7 yr). Across the three APD trials, mean inspiratory (APD-R_i), expiratory (APD-R_e), and average (APD-R_{avg}) resistances were 3.30 ± 1.0, 3.69 ± 1.2, and 3.50 ± 1.1 cm H_2O/L/s. Reference equations were derived from 142 clinically normal volunteers. Height, weight, and body mass index were independently associated with APD-R_i, APD-R_e, and APD-R_{avg} and were combined with age and gender in linear regression models. APD-R_i, APD-R_e, and APD-R_{avg} were significantly inversely correlated with FEV_1 (r = −0.39 to −0.42), FVC (r = −0.37 to −0.40), and $FEF_{25–75}$ (r = −0.31 to −0.35) and positively correlated with R5 (r = 0.61–0.62), R20 (r = 0.50–0.52), X5 (r = −0.57 to −0.59), and FRES (r = 0.42–0.43). Bland–Altman plots showed that the APD-R_r closely approximates iOS when resistance is normal. Conclusion: Rapid testing was achieved with minimal training required, and reference equations were constructed. APD-R_r correlated moderately with iOS and weakly with spirometry. More testing is required to determine whether the APD has value for pre- and post-deployment respiratory assessment.

INTRODUCTION

In response to reports of respiratory disease following duty in South West Asia (SWA) – Iraq, Afghanistan, and Kuwait – a working group convened and recommended screening spirometry before deployment for all service members.[1] Cost estimates put the total price for screening all who deploy in the tens of millions of dollars.[2] The majority of this spending is devoted to hiring and training respiratory therapists to administer testing. Spirometry requires trained professionals to coach subjects to perform the necessary maneuvers that make the testing valid. Cost estimates do not factor in productivity loss from extending pre-deployment processing to include spirometry.

Screening with other existing tests, such as impulse oscillometry (iOS) or body plethysmography, also has limitations. Both require large, fixed equipment and trained personnel and take 20–30 min to complete the requisite repeated trials.[3,4] Ideally, any lung function test employed to screen large numbers of personnel should be portable, low cost, and efficient.

The airflow perturbation device (APD) is an investigational, handheld monitor that uses airflow perturbation, similar in physical design to an airflow-interrupter technique,[5–7] to measure respiratory resistance (R_r).[8–10] However, unlike the interrupter technique, there is no time lag between perturbed and unperturbed breathing states. The APD is small and portable, and each trial takes only 1 min to complete.[11] Measurements are made during tidal breathing, so little coaching is required and no specific training is needed to administer the test. The APD self-calibrates each time it is turned on and has proven to provide reproducible results with low variation.[12] These features make the APD ideal for assessing large numbers of subjects onsite, at low cost.

Animal data and studies with small sample size show that the APD appropriately measures artificial respiratory loads[13–15]

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and correlates with iOS[16] and esophageal manometry.[13] Populations tested in larger studies are poorly described though,[17,18] and little data exist on correlation with spirometry or iOS in health or disease.[19,20] Normal ranges for resistance measured using the APD (APD-R_r) have not been established. Despite increasing interest in using the APD in research, occupational health, and clinical practice,[21] more patient data are needed.

To aid clinical interpretation, we conducted a pilot study and recruited subjects to perform three trials using the APD. All subjects were carefully screened for the presence of respiratory symptoms, respiratory disease, and tobacco exposure. APD-R_r data from those free from symptoms, disease, or tobacco exposure were used to construct regression equations to define normal ranges. A subset of those with and without symptoms, disease, or tobacco exposure was studied with spirometry and iOS. We compared the APD with established pulmonary function tests (spirometry and iOS) to identify which aspects of respiratory physiology are captured using this device (APD). *In vitro* and animal data suggest that the APD reflects resistance of the entire respiratory system, to include the chest wall, but correlations with measures of large and small airways, resistance, and elastance in healthy patients and those with disease have not yet been performed.

METHODS

All participants were prospectively enrolled at the Walter Reed National Military Medical Center (WRNMMC) Pulmonary Diseases Clinic (PDC) between April 2013 and August 2014. All subjects were screened for respiratory disease, tobacco exposure (past, present, or secondhand smoke), or symptoms (cough, sputum production, or any dyspnea). This screening procedure was modeled after the exclusion criteria for the NHANES III data set.[22] Those who screened negative in all three categories and positive for at least one are labeled "normal" and "abnormal," respectively. Spirometry and iOS were encouraged but not required. Data from normal subjects were used to derive reference equations, but the comparison of APD-R_r to spirometry and iOS included normal and abnormal subjects. All participants were ≥ 18 yr old and provided informed consent according to the rules and regulations of the Department of Research Programs and Institutional Review Board at WRNMMC (*Airway Perturbation Device (APD) for the evaluation pulmonary and sleep disorders* [study no.: 383145–7]).

APD Measurements

All subjects had APD testing performed by a medical technician (Navy Corpsman or Army Medic) before their appointment (patients) and/or additional lung function testing. The staff administering the test had no formal respiratory training, but they did receive an informal, 10-min instruction on using the APD. Testing was performed using a rigid, oval mouthpiece with the subject in the sitting position, wearing a nose clip and using the hands to support the cheeks. Because the soft tissue of the cheeks is compressible, lack of support could lead to pressure dissipation proximal to the device and underestimation of R_r,[5] although differences between the APD and the interrupter technique make cheek compression less important for the APD. Three trials were performed, each lasting 1 min. At the end of each minute, the APD provides summary measurements for average inspiratory (APD-R_i) and expiratory resistance (APD-R_e) during tidal breathing, along with resistance averaged across both phases of respiration (APD-R_{avg}).[11,12] Average APD-R_i, APD-R_e, and APD-R_{avg} were recorded after each of the three trials. Approximately, 1 min was allowed between trials. The APD was turned off then on for re-calibration, before being used on each subject.

Impulse Oscillometry

Measurements of oscillatory impedance were obtained using system software (CareFusion MasterScreen IOS; San Diego, CA). All iOS was administered by trained, certified respiratory therapists. Before testing, participants breathed quietly for at least 30 s. For measurement of respiratory resistance, participants were asked to breathe quietly for 20–90 s using a rigid oval mouthpiece (the same mouthpiece used for APD measurements) while supporting both cheeks.[23] Participants completed three to five replicate breathing trials in accordance with published guidelines.[3] Measurements of R5 (total respiratory resistance), R20 (proximal resistance), X5 (distal capacitive reactance), Fres (resonant frequency), and AX (reactance area) were recorded. iOS reference ranges from previously published data were used to calculate percent-predicted values for R5 and R20.[24]

Spirometry

Participants performed a baseline spirometry examination using a VMax spirometer (CareFusion, Yorba Linda, CA). All spirometry testing was administered by trained, certified respiratory therapists. They underwent a standard forced expiratory maneuver from maximal inhalation to maximal exhalation to record the forced expiratory volume in 1 s (FEV_1) and forced vital capacity (FVC) in accordance with American Thoracic Society standards for spirometry.[25] We also included the forced expiratory volume in 3 s (FEV_3)/FVC in our analysis. The FEV_3/FVC is a metric that is easily measured on standard spirometry and can effectively identify early obstruction, particularly in patients with otherwise normal spirometry.[26,27] To calculate percent-predicted values, reference equations from NHANES III[22] and previously published data[28] were used for standard spirometry and FEV_3/FVC, respectively.

Statistics

Data are presented using mean and standard deviation or median with intraquartile range for normally and non-normally distributed variables, respectively. The intra-class coefficient was calculated to demonstrate test–retest reliability. Correlations were established using the Pearson correlation coefficient, and agreement between APD and iOS resistance measurements was assessed according to Bland–Altman plots.[29]

The independent-samples *t*-test and analysis of variance were used to detect differences in means between two or greater than two variables, respectively. Bonferroni correction was used to adjust for multiple comparisons.

Reference equations were established using linear regression. Variables were entered into the model based on significant association with APD measurements ($p < 0.05$) or due to association with lung function testing based on literature review. Backward stepwise regression was used to develop the model. Independent variables were dropped out until a parsimonious model was obtained.

RESULTS

A total of 249 subjects were approached for enrollment (Fig. 1). Baseline demographics for all 199 participants, separated by normal (n = 142) versus abnormal (n = 57), are listed in Table I. The intra-class coefficient for APD-R_i (0.89; $p <$ 0.001), APD-R_e (0.87; $p < 0.001$), and APD-R_{avg} (0.89; $p <$ 0.001) across the three trials showed excellent, statistically significant reproducibility.

Among normal subjects, height, weight, and body mass index (BMI) were independently associated with APD-R_r measurements, whereas race, age, and sex were not. Despite the absence of association, we chose to produce separate equations for each sex to maintain consistency with the existing literature on respiratory function measurements.[25,30,31] Reference equations with associated standard error of the estimate (SEE) and square of the correlation coefficient (r^2) values are in Table II. For males, average APD-R_i, APD-R_e, and APD-R_{avg} were best predicted when age, BMI, and height were included in the equation. Height and weight provided the best model for females. When modeling the entire sample of clinically normal volunteers (n = 142) using age, BMI, and height as covariates, the r^2 values (0.22–0.25) approximated those seen for females.

There were 113 (89 normal and 24 abnormal) and 40 (33 normal and 7 abnormal) subjects who had spirometry and iOS, respectively, in addition to their APD testing. Table III shows lung function testing results for normal and abnormal subjects. Analysis of all 113 subjects with spirometry testing showed that APD-R_i, APD-R_e, and APD-R_{avg} were significantly, inversely correlated with FEV_1 (r = −0.39 to −0.42; $p <$ 0.001), FVC (r = −0.37 to −0.40; $p < 0.001$), FEV_3 (r = −0.40 to −0.45; $p < 0.001$), and FEF_{25-75} (r = −0.31 to −0.35; p < 0.001–0.001). Analysis of all 40 subjects with iOS testing showed that APD values were correlated with R5 (r = 0.61–0.62; $p < 0.001$), R20 (r = 0.50–0.52; $p = 0.001$), X5 (r = −0.57 to −0.59; $p < 0.001$), and FRES (r = 0.42–0.43; $p = 0.001$). APD values did not correlate with AX (r = 0.07–0.20; $p = 0.69$).

Bland–Altman plots comparing average APD-R_i, APD-R_e, and APD-R_{avg} to R5 (Fig. 2A–C) and R20 (Fig. 3A–C) showed that all APD values underestimate R5 (−0.58 to −0.24 cm H_20/L/s). APD-R_i slightly underestimates R20 (−0.01 cm H_20/L/s) and APD-R_e and APD-R_{avg} overestimate R20 by 0.16 H_20/L/s and 0.34 H_20/L/s, respectively. Visualization of plots shows that APD and iOS values are closer at normal resistance ranges (approximately 2.0–4.0 H_20/L/s) than at abnormally high or low resistance.

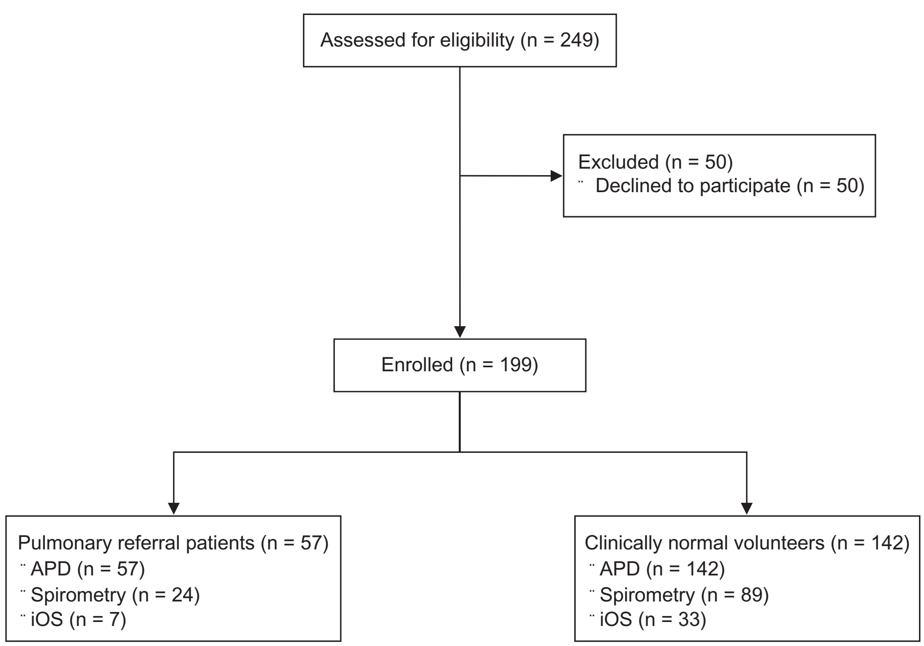

FIGURE 1. CONSORT flow diagram.

TABLE I. Demographic Data

	Abnormal (n = 57)	**Normal** (N = 142)
Age	52.4 ± 15.5	48.8 ± 9.7
Height (in.)	67.0 ± 3.4	67.7 ± 3.7
Weight (lb)	190.4 ± 45.7	176 ± 38.5
BMI (kg/m^2)	29.9 ± 7.9	26.9 ± 5.0
Male	31 (54.4%)	79 (55.6%)
Race		
Caucasian	28 (50.0%)	87 (61.3%)
African American	16 (28.6%)	43 (30.3%)
Other	13 (21.4%)	12 (9.4%)
Tobacco use	22 (42.3%)	N/A
Symptoms		
Dyspnea	10 (17.5%)	N/A
Cough	24 (42.1%)	N/A

BMI, body mass index; kg, kilograms; m, meters.

DISCUSSION

Any test used for pre- or post-deployment respiratory assessment should ideally be portable, low cost, and efficient. The APD would theoretically meet all criteria, given it is effort independent, easy to administer, and requires approximately 5 min for three trials. Because no special maneuvers are needed for valid testing, those who administer the test do not need special respiratory training. Clinical data are limited though, and our goal is to aid interpretation of output by establishing normal ranges and performance characteristics in a well-described population. We developed reference equations for normal and further defined its relationship with commonly used pulmonary tests.

The reference equations we developed include age, height, weight, and BMI. All these variables are included in equations used to model normal ranges for resistance determined

TABLE II. Reference Equations for APD Measurements

	Males					
	Intercept	a	b	c	SEE	r^2
APD-R_i	7.38384	−0.091025	0.0071728	0.059582	0.899	0.15
APD-R_e	7.059246	−0.085366	0.0064808	0.0708428	1.006	0.13
APD-R_{avg}	8.082214	−0.099417	0.007256	0.0624668	0.925	0.16
	Females					
	Intercept	a	d	SEE	r^2	
APD-R_i	9.302704	−0.113718	0.010138	0.734	0.26	
APD-R_e	11.25908	−0.141253	0.0113148	0.891	0.25	
APD-R_{avg}	10.61463	−0.133448	0.0110009	0.766	0.3	

APD-R_i, inspiratory resistance with APD; APD-R_e, expiratory resistance with APD; APD-R_{avg}, average respiratory resistance with APD.
a, height (in.); b, age (yr); c, BMI (kg/m^2); d, weight (lb).
SEE, standard error of the estimate; r^2, square of the correlation coefficient.

TABLE III. Lung Function Testing

	Abnormal	Normal	p-Value*
Spirometry (L [percent predicted])[a]			
FVC	3.7 ± 1.1 (95.2 ± 23.0%)	3.6 ± 1.2 (86.9 ± 18.8%)	0.83
FEV_1	2.6 ± 0.9 (87.3 ± 23.8%)	2.6 ± 1.1 (86.6 ± 21.0%)	0.98
FEV_1/FVC	72.6 ± 10.9% (92.4 ± 14.3%)	72.9 ± 11.7% (92.1 ± 14.2%)	0.91
$FEF_{25–75\%}$	2.2 ± 1.2 (79.2 ± 41.6%)	2.3 ± 1.3 (82.6 ± 45.3%)	0.79
FEV_3/FVC	88.6 ± 7.2% (96.4 ± 7.8%)	89.5 ± 7.7% (97.0 ± 7.6%)	0.59
Impulse oscillometry (cm H_20/L/s [percent predicted])[b]			
R5	4.9 ± 2.2 (149.0 ± 67.0)	3.4 ± 1.8 (123.1 ± 66.3)	0.06
R20	3.9 ± 1.5 (118.9 ± 52.8)	2.9 ± 1.6 (98.9 ± 61.2)	0.16
X5	−1.8 ± 1.0	−1.3 ± 0.8	0.12
AX	19.5 ± 8.3	13.5 ± 10.4	0.17
APD (cm H_20/L/s)[c]			
APD-R_i	3.1 ± 1.1	3.2 ± 0.9	0.15
APD-R_e	4.0 ± 1.4	3.6 ± 1.1	0.048
APD-R_{avg}	3.7 ± 1.2	3.4 ± 1.0	0.08

[a]Patients (n = 27), clinically normal volunteers (n = 89).
[b]Patients (n = 7), clinically normal volunteers (n = 33).
[c]Patients (n = 57), clinically normal volunteers (n = 142).
*$p < 0.004$ considered significant after correction for multiple comparisons.
$FEF_{25–75\%}$, forced expiratory flow between 25% and 75% of the FVC; FEV_1, forced expiratory volume in 1 s; FEV_1/FVC, ratio of the forced expiratory volume in 1 s to the forced vital capacity; FEV_3/FVC, ratio of the forced expiratory volume in 3 s to the forced vital capacity; FVC, forced vital capacity; R5, total (all airways and chest wall) airway resistance as measured by IO; R20, central airway resistance as measured by IO; X5, reactance; AX, resonant frequency; APD-R_i, inspiratory resistance with APD; APD-R_e, expiratory resistance with APD; APD-R_{avg}, average respiratory resistance with APD.

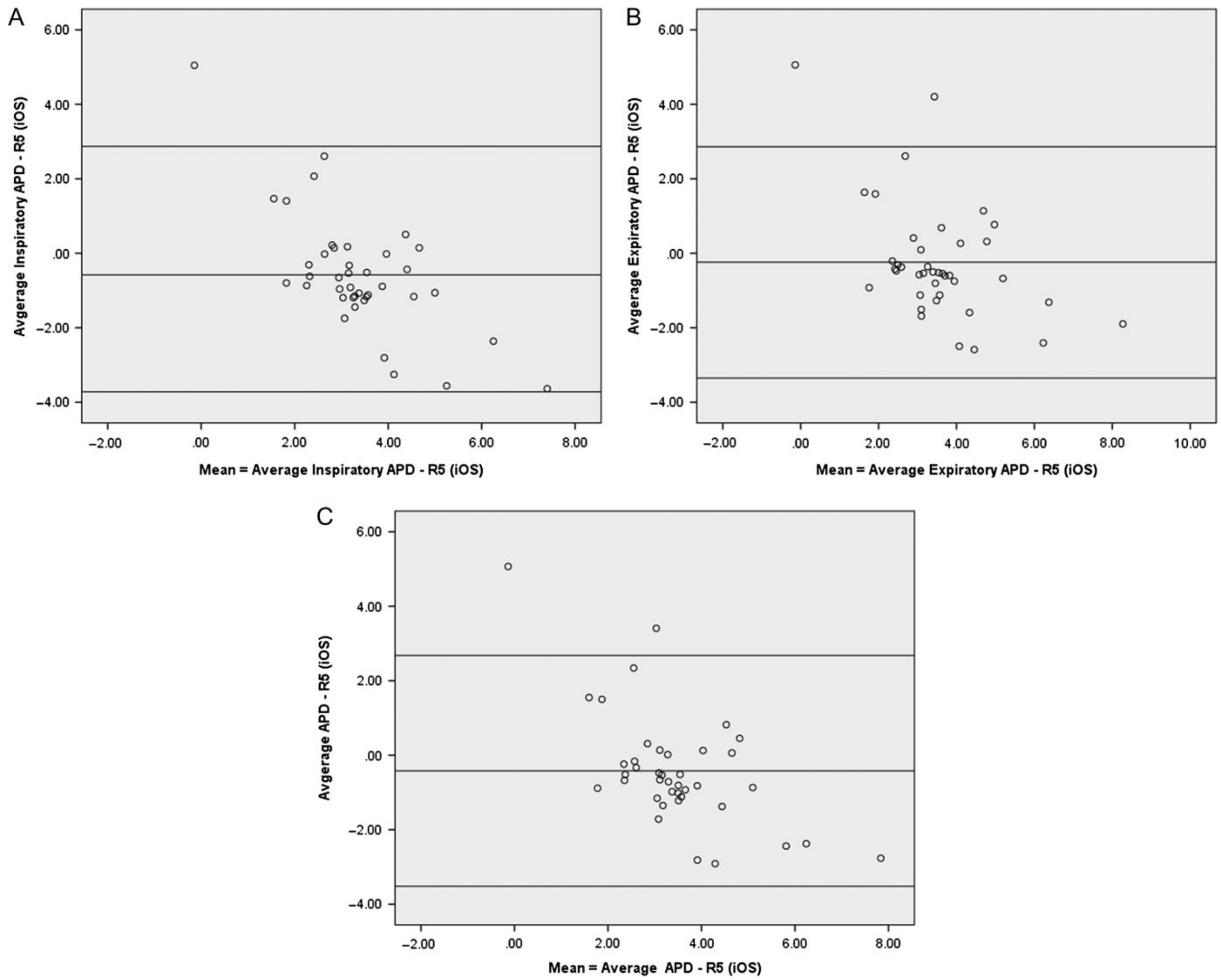

FIGURE 2. (A) The *x*-axis lists average of mean resistance value for inspiratory APD (APDi) plus R5 measured using impulse oscillometry (iOS). The *y*-axis is the difference between APDi and R5 from iOS. Top horizontal line is mean difference between APDi and R5 + 1.96 * standard deviation (SD), or upper limit of the 95% confidence interval (CI), middle horizontal line is mean difference between APDi and R5, and lower horizontal line is mean difference between APDi and R5 − 1.96 * SD, or lower limit of the 95% CI. Visual inspection shows that APDi systematically underestimates R5 (mean difference <0) and agreement between measures is better when resistance is close to normal (2.5–3.5 cm H20/L/s) than when it is high (>4.0 cm H20/L/s) or low (<2.5 cm H20/L/s). Only one data point is outside the 95% CI. (B) The *x*-axis lists average of mean resistance value for expiratory APD (APDe) plus R5 measured using impulse oscillometry (iOS). The *y*-axis is the difference between APDe and R5 from iOS. Top horizontal line is mean difference between APDe and R5 + 1.96 * standard deviation (SD), or upper limit of the 95% confidence interval (CI), middle horizontal line is mean difference between APDe and R5, and lower horizontal line is mean difference between APDe and R5 − 1.96 * SD, or lower limit of the 95% CI. Visual inspection shows that APDe systematically underestimates R5 (mean difference <0) and agreement between measures is slightly better when resistance is close to normal (2.0–4.0 cm H20/L/s) than when it is high (>4.0 cm H20/L/s) or low (<2.0 cm H20/L/s). Only two data points lie outside the 95% CI. (C) The *x*-axis lists average of mean resistance value for average APD (APDavg) plus R5 measured using impulse oscillometry (iOS). The *y*-axis is the difference between APDavg and R5 from iOS. Top horizontal line is mean difference between APDavg and R5 + 1.96 * standard deviation (SD), or upper limit of the 95% confidence interval (CI), middle horizontal line is mean difference between APDavg and R5, and lower horizontal line is mean difference between APDavg and R5 − 1.96 * SD, or lower limit of the 95% CI. Visual inspection shows that APDavg systematically underestimates R5 (mean difference <0) and agreement between measures is slightly better when resistance is close to normal (2.0–4.0 cm H20/L/s) than when it is high (>4.0 cm H20/L/s) or low (<2.0 cm H20/L/s). Only two data points lie outside the 95% CI.

via iOS.[3,24,32,33] Although we factored age and sex into our models, in contrast to prior APD and iOS studies, they did not show a significant relationship with resistance and their inclusion did not meaningfully affect our models.[3,17,24,32,33] The equations for females explained more of the variability in APD-R_r than did those for males – 25–30% versus 13–16%. Most reference equations for iOS do not provide r^2 values, so it is difficult to know whether our models are comparable in performance.[3,24]

There are several caveats to note when comparing different lung function tests. First, resistance measures are not expected to correlate closely with FEV_1, FEV_3, FVC, FEV_1/FVC, or

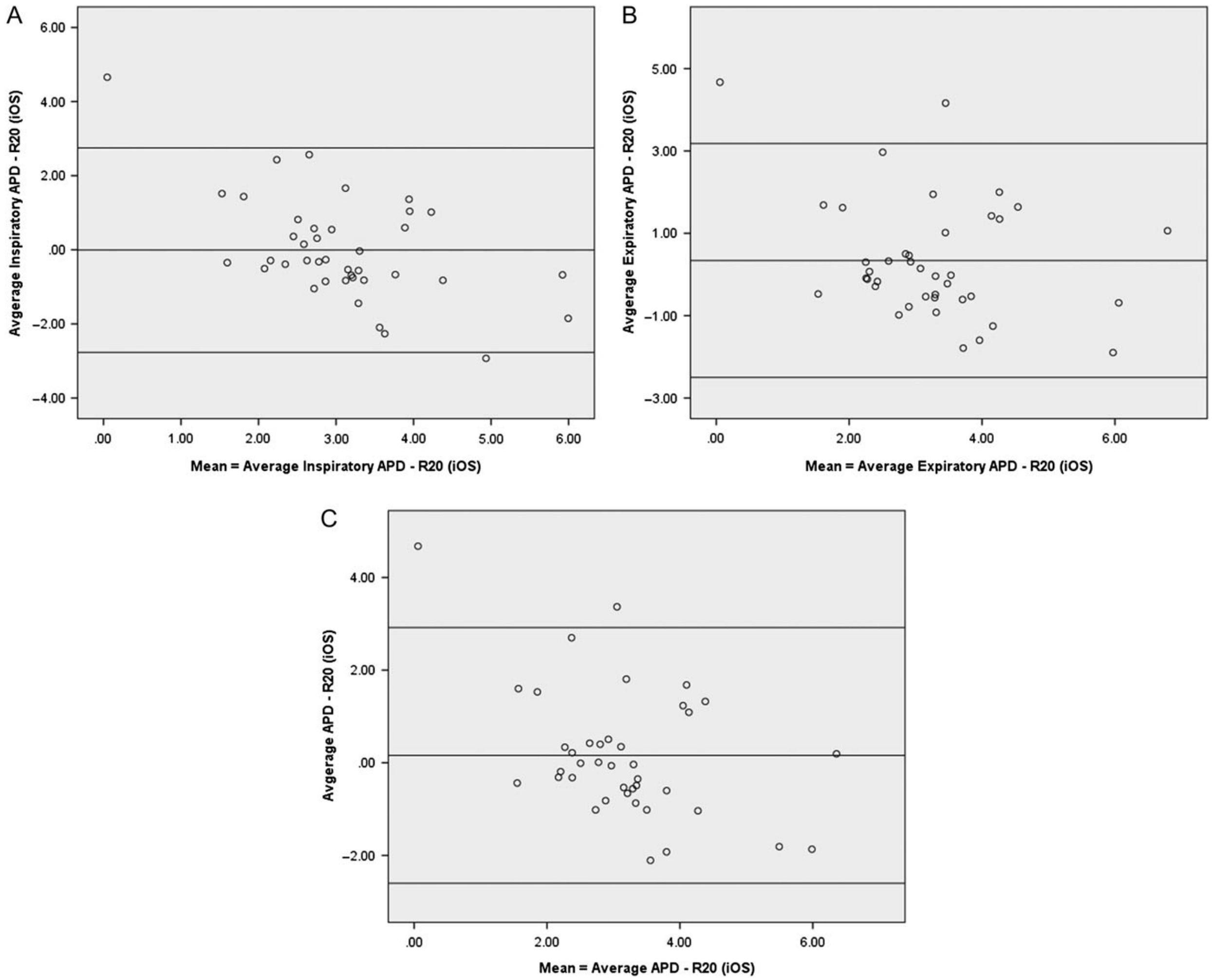

FIGURE 3. (A) The *x*-axis lists average of mean resistance value for average APD (APDi) plus R20 measured using impulse oscillometry (iOS). The *y*-axis is the difference between APDi and R20 from iOS. Top horizontal line is mean difference between APDi and R20 + 1.96 * standard deviation (SD), or upper limit of the 95% confidence interval (CI), middle horizontal line is mean difference between APDi and R20, and lower horizontal line is mean difference between APDi and R5 − 1.96 * SD, or lower limit of the 95% CI. Only two data points lie outside the 95% CI. (B) The *x*-axis lists average of mean resistance value for expiratory APD (APDe) plus R20 measured using impulse oscillometry (iOS). The *y*-axis is the difference between APDe and R20 from iOS. Top horizontal line is mean difference between APDe and R20 + 1.96 * standard deviation (SD), or upper limit of the 95% confidence interval (CI), middle horizontal line is mean difference between APDe and R20, and lower horizontal line is mean difference between APDe and R20 − 1.96 * SD, or lower limit of the 95% CI. Visual inspection shows that APDe systematically overestimates R20 (mean difference >0). Only two data points lie outside the 95% CI. (C) The *x*-axis lists average of mean resistance value for average APD (APDavg) plus R20 measured using impulse oscillometry (iOS). The *y*-axis is the difference between APDavg and R20 from iOS. Top horizontal line is mean difference between APDavg and R20 + 1.96 * standard deviation (SD), or upper limit of the 95% confidence interval (CI), middle horizontal line is mean difference between APDavg and R20, and lower horizontal line is mean difference between APDavg and R20 − 1.96 * SD, or lower limit of the 95% CI. Visual inspection shows that APDavg systematically overestimates R20 (mean difference >0) and agreement between measures is slightly better when resistance is close to normal (2.0–4.0 cm H20/L/s) than when it is high (>4.0 cm H20/L/s) or low (<2.0 cm H20/L/s). Only two data points lie outside the 95% CI.

FEV_3/FVC because spirometry reflects airway resistance indirectly via flow and volume.[18,34] Second, resistance estimates vary by measurement technique.[5,10,21,35] The APD uses a perturbation method to estimate resistance during inspiration and expiration and then provides an average. iOS infers resistance at specific points within the respiratory system, in phase with the respiratory cycle, using sound waves at varying frequencies.[3,36] Therefore, we did not expect perfect correlation or agreement between APD-R_r and iOS or spirometry.

Our goal was to define the relationship between APD-R_r, iOS, and spirometry to provide a frame of reference for interpretation. Our data show that APD-R_r underestimates R5 by 0.24–0.58 (Fig. 2A–C) cm$H_2$0/L/s and APD-R_i closely approximates R20 (Fig. 3A). On average, APD-R_r correlates well with R5 and R20 when resistance is normal (roughly 2.0–4.0 cm

$H_2$0/L/s) but tends to underestimate iOS when it is elevated (Figs 2A–C and 3A–C). The iOS technique does not separate respiratory resistance by breathing phase. Among the 113 subjects who had spirometry, APD-R_r correlated best with FEV_3. FEV_3 identifies late expiratory obstruction and is used as a surrogate for small airway disease or reduced elasticity.[28,37]

Service members deployed to South West Asia frequently report respiratory complaints during or after their tour,[1,38–41] and some may be exposed to elevated levels of particulate matter.[42] The Department of Defense is currently investigating the nature and burden of respiratory disease.[43] The APD could theoretically be used to objectively assess respiratory function in all service members, both pre- and post-deployment. The cost in time, training, and workload would be less than with conventional testing. Our data show that the device provides physiologically relevant values when testing is administered by minimally trained staff (Hospital Corpsmen and Army Medics). Further research could determine feasibility and clinical relevance in the pre- and post-deployment setting.

Our study has several limitations. First, our analysis would have benefited from a larger population.[44] Despite this, our equations identify close to 30% of the variability in APD-R_r and such limitations are common to other reference sets.[3,4,30,45] Using the APD in a previous study involving repeated measurements on 50 subjects has shown that there is a natural variation of respiratory resistance values of 10–12% of the mean that occurs among measurements on any particular person.[46] Second, we compared APD-R_r with lung function measurements, not clinical outcomes or disease. Although iOS and spirometry are commonly used to assess lung function, their ability to predict respiratory symptoms or disease is limited. This is particularly true for iOS.[34,47,48] Preliminary data show that the APD identifies upper airway disorders,[19,20] but more studies will be needed to assess whether APD-R_r correlates with specific respiratory processes. Lastly, we do not know the underlying disease process that drove referral to the pulmonary clinic for the subjects in our study. Although this should not impact the validity of our comparisons or the derivation of reference equations for normal, it further limits our ability to extrapolate findings to specific disease processes. We are unable to make definitive comments on race and its effect on APD measures, but such limitations apply to reference values for spirometry and other lung tests as well.[49] Nevertheless, separation of resistance values by breathing phase should be a help to specific disease diagnosis.

In summary, we found that a small, handheld device called the APD provides a reproducible measure of inspiratory, expiratory, and average respiratory resistance. Testing was successfully administered by minimally trained staff, which obviates much of the cost associated with large-scale lung function screening. Reference equations that explain up to 30% of the variability in APD-R_r were derived. Correlation and agreement with iOS, an accepted technique for measuring respiratory resistance is moderate. Agreement is best within normal ranges. Future research is needed to assess APD performance in larger patient populations with common pulmonary diseases to define clinical relevance.

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