Eur Respir J 1997; 10: 690–694
DOI: 10.1183/09031936.97.10030690
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European Respiratory Journal
ISSN 0903 - 1936

Method to produce American Thoracic Society flow-time waveforms using a mechanical pump

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Method to produce American Thoracic Society flow-time waveforms using a mechanical pump. J.L. Hankinson, J.S. Reynolds, M.K. Das, J.O. Viola. ©ERS Journals Ltd 1997.

ABSTRACT: The American Thoracic Society (ATS) recently adopted a new set of 26 standard flow-time waveforms for use in testing both diagnostic and monitoring devices. Some of these waveforms have a higher frequency content than present in the ATS-24 standard volume-time waveforms, which, when produced by a mechanical pump, may result in a pump flow output that is less than the desired flow due to gas compression losses within the pump.

To investigate the effects of gas compression, a mechanical pump was used to generate the necessary flows to test mini-Wright and Assess peak expiratory flow (PEF) meters. Flow output from the pump was measured by two different independent methods, a pneumotachometer and a method based on piston displacement and pressure measured within the pump.

Measuring output flow based on piston displacement and pressure has been validated using a pneumotachometer and mini-Wright PEF meter, and found to accurately measure pump output. This method introduces less resistance (lower back-pressure) and dead space volume than using a pneumotachometer in series with the meter under test. Pump output flow was found to be lower than the desired flow both with the mini-Wright and Assess meters (for waveform No. 26, PEFs 7.1 and 10.9% lower, respectively).

To compensate for losses due to gas compression, we have developed a method of deriving new input waveforms, which, when used to drive a commercially available mechanical pump, accurately and reliably produces the 26 ATS flow-time waveforms, even those with the fastest rise-times.

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Keywords: Peak expiratory flow
spirometer testing
spirometry

Received: February 22 1996
Accepted after revision December 2 1996

Mechanical pumps have been used for several years to routinely test volume spirometers using the American Thoracic Society's (ATS) 24 standard volume-time waveforms [1]. Simulating the forced vital capacity (FVC) manoeuvre with a mechanical pump has proved to be very useful in evaluating spirometers. The success in accurately producing these waveforms is in part due to the relatively low frequency content of the 24 ATS standard volume-time waveforms. Recently, the ATS adopted a set of 26 flow-time waveforms [2], developed by HANKINSON and CRAPO [3], to test portable peak expiratory flow (PEF) meters as well as spirometers. These waveforms are recordings from actual subjects and have a higher frequency content than the standard ATS volume-time waveforms, particularly if compared to volume-time waveform No. 24 (ATS-24), which has been recommended for use in testing PEF meters [4]. PEF is a dynamic parameter that occurs early in the FVC manoeuvre when expiratory flow is changing rapidly. This rapid change in flow is usually quantified as rise-time, or the time required for flow to rise from 10 to 90% of PEF. These 26 ATS flow-time waveforms have rise-times in the range of those observed by PEDERSEN *et al.* [5], median 70 and 88 ms, 5th percentiles 45 and 55 ms for males and females, respectively.

In using scale versions of ATS-24, MILLER *et al.* [6] expressed concern that gas compression within the pump might distort the waveform. To investigate the effects of gas compression, they compared results using a "cusp" waveform with ATS-24 when testing a Vitalograph PEF meter. They found little difference between these two waveforms, suggesting that gas compression was not a major concern. Because the new ATS flow-time waveforms [3] have even faster rise-times than ATS-24, we evaluated the ability of a commercially available mechanical pump to produce these flow-time waveforms accurately. Due to limitations observed in mechanical pumps associated with gas compression, we developed a new method to produce these flow-time waveforms with higher frequency content accurately.

Methods

A commercially available mechanical pump (Pulmonary Waveform Generator System; MH Custom Design, Midvale, UT, USA) driven by a personal computer (PC) was used for all testing. To minimize the loss of energy in conversion from pump cylinder to nozzle, the front plate of the pump was modified by the addition of a slight bevel in the transition between the flat plate and the pump nozzle (bevel radius of curvature greater than 0.14 times the diameter of the nozzle [7]). All signals were acquired using a 0.5 ms sampling interval. Input waveforms were sent to the pump system using a 2 ms sampling interval. A digital encoder was attached to the pump piston to measure piston displacement. In addition, the manufacturer provides a digital encoder signal of "motor counts", which reflects pump piston displacement by measuring the motor shaft rotation. Since the "motor counts" encoder always agreed with the piston displacement encoder, we used only the "motor counts" to determine piston displacement and calculate displacement volume (V_{D}). A pressure transducer (Setra Systems model 239, Acton, MA, USA) was used to measure pressure inside the pump (P_{s}), and a pneumotachometer was placed in-line with the tubing connecting the pump to the PEF meter (fig. 1) to measure the flow output from the pump (V'_{p}). The starting volume within the pump was set to the minimum needed to produce the total displacement volume of the test waveform. The residual dead space in the pump with the piston fully forward (pump empty) was 2.05 L. Therefore, for waveform No. 26 with a FVC of 5.27 L, the starting volume within the pump would be 7.32 L.

To validate that the simulator was producing the desired output flow, the flow output of the pump was measured with a pneumotachometer, a method based on piston displacement and pump back-pressure, and a mini-Wright PEF meter. The pneumotachometer method (V'_{p}) used a Hans-Rudolph pneumotachometer (3-screen model 3813) connected to a pressure transducer (Micro-Switch model 176PC14HD2, Freeport, IL, USA). The frequency response characteristics of the pneumotachometer system were determined using a small cam-driven mechanical pump. The pneumotachometer was found to have a flat frequency response up to 22 Hz, similar to the findings of JACKSON and VINEGAR [8]. The pneumotachometer was calibrated using 35 different constant flows (volume ramps) from 0.4 to 14 $\mathrm{L \cdot s^{-1}}$, in approximately 0.4 $\mathrm{L \cdot s^{-1}}$ increments. The meter to be tested was attached to the waveform generator pump during calibration of the pneumotachometer. The pneumotachometer flow was integrated over the expiratory time of the volume ramp and was compared to the total volume delivered by the pump. The pneumotachometer calibration factor, at each flow rate, was then adjusted to equalize these volumes. This was necessary because the actual flow output from the pump during volume ramps varies slightly due to gas compression; however, the volume delivered should be independent of any gas compression effects.

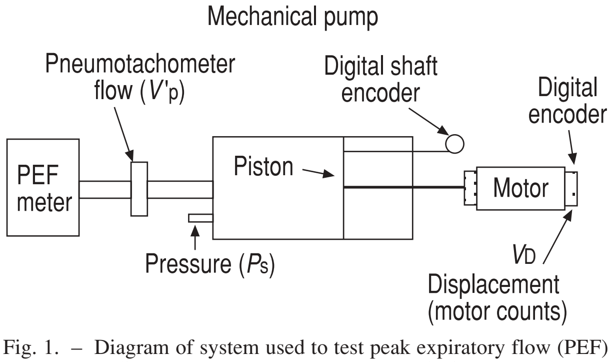

Fig. 1. – Diagram of system used to test peak expiratory flow (PEF) meters. V_{D}: displacement volume; P_{s}: pressure inside the pump.

To determine a particular calibrated flow data-point, linear interpolation was performed between adjacent values of the 35 calibration values. The pneumotachometer calibration was also independently checked using a 7 L syringe injected at different flow rates, and the volumes measured were all within ±1.5% of 7 L. The flow was also checked in approximately 0.5 $\mathrm{L \cdot s^{-1}}$ increments from 1 to 7.5 $\mathrm{L \cdot s^{-1}}$ with a mass flow meter (Teledyne model NALL; Hasting-Raydist, Hampton, VA, USA). The pneumotachometer flow agreed to within 3% with the mass flow meter.

The second method of measuring pump output flow used the digital "motor counts" to estimate the displacement of the pump piston. This displacement was then differentiated to calculate displacement flow (V'_{D}). The back-pressure (P_{s}) inside the pump cylinder was measured (model 239; Setra System, Acton MA; frequency response flat to 2 kHz [8]) to compute the flow lost to gas compression (V'_{c}). Assuming adiabatic compression and an ideal gas, flow lost to gas compression (V'_{c}) (calculated using pump pressure, P_{s}) was combined with displacement flow (V'_{D}) to estimate pump-corrected displacement flow (V'_{s}) The pump-corrected displacement flow closely matched the flow measured with the pneumotachometer.

Because both the pressure and flow signals were subjected to cascaded low-pass anti-aliasing filters with cut-off frequencies of approximately 150 Hz, similar low-pass digital filters were applied to the signal from the digital "motor count" encoder to maintain the phase relationship between displacement and pressure. All three signals (pneumotachometer flow, displacement flow, and pressure) were also filtered with a zero phase shift low-pass filter with a cut-off frequency of 50 Hz. The instantaneous volume lost to gas compression ($V_{\mathrm{c}(t)}$) was calculated [9] using:

$$V_{\mathrm{c}(t)} = V_{\mathrm{s(t)}} \cdot \left[\left(\frac{P_{\mathrm{s(}t\mathrm{)}} + P_{\mathrm{B}}}{P_{\mathrm{B}}} \right)^{\frac{1}{\gamma}} -1.0 \right]$$

where; $V_{\mathrm{s(t)}}$=instantaneous volume within the pump, including connecting tubing; $P_{\mathrm{s}(t)}$=instantaneous back-pressure; P_{B}=barometric pressure; and, γ=ratio of the molar heat capacity at a constant pressure to the molar heat capacity at a constant volume (for air, γ=1.4).

The pump-corrected displacement flow (V'_{s}) was calculated by:

$$V'_{\mathrm{s}} = V'_{\mathrm{D}} - V'_{\mathrm{c}}$$

where:

$$V'_{\mathrm{c}(t)} = \frac{V_{\mathrm{c}(t)} - V_{\mathrm{c(t-1)}}}{0.0005}$$

To determine the extent of gas compression and the variability in these flow measurements, mini-Wright-mechanical scale (Armstrong Medical Industries, Columbus, OH, USA) and Assess (Healthscan Products Inc., Cedar Grove, NJ, USA) PEF meters were tested on three different occasions using the ATS 26 flow-time waveforms.

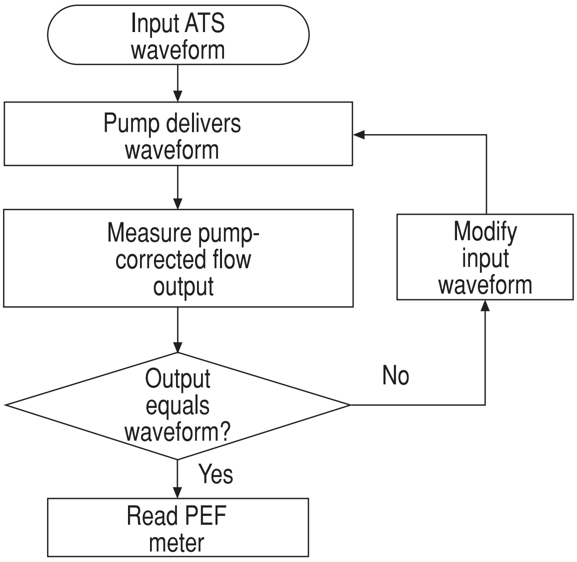

Fig. 2. – Outline of steps used to derive new input waveforms. ATS: American Thoracic Society; PEF: peak expiratory flow.

The mini-Wright PEF meter with the new mechanical scale was used because it has been shown to be superior to the standard mini-Wright scale [6, 10].

For the waveforms with faster rise-times, especially waveforms Nos. 2 and 26, the pump peak flow output was less than the desired target waveform PEF. In addition, the shape of the flow-time curve produced by the mechanical pump, as measured by the pneumotachometer or the corrected displacement flow, did not reflect the desired output accurately. To correct for the mechanical properties of the simulator system (losses due to gas compression), a new input waveform was derived which, when used as an input to the simulator system, resulted in the pump output flow essentially duplicating the target waveform. The steps used to derive the new input waveform are outlined in figure 2. With a PEF meter attached to the pump, the standard flow-time waveform is sent to the mechanical pump, and the resultant output flow is measured using the method based on piston displacement and pump back-pressure described previously. If the waveform is accurately reproduced based on measured flow, then no modification to the input waveform is needed.

If flow loss to gas compression becomes significant and the measured flow and the target flow do not agree within acceptable limits, a new trial input waveform is calculated using the steepest descent method [11], and this new waveform is injected into the PEF meter. These steps are repeated until output flow matches the target flow-time waveform, especially near PEF. Typically, 10–20 iterations were needed to converge to the target waveform flows.

Because the mechanical pump must be filled with air between manoeuvres and the mini-Wright meter only allows flow in one direction, a one-way valve was used to allow automation of this procedure.

Results

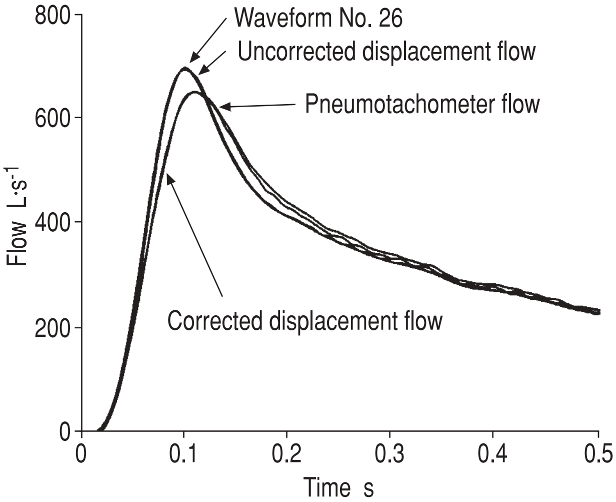

Fig. 3. – Results for standard flow-time waveform No. 26, mini-Wright peak expiratory flow (PEF) meter, minimum dead space (7.32 L).

Figure 3 shows the results for the mini-Wright PEF meter using standard flow-time waveform No. 26 with minimum dead space volume (7.32 L). Notice that the pump piston uncorrected displacement flow is essentially the same as the target waveform flow, but both the pneumotachometer and the corrected displacement flows are lower, PEFs of 652 and 653 L·min^{-1}, respectively (6.1 and 6.3% lower than target PEF of 695.7 L·min^{-1}). In a similar experiment using the Assess PEF meter, the corrected displacement flow for waveform No. 26 was 10.9% lower than the target PEF. The mini-Wright PEF meter has a resistance at 720 L·min^{-1} of approximately 2.6 cmH$_2$O·L^{-1}·s^{-1} compared to 3.2 cmH$_2$O·L^{-1}·s^{-1} for the Assess. The estimated pump output flow in figure 3, flow based on piston displacement and back-pressure, was essentially the same as that measured by the pneumotachometer.

Figure 4 shows the results using standard flow-time waveform No. 26 with a maximum dead space (piston fully back, 14.05 L) for the Assess PEF meter. The larger dead space volume results in considerably larger flow lost to gas compression, and pneumotachometer and corrected displacement flows of 550 and 554 L·min^{-1}, respectively (20.9 and 20.4% lower than the target PEF of 695.7 L·min^{-1}).

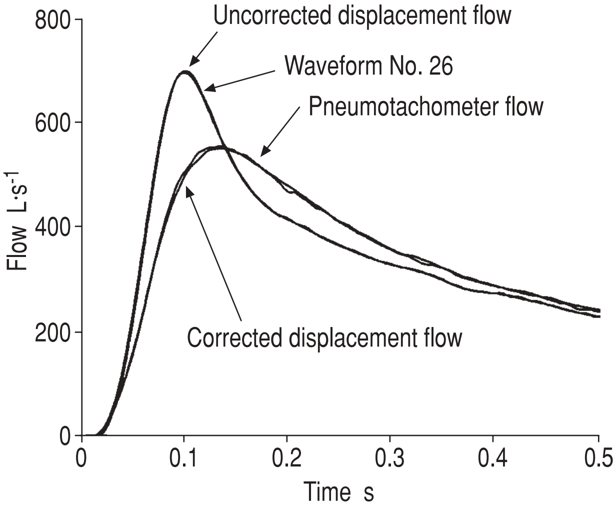

Fig. 4. – Results for standard flow-time waveform No. 26, Assess peak expiratory flow (PEF) meter, maximum dead space (14.05 L).

Table 1 presents the results (mean±SD) of three repeat measurements of PEF using the mini-Wright meter, for all 26 ATS flow-time waveforms. The PEF differences (P-C) between the pump output flow measured by the pneumotachometer (P) and corrected displacement flows (C) were all less than 2%, within the error limit recommended by the ATS. In addition, almost all of the PEF differences between the corrected displacement flow (C) and those measured by the mini-Wright were less than 2.5%.

As shown in the last column of table 1, the differences between target (T) and corrected displacement flows (C) were less than 2% or 5 L·min^{-1} for all but five waveforms (Nos. 2, 6, 8, 9, and 26). These five waveforms all had rise-times less than 57 ms, and should, therefore, be affected more by gas compression. The two waveforms with the largest differences (waveforms Nos. 2 and 26) also have larger PEFs and FVCs, with correspondingly larger starting volumes, resulting in greater flow losses to gas compression. One waveform (No. 12),

Table 1. – Mini-Wright PEF values obtained using ATS 26 standard flow-time waveforms measured using pneumotachometer (P), piston displacement corrected for back-pressure (C), and a mini-Wright PEF meter with the new "mechanical scale" (M)

Waveform No.	Rise-time ms	Target PEF	Pneumo-tachometer*	Corrected Displacement*	Mini-Wright PEF (%M-C)	P-C Diff (%)	T-C Diff (%)
1	93.5	446.7	453.7 (0.83)	446.6 (0.54)	445.0 (-0.4)	7.1 (1.6)	0.1 (0.0)
2	55.7	651.6	630.3 (1.31)	621.7 (0.56)	611.7 (-1.6)	8.6 (1.4)	29.9 (4.6)
3	68.3	287.6	286.3 (0.57)	282.5 (0.24)	281.7 (-0.3)	3.8 (1.3)	5.1 (1.8)
4	76.0	264.1	267.1 (0.56)	263.6 (0.45)	265.0 (0.5)	3.5 (1.3)	-0.5 (-0.2)
5	159.5	217.8	222.4 (0.37)	219.0 (0.97)	223.3 (2.0)	3.4 (1.5)	1.2 (0.6)
6	44.5	185.3	181.2 (0.17)	180.2 (0.57)	180.0 (-0.1)	1.0 (0.6)	5.1 (2.8)
7	148.0	150.5	146.8 (0.97)	147.7 (0.33)	150.0 (1.5)	-1.0 (-0.7)	2.8 (1.8)
8	42.4	139.7	134.5 (0.66)	134.5 (0.43)	135.0 (0.4)	0.0 (0.0)	5.2 (3.7)
9	57.0	315.5	311.2 (1.27)	306.8 (0.19)	308.3 (0.5)	4.4 (1.4)	8.7 (2.7)
10	46.7	284.0	291.0 (0.74)	287.8 (1.06)	290.0 (0.8)	3.2 (1.1)	-3.8 (-1.3)
11	81.1	412.2	417.1 (0.95)	410.3 (1.71)	410.0 (-0.1)	6.8 (1.7)	1.9 (0.5)
12	115.3	641.0	661.7 (2.82)	656.2 (0.37)	640.0 (-2.5)	5.5 (0.8)	-15.2 (-2.4)
13	105.3	288.2	293.9 (0.08)	291.1 (0.82)	293.3 (0.7)	2.8 (0.9)	-2.9 (-1.0)
14	124.7	229.3	233.2 (0.34)	231.3 (0.81)	233.3 (0.9)	1.8 (0.8)	-2.0 (-0.9)
15	174.9	477.4	493.5 (1.68)	484.9 (0.73)	480.0 (-1.0)	8.6 (1.8)	-7.5 (-1.6)
16	76.3	315.1	319.3 (0.48)	316.3 (0.45)	318.3 (0.6)	3.0 (1.0)	-1.2 (-0.4)
17	165.1	350.5	359.8 (1.36)	355.1 (0.80)	356.7 (0.4)	4.7 (1.3)	-4.6 (-1.3)
18	132.9	515.6	525.9 (0.33)	521.7 (0.43)	513.3 (-1.6)	4.2 (0.8)	-6.1 (-1.2)
19	76.5	417.2	416.6 (0.84)	411.9 (0.39)	410.0 (-0.5)	4.6 (1.1)	5.3 (1.3)
20	120.9	445.8	456.0 (0.86)	451.5 (0.99)	448.3 (-0.7)	4.5 (1.0)	-5.7 (-1.3)
21	130.3	238.4	239.5 (0.50)	237.6 (0.42)	240.0 (1.0)	2.0 (0.8)	0.8 (0.3)
22	184.2	202.6	206.0 (0.74)	205.0 (0.95)	210.0 (2.4)	1.0 (0.5)	-2.4 (-1.2)
23	84.8	487.9	498.1 (1.16)	491.4 (1.90)	485.0 (-1.3)	6.7 (1.4)	-3.5 (-0.7)
24	50.3	249.3	248.0 (0.48)	246.9 (0.33)	245.0 (-0.8)	1.0 (0.4)	2.4 (0.9)
25	57.9	851.6	877.4 (1.31)	860.7 (1.88)	856.7 (-0.5)	16.7 (1.9)	-9.1 (-1.1)
26	49.6	695.7	651.9 (2.41)	646.1 (1.25)	636.7 (-1.5)	5.7 (0.9)	49.6 (7.1)

*: PEF values presented as mean, and SD in parenthesis. The last two columns present the difference between pneumotachometer and corrected displacement measurements of PEF (P-C), and the difference between target and corrected displacement PEF (T-C). All values, unless specified, are in L·min^{-1}. PEF: peak expiratory flow; ATS: American Thoracic Society; Diff: difference.

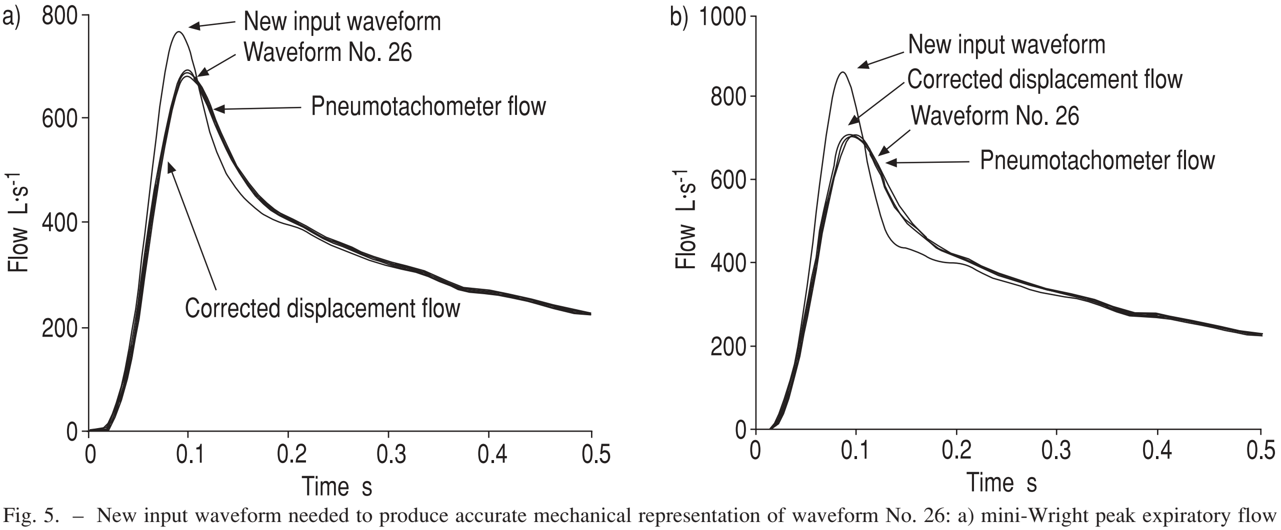

Fig. 5. – New input waveform needed to produce accurate mechanical representation of waveform No. 26: a) mini-Wright peak expiratory flow (PEF) meter; b) Assess peak expiratory flow (PEF) meter.

had an output flow that was 2.4% greater than the target value. This was probably due to the shape or slow rise-time of the waveform, which resulted in previously compressed volumes being recovered at the time of PEF.

Because the pneumotachometer and corrected flows observed in figure 3 were below the target PEFs for both the mini-Wright and Assess meters, the steps outlined in figure 2 were followed to produce the new input waveforms shown in figure 5a (mini-Wright) and figure 5b (Assess). New input waveforms with PEFs of 782 and 854 L·min^{-1} were needed to obtain the target output PEF of 695.7 L·min^{-1} for the mini-Wright and Assess meter, respectively. These new input waveforms resulted in both the pneumotachometer flow and corrected displacement flow essentially mirroring the target flow of waveform No. 26, as shown in figure 5.

Discussion

If the pump dead space is kept to a minimum and the PEF meter resistance is not excessive, then for most of the waveforms (21 out of 26) gas compression should be minimal and it should not be necessary to generate new input waveforms. However, for those waveforms with fast rise-times, the results obtained in figure 5 show that it is possible to generate these flow-time waveforms accurately using the procedures described in figure 2, without the need for a new sophisticated mechanical pump. This has been demonstrated using two different types of PEF meter, the mini-Wright and Assess. In addition, a similar procedure, described in figure 2, has been used successfully to generate waveforms with even higher frequency content than those observed in the 26 standard flow-time waveforms [12].

For several reasons, it is important to keep the pump volume and associated tubing volume to a minimum, and, therefore, elimination of the pneumotachometer in series with the PEF meter is desirable. With increasing dead space volume, the gas compression effect increases and more waveforms will require the methods described in figure 2. In addition, the natural resonant frequency of the pump decreases with increasing pump and tubing volume. For our pump without the pneumotachometer, the natural frequency varied from 85 Hz (pump empty) to 32 Hz (pump full), based on the Helmholtz resonator equation [13] and verified with our measurements. If the pump and tubing volumes are large, then the natural resonance frequency of the pump will be within the range of those present in the flow-time waveforms, causing potential errors in output flow. With our sampling rate of 2,000 samples·s^{-1}, we did not observe significant natural frequency resonance when the waveforms were used. We did observe some small resonant frequency noise at large pump volumes when the calibrating ramps were used.

Using corrected displacement flow and the methods described in figure 2, a commercially available simulator system has been used to produce the 26 flow-time waveforms accurately, including those with fast rise-times. Pump output flow has been verified using three different flow measuring techniques: pneumotachometer flow; corrected displacement flow; and mini-Wright peak expiratory flow meter. The critical step in producing these waveforms is an accurate and reliable method of estimating the flow output from the pump. Measuring output flow based on piston displacement and pressure, instead of measuring flow with a pneumotachometer, eliminates the need for a pneumotachometer to be placed in series with the meter under test.

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