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Gas compression artefacts when testing peak expiratory flow meters with mechanically-driven syringes

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Gas compression artefacts when testing peak expiratory flow meters with mechanically-driven syringes. D. Navajas, J. Roca, R. Farré, M. Rotger. ©ERS Journal Ltd 1997.
ABSTRACT: Mechanically-driven syringes used to test peak expiratory flow (PEF) meters must produce the American Thoracic Society (ATS) standard waveforms with PEF accuracy of 2%. However, gas compression within the syringe could result in significant PEF inaccuracy when testing high resistance meters.

The gas compression artefact was investigated in a mechanical syringe (PWG; MH Custom Design & Mfg L.C., Midvale, Ut, USA) of 13.6 L connected to a standard range mini-Wright PEF meter (Clement Clarke International, Harlow, UK). Scaled versions of the ATS standard waveform No. 24, with peak flows of 750 and 450 L·min⁻¹, were discharged through the PEF meter from different starting piston positions to vary syringe volume (V_{syr}).

The PEF recorded by the meter decreased linearly with increasing V_{syr}. PEF decreased by 0.31 and 0.27% per litre for the ATS standard waveforms with PEF of 750 and 450 L·min^{-1}, respectively. The target PEF computed from piston displacement overread the actual PEF delivered into the PEF meter by ≈4% when V_{syr} = 13.6 L. Overreading fell to ≈1% when V_{syr} was reduced to 3.62 L.

Therefore, gas compression error in commercially available large mechanical syringes can exceed the 2% inaccuracy limit when testing high resistance portable PEF meters. Measurements can be corrected for gas compression by linearly extrapolating PEF recordings to zero volume.
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The use of computer-controlled mechanical syringes for testing peak expiratory flow (PEF) meters has been recommended [1–3]. Mechanical syringes must accurately generate the standard spirometry waveforms defined by the American Thoracic Society (ATS) [1, 4]. Specifically, the PEF of these standard waveforms must be produced within an accuracy of ±2% of reading [3]. Peak flow delivered by the syringe is usually estimated from the displacement of its piston head [5], which assumes that flow losses due to gas compression within the syringe are negligible. Although syringe volume (V_{syr}) can be rather large (>10 L), this assumption may be reasonable when testing low resistance spirometers. However, the large pressure generated within the syringe when testing high resistance portable PEF meters [5, 6] could result in significant gas compression artefacts.

The aim of the present study was to investigate gas compression errors when testing a portable PEF meter with a computer-controlled mechanical syringe designed to generate the ATS standard waveforms. Gas compression error was assessed by discharging scaled versions of the ATS standard waveform No. 24 from different starting positions of the piston through a standard range mini-Wright PEF meter. The target PEF computed from piston displacement was corrected for gas compression by means of linear regression of the PEF values recorded at different V_{syr}.

Methods

The study was carried out on a commercially available computer-controlled mechanical syringe (PWG; MH Custom Design & Mfg L.C., Midvale, Ut, USA), with a piston of 25.4 cm in diameter, which moves inside a flat-ended cylindrical chamber. When its piston is located at starting position set by the factory (home position), the volume of the syringe is 13.6 L. The piston is driven by a direct current (DC) motor servocontrolled with a PC-386 microcomputer. The servocontrol is based on the displacement of the piston. Thus, the PEF value displayed by the system (target PEF) corresponds to the rate of volume change of the syringe and not to the actual flow discharged through the PEF meter.

A standard range mini-Wright peak flow meter (Clement Clarke International, Harlow, UK) was connected directly to the outlet of the syringe (volume of connecting tubing = 130 mL). Resistance of the PEF meter (R_{PEFM}) was measured by injecting constant flow ranging 100–800 L·min^{-1} (100 L·min^{-1} steps). Pressure was recorded at the outlet of the syringe with a ±50 cmH_2O transducer (MP45 Validyne, Northridge, CA, USA). R_{PEFM} was computed as the quotient between pressure and flow recorded when a plateau was reached. Before each measurement, the pointer of the PEF meter was returned to zero.

The syringe was driven with scaled versions of the ATS standard volume-time waveform No. 24 (ATS24) to achieve different PEF values [2]. Scaled versions of waveform ATS24 [1, 4] with peak flows of 450 $L \cdot min^{-1}$ (ATS24-450) and of 750 $L \cdot min^{-1}$ (ATS24-750) were produced as follows. Firstly, the digitized volume-time file of waveform ATS24 was truncated at 240 ms (70 ms after reaching PEF), to minimize its volume and, thereby, piston stroke. Secondly, this truncated volume-time file was scaled to produce two waveforms with peak flows of 450 and 750 $L \cdot min^{-1}$. Finally, a slowly rising volume ramp was added to these volume-time profiles, to advance the starting position of the piston to the desired V_{syr} value before discharging the waveform. V_{syr} was varied from 13.6 L (home position) to 3.6 L (lowest attainable V_{syr} for waveform ATS24-750) in 1 L steps.

The gas compression artefact was assessed by discharging the scaled waveforms with PEF of 450 and 750 $L \cdot min^{-1}$ five times. The set of measurements for each flow range was performed in random order. Peak flow recorded by the PEF meter was read within 0.4 $L \cdot min^{-1}$ by measuring the displacement of its pointer using callipers (1/20 mm). The tests were performed with room air at a temperature of 23–25°C, a pressure of 757–762 mmHg, and a relative humidity of 75–82%.

Peak flow recordings (PEF_m) are reported as mean±SD. Linear regressions of PEF recordings for 750 and 450 $L \cdot min^{-1}$ were performed according to: $PEF_m = a + b \cdot V_{syr}$. The value of PEF_m extrapolated to $V_{syr} = 0$ (a) is an estimate of the true PEF value corrected for the gas compression artefact. The percentage error of the syringe due to gas compression was computed as $\varepsilon = 100 \cdot b \cdot V_{syr}/a$.

Results

Pressure recorded at the outlet of the syringe when a constant flow of 100 $L \cdot min^{-1}$ was delivered into the PEF meter was 4.66 cmH_2O, and rose linearly to 28.9 cmH_2O for 800 $L \cdot min^{-1}$. Consequently, R_{PEFM} varied little with flow, decreasing slightly from 2.80 $cmH_2O \cdot s \cdot L^{-1}$ for 100 $L \cdot min^{-1}$ to 2.17 $cmH_2O \cdot s \cdot L^{-1}$ for 800 $L \cdot min^{-1}$ (fig. 1).

PEF recorded by the PEF meter increased with decreasing V_{syr} both at high- and low-flow ranges (fig. 2). With waveform ATS24-750 (fig. 2a), PEF_m increased by 3.1%

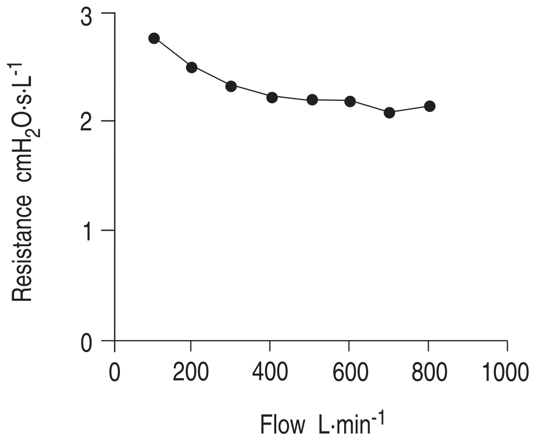

Fig. 1. – Resistance of a standard range mini-Wright peak expiratory flow meter.

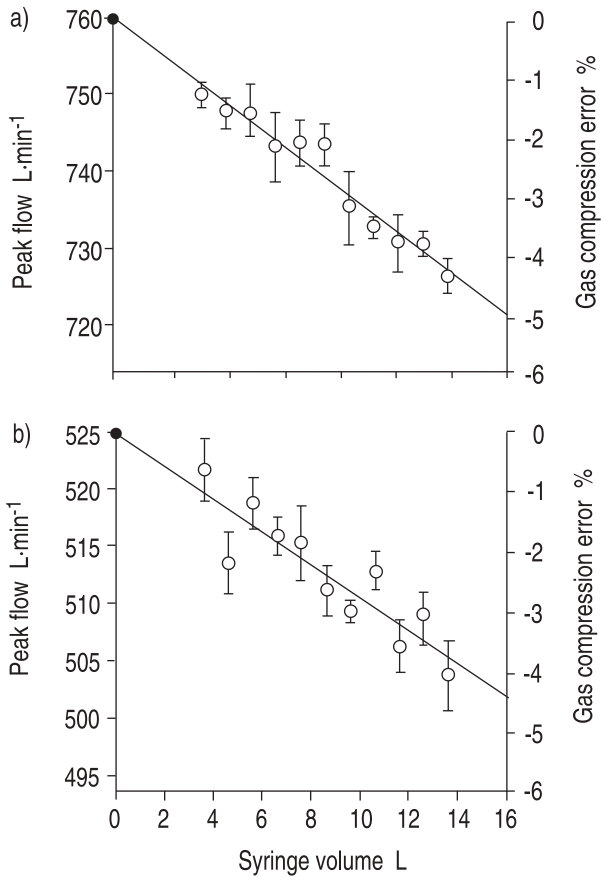

Fig. 2. – Peak flow recorded by a mini-Wright meter when scaled versions of the American Thoracic Society (ATS) waveform No. 24, with peak flows of: a) 750 $L \cdot min^{-1}$; and b) 450 $L \cdot min^{-1}$ were discharged from different syringe volumes (hollow circles). Values are presented as mean±SD. Solid lines are linear regressions. Closed circles are peak flow values extrapolated to zero syringe volume.

when V_{syr} was reduced from 13.6 to 3.62 L. The linear regression fit was PEF_m = 760 $L \cdot min^{-1}$ - 2.37 $min^{-1} \cdot V_{syr}$ (L) (r^2=0.97). Flow losses within the syringe increased by 0.31% (2.37/760) per litre of syringe volume. Hence, the actual peak flow delivered by the syringe when the piston started from its home position (V_{syr} = 13.6 L) was 4.2% lower than the target value displayed. Syringe overreading fell to 1.1% when the starting position of the piston was advanced to minimize V_{syr} (3.6 L). Similar results were found with waveform ATS24-450 (fig. 2b). In this case, the linear regression fit was PEF_m = 525 $L \cdot min^{-1}$ - 1.44 $min^{-1} \cdot V_{syr}$ (L) (r^2=0.89). Flow losses increased by 0.27% per litre, resulting in an error of 3.7% for V_{syr} = 13.6 L and falling to 0.98% for V_{syr} = 3.62 L.

Discussion

Computer-controlled mechanical syringes used for testing PEF meters must produce the PEF of the ATS standard waveforms within an accuracy of ±2% of reading [3]. However, the accuracy of the mechanical syringes available has not been established [3]. This study shows that gas compression within a syringe of ≈13 L results in PEF inaccuracy of ≈4% when the ATS waveform No.

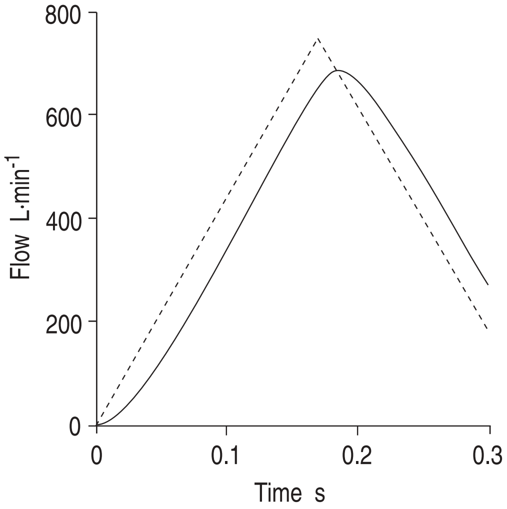

Fig. 3. – Simulation of the effect of gas compression on a triangular flow-time waveform for a syringe of 13.6 L connected to a mini-Wright meter. ········ : target flow-time profile; —— : actual flow delivered into the peak flow meter.

24 is discharged through a mini-Wright PEF meter.

Gas within the syringe acts as a compliance (C_{syr}), which shunts the input of the PEF meter. Considering the small mass of the moving parts of the PEF meter, the load imposed on to the syringe can be attributed mainly to the resistance of the meter [6]. Therefore, the gas compression artefact can be interpreted in terms of a low-pass filter, with a time constant $\tau = R_{PEFM} \cdot C_{syr}$ (see Appendix). Gas compliance is proportional to V_{syr} and, assuming adiabatic conditions, it can be calculated as $C_{syr} \approx V_{syr}/(1.4 \cdot P_B)$, where P_B is barometric pressure. Figure 3 shows the effect of a low-pass filter with τ = 21 ms on a triangular flow-time profile with a time-to-peak flow (time required for flow to rise from zero to PEF) Δt = 170 ms. This simulation was performed with the τ value of the syringe and PEF meter used in this study (V_{syr} = 13.6 L, R_{PEFM} = 2.2 $cmH_2O \cdot s \cdot L^{-1}$; τ = 21 ms) for a triangular flow-time profile with PEF and Δt similar to those of waveform ATS24-750. The filter flattens the flow-time profile reducing its PEF proportionally to V_{syr}. In accordance with the experimental findings of this study (fig. 2), the simulation predicts that the readings of the PEF meter for a target PEF decrease linearly with increasing V_{syr} (see Appendix). This gives support to our empirical approach of correcting the readings of the PEF meter for a target PEF by linearly extrapolating, to zero volume, the data obtained with decreasing V_{syr} values.

In agreement with previous reports [5, 6], mini-Wright resistance depended little on flow amplitude (fig. 1). This can explain the similarity in syringe inaccuracy found for different PEF ranges. However, gas compression errors are expected to increase with the PEF level, when testing PEF meters with flow-dependent resistances. The resistance of the mini-Wright (fig. 1) was close to the 2.5 $cmH_2O \cdot s \cdot L^{-1}$ limit established by the ATS for monitoring devices [3]. Gas compression losses when the ATS waveform No. 24 was discharged into this portable PEF meter from the minimum volume (V_{syr} = 3.6 L) were only ≈1% (fig. 2). The resistance limits established by the ATS and by the European Respiratory Society (ERS) for diagnostic spirometers are 1.5 and 0.5 $cmH_2O \cdot s \cdot L^{-1}$, respectively [3, 7]. Since τ is proportional to R_{PEFM}, gas compression errors found in this study are expected to decrease substantially when the syringe is used to validate diagnostic spirometers. This indicates that gas compression errors in PEF can be easily maintained below 2% when testing monitoring and diagnostic devices with the ATS waveform No. 24 by advancing the starting position of the piston.

Gas compression error was assessed in this study with scaled versions of the ATS volume-time waveform number No. 24 [1, 4]. This procedure was recommended for testing peak flow meters [2], and has been used in recent studies [5, 8, 9]. The ATS waveform No. 24 has a rather slowly rising flow-time profile with Δt ≈170 ms. Some authors have suggested minimizing gas compression artefacts by using cusp waveforms, without abrupt accelerations [5, 6, 10]. However, the last update of the ATS standardization of spirometry published recently recommends a new set of 26 flow-time waveforms [2, 11], which includes very fast rising flow-time profiles with sharp peaks and Δt down to 42 ms. Since the low-pass filter simulation shows an inverse dependence of ε on Δt (see Appendix), gas compression errors for some of the new flow-time ATS waveforms could be four times larger than those found with scaled versions of waveform No. 24.

In conclusion, this study demonstrates that gas compression error in the large mechanical syringes currently available exceeds the inaccuracy limit specified by the ATS for waveform generators used to validate monitoring PEF meters. However, PEF_m determined from piston displacement can be corrected for gas compression by linearly extrapolating, to zero volume, data recorded for different V_{syr}. Moreover, gas compression error can be easily minimized by advancing the starting position of the piston as much as possible. Scaled versions of the ATS waveform No. 24 truncated at 240 ms allowed us to reduce V_{syr} below 4 L. Gas compression error could then be reduced to ≈1% when testing peak expiratory flow meters with resistances within the range recommended by the American Thoracic Society. However, larger gas compression artefacts can be expected when using the new American Thoracic Society flow-time waveforms.

Appendix

Assuming that the load impedance of the PEF meter can be represented by a resistance (R_{PEFM}), the input/output relationship of the syringe can be analysed by means of the following differential equation:

$$V'_o \cdot R_{PEFM} = (V_i - V_o)/C_{syr}$$

where C_{syr} is the compliance of the gas within the syringe, V_i is the instantaneous volume of the syringe computed from the displacement of its piston, and V_o and V'_o the actual volume and flow, respectively, delivered to the PEF meter.

If the syringe is driven with a triangular flow waveform (V'_i) with its peak flow (PEF) at $t = \Delta t$, the rate of change in the syringe volume is:

$$V'_i = (PEF/\Delta t)\cdot t;\ 0 \le t \le \Delta t \quad \text{(A2)}$$

$$V'_i = PEF - (PEF/\Delta t)\cdot(t-\Delta t);\ \Delta t < t \le 2\cdot\Delta t \quad \text{(A3)}$$

Solving Equation (A1) for this triangular waveform, the flow delivered by the syringe is:

$$V'_o = V'_i - (PEF/\Delta t)\cdot\tau\cdot(1-\exp(-t/\tau));\ 0 \le t \le \Delta t \quad \text{(A4)}$$

$$V'_o = V'_i + (PEF/\Delta t)\cdot\tau\cdot(1+(1-2\cdot\exp(\Delta t/\tau))\cdot\exp(-t/\tau));$$

$$\Delta t < t \le 2\cdot\Delta t \quad \text{(A5)}$$

where $\tau = R_{PEFM}\cdot C_{syr}$. The actual peak flow ($PEF_{syr}$) as computed from $dV'_o/dt = 0$ is:

$$PEF_{syr} = PEF - PEF\cdot(\tau/\Delta t)\cdot\ln(2-e^{-\Delta t/\tau}) \quad \text{(A6)}$$

Thus, the percentage reduction of PEF of a triangular flow-time profile due to gas compression within the syringe is:

$$\varepsilon = 100\cdot(\tau/\Delta t)\cdot\ln(2-e^{-\Delta t/\tau}) \quad \text{(A7)}$$

For $\Delta t > 2.5\ \tau$, which corresponds to ε <26%, the former expression can be simplified within an absolute difference of 2% to:

$$\varepsilon \approx 100\cdot\ln 2\cdot(\tau/\Delta t) \quad \text{(A8)}$$

Since τ is proportional to V_{syr} the error increases proportionally with V_{syr}.

Therefore, assuming that the PEF meter behaves linearly within a small region around any operating point, the readings obtained for a given PEF decrease linearly with increasing V_{syr}:

$$PEF_m = a + b\cdot V_{syr} \quad \text{(A9)}$$

Thus, the extrapolated value at zero volume (a) can be taken as the true reading of the PEF meter for the target PEF.

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