Comparison of two devices for respiratory impedance measurement using a forced oscillation technique: Basic study using phantom models

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Abstract

Since commercial forced oscillation technique (FOT) devices became available, they have been widely used for physiological assessments, mainly of obstructive lung diseases. However, it is not known whether the impedance values measured with different devices are identical. In this study, two FOT devices—the impulse oscillometry system (IOS) and the MostGraph (MG)—were compared using phantom models. The resistance values varied up to 10% from estimated values in both devices. Additionally, there was a difference in frequency dependence for the resistance between the devices. The reactance values measured with MG were higher than those measured with IOS. The effects of ventilation on the measured impedance values were higher for IOS than for MG, especially at lower frequencies. We concluded that the devices do not always generate identical impedance values. Thus, differences between the devices should be taken into consideration when evaluating clinical data.

Keywords: forced oscillation • impedance • resistance • reactance • frequency dependence

Introduction

The forced oscillation technique (FOT) is a noninvasive method for measuring respiratory mechanics [1–3]. Respiratory impedance, including resistance (R) and reactance (*X*), can be measured using the relation between airway opening pressure and flow by imposing oscillation signals on normal breathing. As commercial equipment for FOT, such as impulse oscillometry, has become available, this method has been widely applied to physiological assessments of various lung diseases such as chronic obstructive pulmonary disease (COPD) [4, 5], asthma [6, 7], and interstitial lung disease [8]. This method is very useful as a respiratory function test for lung diseases including asthma especially for children [9, 10] because the FOT enables us to measure respiratory mechanics during tidal breathing without requiring an effort-dependent maneuver such as forced expiration.

In Japan, two devices are available for clinical use: MasterScreen IOS-J® (IOS) (CareFusion, San Diego, CA, USA) and MostGraph-01® (MG) (CHEST M.I., Tokyo, Japan). Both of these devices generate oscillation signals of multiple frequencies to provide resistance and reactance at 5–35Hz. Several clinical studies have been performed using the IOS [8, 11, 12] and the MG [13, 14]. There are some differences in the hardware and software of these two devices, including the waveform of the oscillation signal and data processing. For example, with IOS, positive and negative impulse signals are generated alternately independent of the direction of airway opening flow. In contrast, with MG the direction of the pulse signals can be changed in the same direction of flow according to inspiration or expiration.

Additionally with MG, a noise signal is available to provide another type of oscillation. Hellinckx et al. reported that IOS using an impulse signal yields respiratory impedance values that are similar, but not identical, to those provided by FOT using a pseudorandom noise signal [2]. Thus, there may be some differences in the impedance measurements between the two devices and between the two kinds of signals with MG. Although it is important to estimate these differences when comparing clinical results measured in different institutions using IOS or MG, there have been no reports of an investigation of the differences in measured impedance between the devices or between the imposing signals.

The purpose of this study was to reveal the differences in impedance between IOS and MG using phantom models that include known resistance and compliance levels.

Methods

FOT measurements

Two FOT devices, IOS and MG, were used in this study. Both devices were calibrated according to the manufacturer's instructions for each apparatus before starting the measurements. Each measurement was performed during 30 s with impulse signals generated every 0.2 s. With the MG device, not only pulse waveform signals (MG-pulse) but also noise signals (MG-noise) were used for measurements.

Phantom models

We measured impedance using four phantom models (Fig. 1). Each model was connected to the outlet of the device without a mouth piece or bacterial filter. All measurements in each experiment were repeated three times. The results for each experiment are shown as the mean of the three measurements.

- *R* model: A standard resistor (CHEST M.I.) was connected to the outlet of each FOT device, and impedance was measured (Fig. 1a). We used three standard resistors with different known resistances (0.196, 0.402 and 0.951 kPa·s/L).
- *C* model: This simple gas compliance model was based on air compression in an airtight rigid wooden box (Fig. 1b). Two boxes with different air volumes (8.35 and 16.7 L for *C* model-1 and *C* model-2, respectively) were used.
- *RC* model: A standard resistor (0.196 kPa·s/L) was serially connected to the *C* model-1 (8.35 L) (Fig. 1c).
- *RC* ventilation model: A 3.0-L syringe used for calibration was connected in series to a wooden box (*RC* model). Ventilation was performed manually using the syringe during measurements with different respiratory rates (10, 20, or 30/min) and tidal volumes (0.5, 1.0, or 1.5 L) (Fig. 1d).

Statistical analysis

The data were expressed as the mean ± SD. Statistical analyses were performed using JMP10 software (SAS institute, Cary, NC, USA). One-way repeated measures analysis of variance (ANOVA) was used to evaluate the frequency dependence of the impedance. The differences in the frequency dependence of the impedance between IOS, MG-pulse, and MG-noise were evaluated with a two-way repeated-measures ANOVA. Statistical significance of the differences in the impedance parameters among IOS, MG-pulse, and MG-noise was determined with the Tukey-Kramer analysis. A value of $p<0.01$ was considered significant.

Results

R model

Table 1 shows the measured resistance values of three standard resistors at 5, 25, and 35Hz using IOS and MG. Although there were some variations in resistance values between the two devices, standard deviations in the three repeated measurements were quite low for all values from both devices. Figure 2 shows the percentage ratios of measured resistance values at different frequencies (range 5–35 Hz) to the estimated values of standard resistance. For both devices, the measured values of resistance varied up to about 10% from standard values. Additionally, the resistance significantly changed with the frequency in both devices and signals ($p<0.0001$). Moreover, there were significant differences in frequency dependence for the resistance among IOS, MG-pulse, and MG-noise ($p<0.0001$).

C model

The measured impedance values of a simple compliance model with two different gas volumes are shown in Fig. 3. In both devices, the reactance increased with the compliance, which corresponds to the box volume, and the resistance decreased a little with box volume in both models. At 5Hz ($X5$) the reactance of IOS was significantly lower than that of MG ($p<0.0001$), and the X values of IOS were close to the estimated values calculated by the following equation:

$$X = -1/(2\pi f C_{\mathrm{air}}),$$

where f is the frequency (Hz) and C_{air} is the gas compliance of air (L/kPa), except for $X5$ in C model-2.

RC model

Figure 4 shows the impedance measured for the RC model consisting of serial connections by a standard resistor (0.196 kPa·s/L), which is around the values in healthy subjects—and the C model-1 (8.35-L box). The resistance values in the RC model corresponded to the sum of the values in the R model (standard resistor 0.196 kPa·s/L) and those in the C model-1 (Fig. 3a). Additionally, the differences between the resistance value at each frequency in the RC model and the sum of that in the R model and C model-1 were <7.1%, 2.7%, and 1.0% with IOS, MG-pulse, and MG-noise, respectively. Similar to the results for the R model, the resistance significantly changed with frequency in both devices and signals ($p<0.0001$). The difference between the resistance at 5Hz ($R5$) and at 20Hz ($R20$) (i.e., $R5$-$R20$), which reflects frequency dependence, was highest with IOS ($p<0.0001$) and lowest with MG-noise ($p<0.0001$). Similar to the results for the *C* model, the reactance values were significantly lower with IOS than those with MG ($p<0.0001$). Additionally, the resonant frequency (*F*res)—i.e., the frequency at which reactance becomes “0” —was significantly higher ($p< 0.0001$) with IOS than with MG (31.5±0.04, 21.9±0.01, and 21.5±0.02 Hz in the IOS, MG-pulse, and MG-noise, respectively).

RC ventilation model

Figures 5 and 6, respectively, show the effect of the respiratory rate and tidal volume on impedance when the *RC* model was ventilated. The respiratory rate was changed from 0 (static) to 30/min, and the respiratory rate errors (the differences between the setting and the performed rate) were <1.3%. The tidal volume was changed from 0 (static) to 1.5L. The differences between the setting and the delivered volume were <16%, and the coefficient of variation in tidal volume within the measurement was <8%. When the model was ventilated, the resistance increased in both devices and signals, and the maximum change was observed at 5 Hz (*R*5). The frequency dependence of resistance (*R*5-*R*20) was significantly highest with IOS ($p<0.0001$) and lowest with MG-noise ($p<0.001$). *X*5 measured with IOS increased to be larger than the values at 10 Hz when the model was ventilated. The reactance using MG showed similar values. *X*5 with IOS increased with the respiratory rate ($p<0.0001$ for respiratory rates of 10 vs. 30) and the increasing tidal volume ($p<0.01$ for tidal volumes of 0.5 vs. 1.5).

Discussion

This is the first study to investigate differences in the measured impedance between IOS and MG. The results of this study are summarized as follows.

1. The resistance values varied by approximately ±10% for both devices and signals. The frequency dependence of the resistance was different between IOS and MG.
2. MG provided significantly higher reactance values than IOS, and thus *F*res was significantly lower with MG than with IOS.
3. Ventilation increased the resistance, especially at lower frequencies, with both devices. It resulted in increased frequency dependence of the resistance. There were greater effects of ventilation on *X*5 with IOS.

The FOT is a noninvasive method for assessing respiratory mechanics in subjects ranging from adults to children. Recently, the use of IOS and MG has widely increased in Japan, and the usefulness of both FOT devices in various respiratory diseases has been reported [8, 10–14]. Although it has also been reported that the FOT devices did not always generate identical measurement results [2, 15], the actual differences between IOS and MG were not yet known. Thus, it was necessary to estimate these differences and similarities for proper comparisons of clinical results based on these measurements.

Resistance

The resistance values represent the in-phase component of the impedance obtained from the relation between pressure and airflow. Additionally, resistance can be increased by airway obstruction. Thus, the changes in resistance such as $R5$, $R20$ and $R5$–$R20$ have been used for determining physiological parameters in patients with obstructive lung diseases. In the present study, the experiment using a simple R model of a standard resistor ranging from 0.196 to 0.951 kPa·s/L showed that the resistance values varied up to ≈10% in both devices and that frequency dependence of the resistance was different between the devices and signals. Although the factors contribute most to the differences between two devices could not be specified, they may derive from differences in apparatus characteristics, oscillation signal and data processing between these two devices.

In the C and RC models, the measured resistance changed significantly with frequency in both devices, although the R values in the static RC model represented linearity based on the results that the R values in the RC model were close to the sum of those in the simple R and C models. Moreover, the resistance, especially at lower frequencies, increased when the model was ventilated (Figs. 5, 6) with the result that frequency dependence of the resistance increased. Recently, one of the parameters representing frequency dependence of the resistance, $R5$–$R20$ has been used to assess small airways [16–19]. The present study suggested that there may be some variations in the measured resistance and that the measured values should overcome these variations to be significant in clinical studies using IOS and MG.

Regarding the comparison of the waveform of the oscillation signals, the effect of ventilation on the resistance was lowest with the MG-noise. Hellinckx et al. also reported that *R* values using the IOS were slightly greater than those using FOT with a pseudorandom noise signal especially at lower frequencies [2]. According to the nature of the FOT, the impedance at lower frequencies can have a lower signal-to-noise (S/N) ratio with the result that the impedance at low frequencies may have more variations. The pulse wave is of quite short signal duration and hence may be more susceptible to a poor S/N ratio compared with a pseudorandom noise signal [2]. The short signal duration, however, is advantageous when investigating the pulmonary mechanics at specific lung volumes.

Reactance

Reactance values represent the out-of-phase component of impedance. These values are related to the elastic and inertial properties dominant at lower and higher frequencies, respectively [3]. In the present study, using the *C* and *RC* models, the reactance values were significantly higher and the *F*res was lower with the MG than with the IOS. When compared with MG, IOS produced *X* values that were closer to the estimated values of the mathematical simple gas compliance model, although IOS suffered a larger effect of ventilation on *X*5. IOS may be more susceptible to a poor S/N ratio at low frequencies. These results suggest that it is necessary to pay attention to these factors when comparing results derived from IOS and MG measurements.

This study has the limitation that the results may not be directly extrapolated to measurements in humans because the actual human lung is more complex and inhomogeneous regarding structure and ventilation. However, measurements in human subjects can have intra- and inter-subject variations, and it is not possible to perform direct and accurate comparisons between the devices. Thus, in the present study, the measurements were performed using the same physical structures to investigate and compare the results for the two devices.

In conclusion, two FOT devices, the IOS and MG, have some differences in their resistance and reactance values and their frequency dependence. Additionally, the devices may have some variations in the measurements and the effect of ventilation on the results. It is necessary to understand these differences and variations to interpret the measurements data in a clinical setting, especially in multicenter studies. Standardization of the measurements using different FOT devices is warranted.

Conflict of interest

The authors declare that they have no conflict of interest.

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Figure legends

Fig. 1 Schema for four phantom models. **a** *R* model. **b** *C* model. **c** *RC* model. **d** *RC* ventilation model.

R: resistance using a standard resistor; *C*: air compliance using a wooden box of known volume

Fig. 2 Percentage ratio of resistance values measured with the impulse oscillometry system (IOS) and MostGraph (MG) devices. IOS, MG-pulse, and MG-noise values are compared to the estimated values of standard resistance. **a** Resistance of 0.196 kPa·s/L. **b** Resistance of 0.402 kPa·s/L. **c** Resistance of 0.951 kPa·s/L. Plotted data are the mean values of three measurements

Fig. 3 Comparison of impedance values in the *C* model measured with the IOS, MG-pulse, and MG-noise. Plotted data are the mean values of three measurements. The estimated reactance values were calculated from the mathematical model: $X = -1/(2\pi f C_{\mathrm{air}})$, where f is the frequency (Hz), and C_{air} is the gas compliance of air (L/kPa). **a** *C* model-1 (8.35-L box). **b** *C* model-2 (16.7-L box)

Fig. 4 Comparison of impedance values in the *RC* model (resistance of 0.196 kPa·s/L and *C* model-1) measured with IOS, MG-pulse, and MG-noise. Plotted data are the mean values of three measurements

Fig. 5 Effects of the respiratory rate on the impedance measured with IOS (**a**), MG-pulse (**b**), and

MG-noise (**c**), when the *RC* model was ventilated with a fixed tidal volume (1.0 L). Plotted data are the mean values of three measurements. Respiratory Rate (RR) was set at 0, 10/min, 20/min, and 30/min.

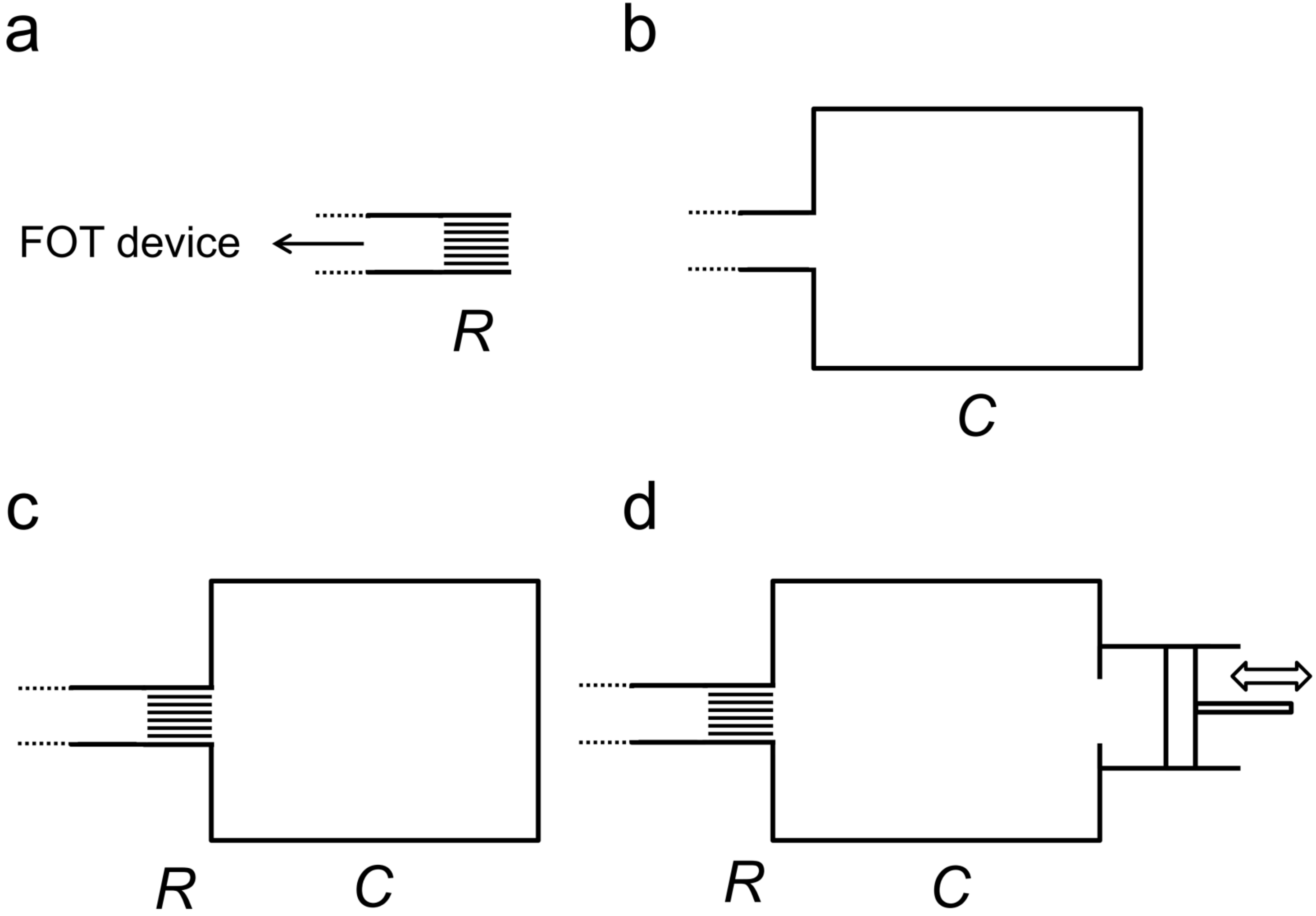
Fig. 6 Effects of the tidal volume on impedance measured with IOS (**a**), MG-pulse (**b**), and MG-noise (**c**), when the *RC* model was ventilated at a respiratory frequency of 20/min. Plotted data are the values of three measurements. Tidal volume (TV) was set at 0, 0.5 L, 1.0 L, and 1.5 L.

Table1. Comparison of resistance values at various frequencies measured in the *R* model

Standard resistor (kPa·s/L)		5 Hz	20 Hz	35 Hz
0.196	IOS	0.174 (0.001)	0.178 (0.000)	0.187 (0.001)
	MG-noise	0.191 (0.001)	0.191 (0.001)	0.194 (0.001)
	MG-pulse	0.188 (0.001)	0.193 (0.001)	0.195 (0.003)
0.402	IOS	0.371 (0.001)	0.380 (0.000)	0.409 (0.001)
	MG-noise	0.437 (0.001)	0.422 (0.001)	0.413 (0.001)
	MG-pulse	0.428 (0.003)	0.431 (0.001)	0.429 (0.001)
0.951	IOS	0.848 (0.001)	0.878 (0.000)	0.965 (0.001)
	MG-noise	1.020 (0.001)	0.932 (0.001)	0.843 (0.001)
	MG-pulse	0.985 (0.001)	0.951 (0.001)	0.899 (0.003)

The data are shown as the mean (SD) of three measurements.

IOS: MasterScreen IOS-J®; MG: MostGraph-01®


a
FOT device
R
b
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d
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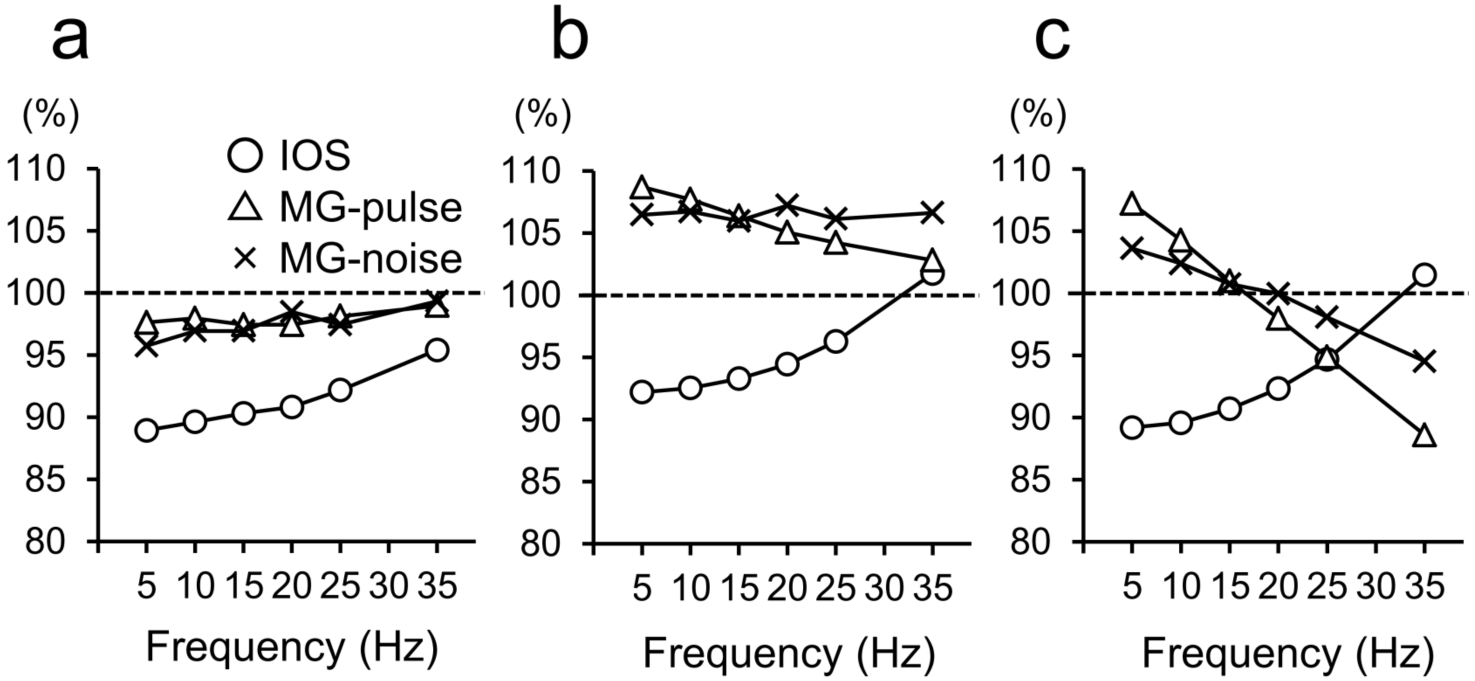
C


a
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(%)
110
105
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85
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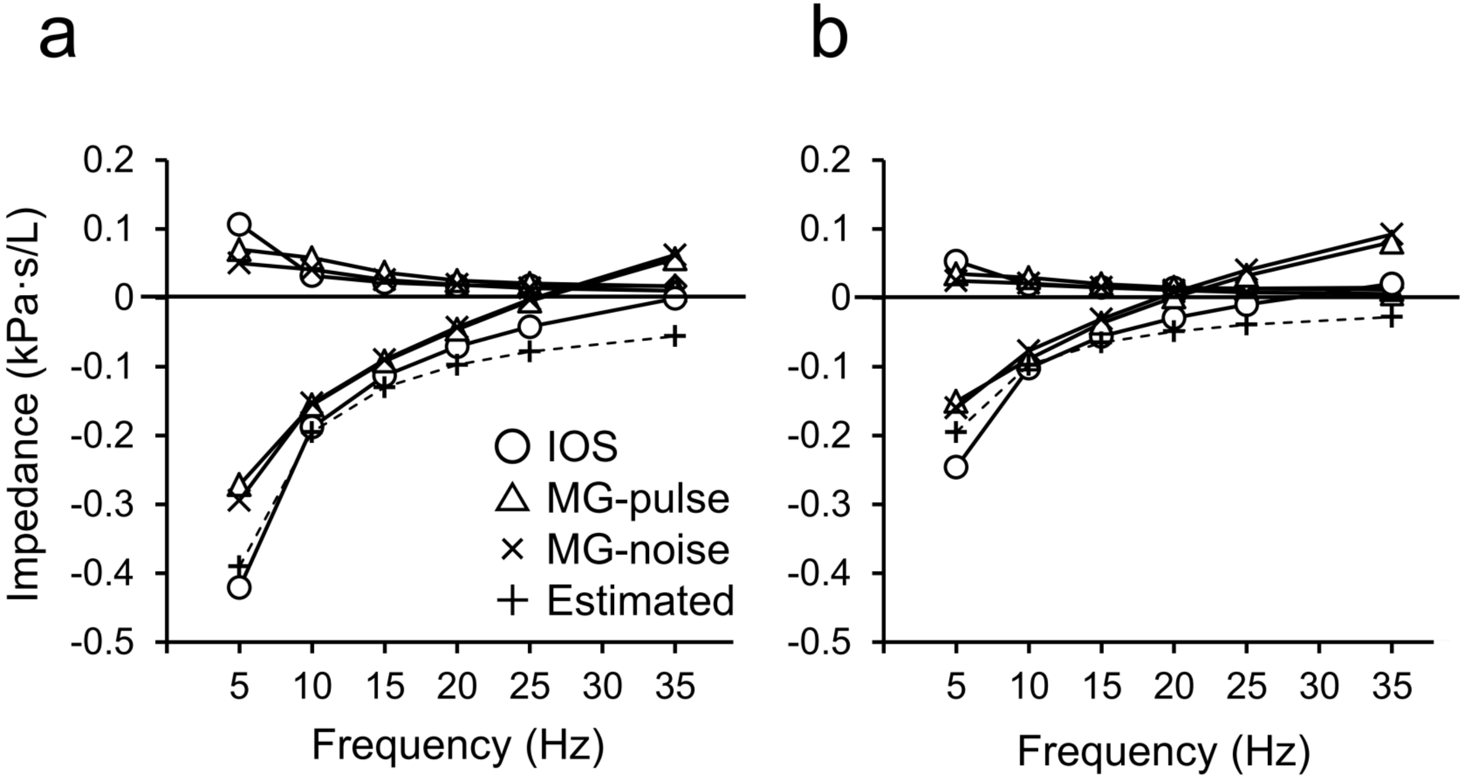
5 10 15 20 25 30 35
Frequency (Hz)


a
b
Impedance (kPa·s/L)
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
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15
20
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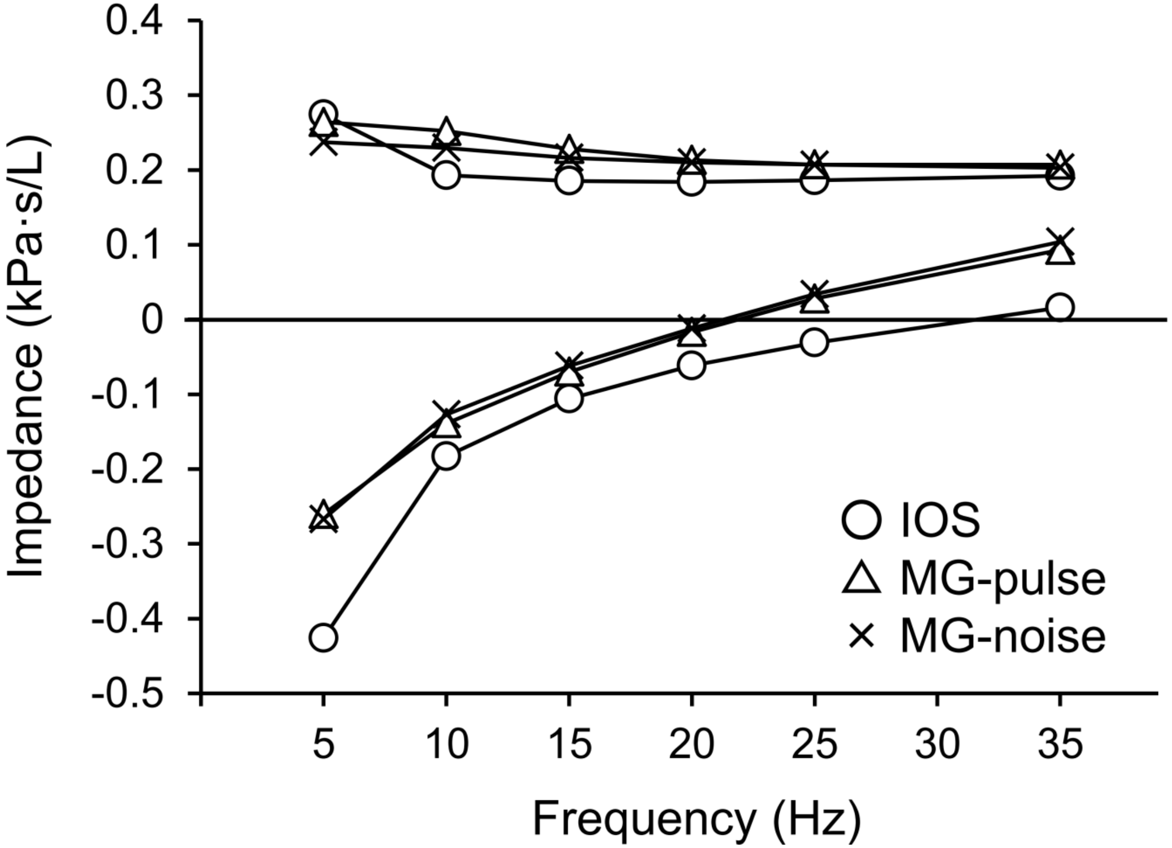
Frequency (Hz)
○ IOS
△ MG-pulse
× MG-noise
+ Estimated


0.4
0.3
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0
-0.1
-0.2
-0.3
-0.4
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Impedance (kPa·s/L)
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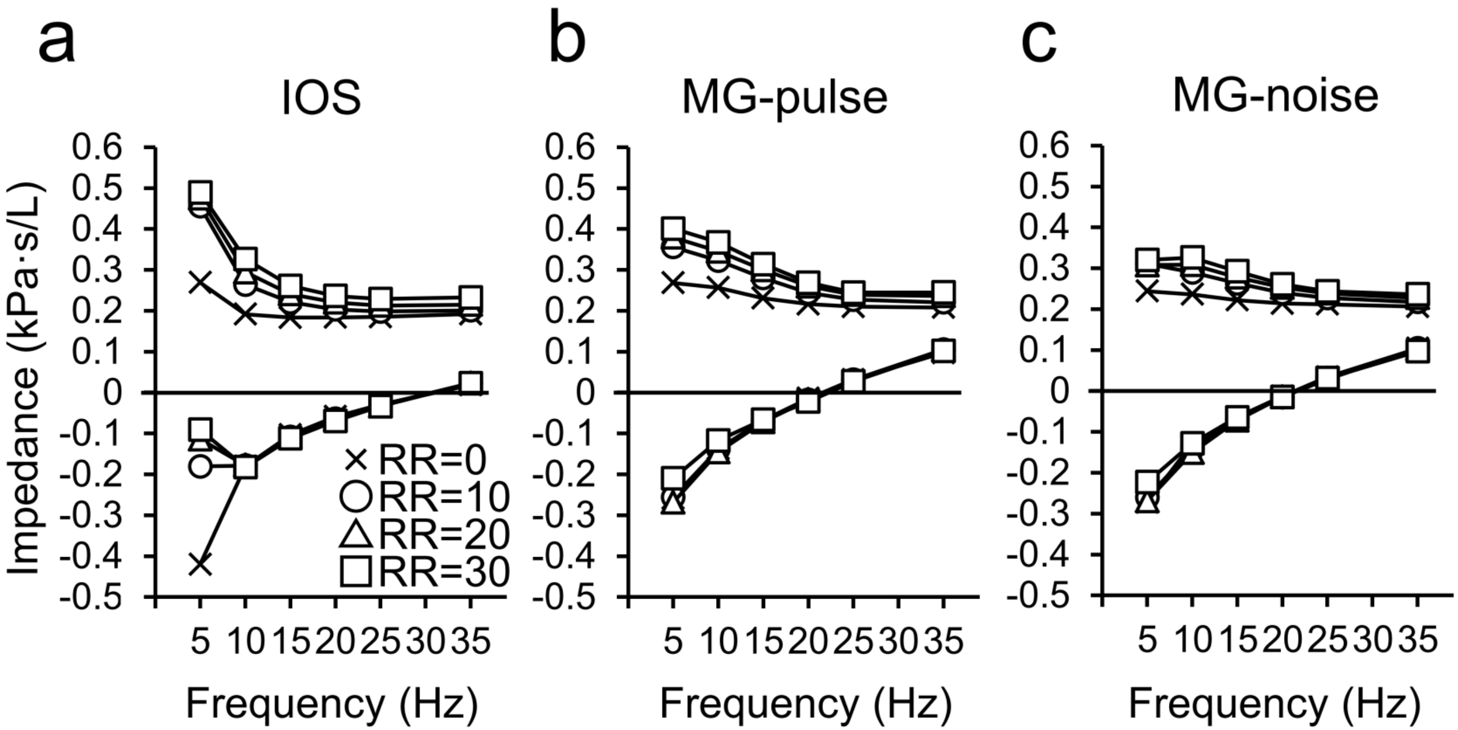
Frequency (Hz)
IOS
MG-pulse
MG-noise

 a
IOS
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Impedance (kPa·s/L)
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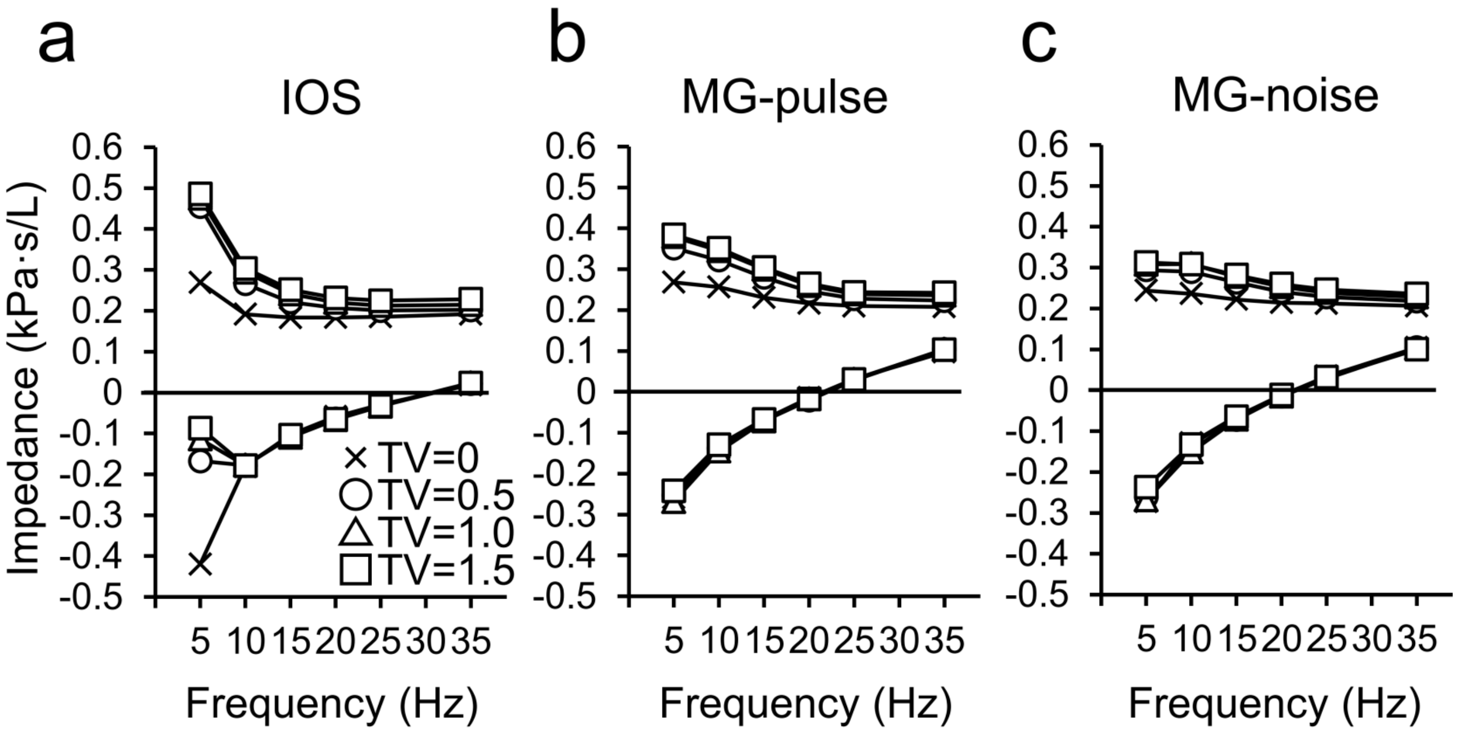
□ RR=30


a
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Impedance (kPa·s/L)
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Frequency (Hz)
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△ TV=1.0
□ TV=1.5