IOP Publishing | Institute of Physics and Engineering in Medicine Physiological Measurement

Physiol. Meas. **00** (2015) 1–4 UNCORRECTED PROOF

Comments

A comment on 'Comparative analysis of the isovolume calibration method for non-invasive respiratory monitoring techniques based on area transduction versus circumference transduction using the connected cylinders model' (2011 *Physiol. Meas.* 32 1265–74)

A T Augousti[1] and A Radosz[2]

[1] Faculty of Science, Engineering and Computing, Kingston University, Penrhyn Rd, Kingston, Surrey KT1 2EE, UK
[2] Institute of Physics, Wroclaw University of Technology, Wybrzeze Wyspianskiego 27, 50370 Wroclaw, Poland

E-mail: augousti@kingston.ac.uk

Received 9 September 2014, revised 12 January 2015
Accepted for publication 3 February 2015
Published

Abstract

An analysis introduced by the authors in 2011 examining the robustness of the isovolume method for the calibration of the Respiratory Inductive Plethysmograph based on the Connected Cylinders particular model of Konno and Mead's generalized two-compartment model of respiration is extended. It is demonstrated that extending this to a more physically realistic geometrical model, termed the Connected Prismatic Elliptical Segments model, does not enhance the earlier analysis, and that the analysis can easily be proven to cover all area-based transduction sensors, irrespective of the actual geometry of the compartments.

Keywords: plethysmography, respiratory monitoring, respiratory inductive plethysmograph, fibre-optic respiratory plethysmograph, biomedical instrumentation, fibre-optic sensors

AQ1 (Some figures may appear in colour only in the online journal)

JNL:PMEA PIPS: 509481 TYPE: COM TS: NEWGEN DATE:11/2/15 EDITOR: IOP SPELLING: UK

The authors published a paper in Physiological Measurement in 2011 (Augousti and Radosz 2011) in which they extended work carried out earlier (Augousti 1997). This work examined the relative robustness of the isovolume method of calibration for the Respiratory Inductive Plethysmograph (RIP) (Cohn *et al* 1975, 1982, Sackner *et al* 1980), which is based on transduction of a cross-sectional area, and compared it to a similar analysis that was conducted for the Fibre Optic Respiratory Plethysmograph (FORP), which by contrast is based on transduction of circumference (Raza and Augousti 1994, Davis *et al* 1997, 2000, Babchenko *et al* 1999, Augousti *et al* 2005, 2006). One of the key outcomes of this analysis was that the procedure was, to first order, essentially more robust for the RIP than for the FORP, manifested as a dependence of calibration coefficients on the value of the compartmental volume in the case of the FORP whereas by contrast the coefficients obtained for the RIP were independent of compartmental volume. The notion of a two compartment model, and hence two degrees of freedom, was introduced by Konno and Mead (1967), one representing the thoracic cavity (usually referred to as the ribcage compartment) and the other the abdominal cavity, although the shape of each of the compartments was not specified. The idea of two separate compartments is not physically realistic from an anatomical perspective, however this model does provide a very useful conceptual framework for analysis of measurements based on two channels, which is helpful in terms of permitting the equivalent of 'common-mode' rejection of spurious values (which may arise from flexing of the torso). One of the authors of this paper devised a model termed the Connected Cylinders Model (Augousti 1997) which provided an analysis of the calibration of the FORP using this model based on first-order changes. The coefficients in question determined the relative contribution of each compartment to the total inspired volume. A second result demonstrated in the latter paper (Augousti and Radosz 2011) that the effect of neglecting second-order terms, as would be included in an exact analysis of area-based transduction based on the Connected Cylinders model, was negligible for realistic assumptions regarding the functional interdependence of compartmental heights and areas.

In the Further Work section of that paper it was suggested that this analysis could be extended to more physically realistically geometries for the two compartments, proposing, for instance, two compartments with elliptical segment cross-sectional areas. A preliminary analysis based on the following geometry has been carried out. The abdominal compartment consists of a right-angled prism of elliptical cross-sectional area, whose major and minor axes can both vary, and the thoracic compartment consists of a prismoidal shape, also of elliptical segment cross-sectional area, but in this case this it is not a right-angled prism. The angle of inclination of the cross-sectional area to the normal axis varies during breathing, thereby changing the volume (figure 1). The height of both compartments remains fixed during breathing. Such a geometrical model would provide a somewhat more realistic framework for analysis, providing a model that is more akin to the pump- and bucket-handle motions, as well as the caliper motion in the lower ribs, that occur during normal breathing (De Groote *et al* 1997, Rib Cage Biomechanics link 2014).

Following some work devising an analysis based on this Connected Prismatic Elliptical Segments Model, it has become clear that in fact the analysis is independent of the cross-sectional area of each compartment, subject only to the constraint that the height of each compartment is fixed. In fact this can be shown by a relatively trivial analysis, which is reproduced below.

Using the same terms to represent quantities as introduced by Augousti and Radosz (2011) $V = hA$ and hence $\mathrm{d}V = h\,\mathrm{d}A$. If $\Delta F_i = K_i \mathrm{d}A_i$ then

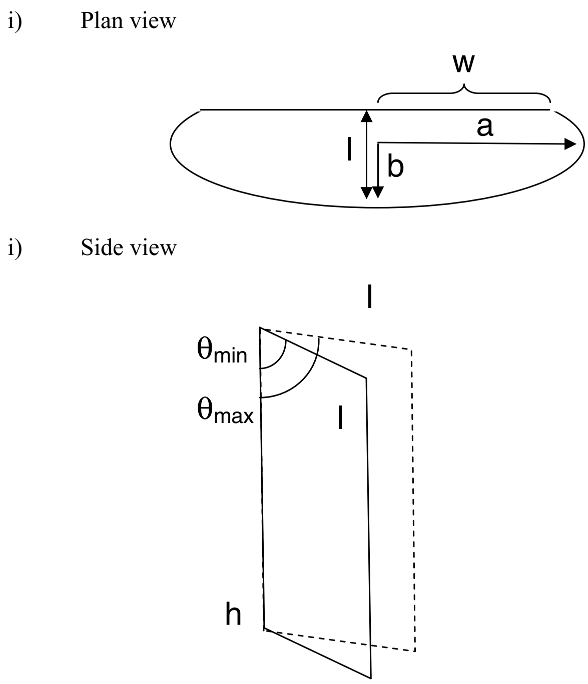

Figure 1. The prismatic elliptical segments model, showing only the upper (thoracic) compartment. The first part shows the cross section of the elliptical segment, and the latter shows the motion as this compartment changes shape. In order to calculate the volume, of the prism, and more importantly the change in the volume ΔV as a change in the angle of inclination $\Delta\theta$, the elliptical cross-sectional area of the prism must be determined in terms of w. It can be shown using elementary calculus that $A = ab\,(\pi / 2 + \cos^{-1} w / 2a)$.

$$\Delta V_i = \frac{\Delta F_i}{K_i} h_i = k_i \Delta F_i$$

where h represents compartmental height, K_i represents a channel calibration constant incorporating the channel sensitivity, ΔF_i represents changes in the signal recorded in channel i (where i = RC, ABD represents the thoracic or abdominal compartment respectively) and $k_i = h_i / K_i$. The ensuing analysis then proceeds as in $\oint$ 2.3 in Augousti and Radosz (2011).

In conclusion, this strengthens the outcomes of the previous analysis, and extends them easily to arbitrary compartmental geometries, subject to the constraint of fixed height, for systems whose transduction depends on the area of cross-section ther than the perimeter.

The clinical significance of this work is to establish why such a relatively simple calibration method, compared, for instance to least-squares fitting techniques, should work so well. For example Raza (1997) has demonstrated that isovolume-based techniques differ from least-squares fitting methods for the inference of tidal volume by as little as 3%, even under extreme tidal excursions. This extension of the original analysis carried out by Augousti and Radosz (2011) demonstrates that it is no coincidence that this calibration technique works so well, largely as shown above due to the fact that the method does not depend on the particulars of the compartmental geometries (subject to the constraint of fixed compartmental height), for area-based transduction systems.

AQ2 References

Augousti A T 1997 A theoretical study of the robustness of the isovolume calibration method for a two-compartment model of breathing based on an analysis of the connected cylinders model *Phys. Med. Biol*. **42** 283–91

Augousti A T, Maletras F-X and Mason J 2005 Improved fibre optic respiratory monitoring using a figure-of-eight fiber optic coil *Physiol. Meas.* **26** 585–90

Augousti A T, Maletras F-X and Mason J 2006 Evaluation of cardiac monitoring using fibre optic plethysmography *Ann. Biomed. Eng.* **34** 416–25

Augousti A T and Radosz A 2011 Comparative analysis of the isovolume calibration method for non-invasive respiratory monitoring techniques based on area transduction versus circumference transduction using the connected cylinders model *Physiol. Meas.* **32** 1265–74

Babchenko A, Khanoch B, Shomer Y and Nitzan M 1999 Fibre optic sensor for the measurement of respiratory chest circumference changes *J. Biomed. Opt.* **4** 224–9

Cohn M A, Rao A S V, Broudy M, Birch S, Watson H, Atkins N, Davis B, Stott FD and Sackner M 1982 The respiratory inductive plethysmograph: a new non-invasive monitor of respiration *Bull. Eur. Physiopath. Resp*. **18** 643–58

Cohn M A, Watson H, Weisshaut R, Stott F and Sackner M A 1975 A transducer for non-invasive monitoring of respiration *ISAM Proc. of the 2nd Int. Symp. on Ambulatory Monitoring* (London:
AQ3 Academic) pp 119–28

Davis C, Mazzolini A, Mills J and Dargaville P 2000 A new sensor for monitoring chest wall motion during high frequency oscillatory ventilation *Med. Eng. Phys*. **21** 619–23

Davis C, Mazzolini A and Murphy D A 1997 new fibre optic sensor for respiratory monitoring *Autralas. Phys. Eng. Sci. Med.* **20** 214–9

De Groote A, Wantier A, Cheron G, Estenne M and Paiva M 1997 Chest wall motion during tidal breathing *J. Appl. Physiol.* **83** 1531–7

Konno K and Mead J 1967 Measurements of the separate volume changes of rib cage and abdomen during breathing *J. Appl. Physiol*. **22** 407–22

AQ4 Raza A 1997 *PhD Thesis* Kingston University, UK

Raza A and Augousti A T 1994 Further development of a fibre optic respiratory plethysmograph (FORP) *Proc. of Applied Optics and Optoelectronics Conf.* pp 271–3

Rib Cage Biomechanics link 2014 http://hal.bim.msu.edu/cmeonline/ribcage/Biomechanics/start.html last accessed 29 August 2014

Sackner J D, Nixon A J, Davis B, Atkins N and Sackner M A 1980 Non-invasive measurement of ventilation during exercise using a respiratory inductive plethysmograph *Amer. Rev. Resp. Dis.* **122** 867–71

QUERIES

Page 1
AQ1
Please be aware that the colour figures in this article will only appear in colour in the web version. If you require colour in the printed journal and have not previously arranged it, please contact the Production Editor now.
Page 4
AQ2
Please check the details for any journal references that do not have a link as they may contain some incorrect information.
AQ3
Please provide location of the conference and date in references Cohn et al (1975), Raza and Augousti (1994).
AQ4
Please provid thesis title in Raza (1997).