Validation of Airway Resistance Models for Predicting Pressure Loss through Anatomically Realistic Conducting Airway Replicas of Adults and Children

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BACKGROUND & METHODS

BACKGROUND:

Analytical models of airway resistance are frequently employed in modeling breathing mechanics and ventilation distribution. The present work was conducted to evaluate the accuracy of three previously published airway resistance models[1-3] in predicting total pressure drop through central conducting airway replicas.

METHODS:

Experimental measurement was made of the total pressure drop at varying steady inspiratory flow rate through anatomically realistic conducting airway replicas of ten children, 4 to 8 years old, and five adults (Table 2). Conducting airways were identified in CT images using Mimics software (MIMICS 3D; Materialise, USA) and replicas were built in acrylonitrile butadiene styrene (ABS) plastic using a 3D printer (Invision® SR; 3D systems, USA).

Experimental results were compared with analytical predictions made using published airway resistance models (Table 1). For analytical calculations, diameters and lengths for all airway segments in each replica were measured from segmented CT images using a post processing software package (MAGICS; Materialise, USA).

For a given flow rate the total pressure drop through a replica was calculated by treating the conducting airways as a network of hydraulic resistances, R:

$$R = \frac{\Delta P}{\rho Q^2}$$

where Q is the flow rate through an airway segment, ρ is the gas (air) density, and ΔP is the pressure drop across the segment.
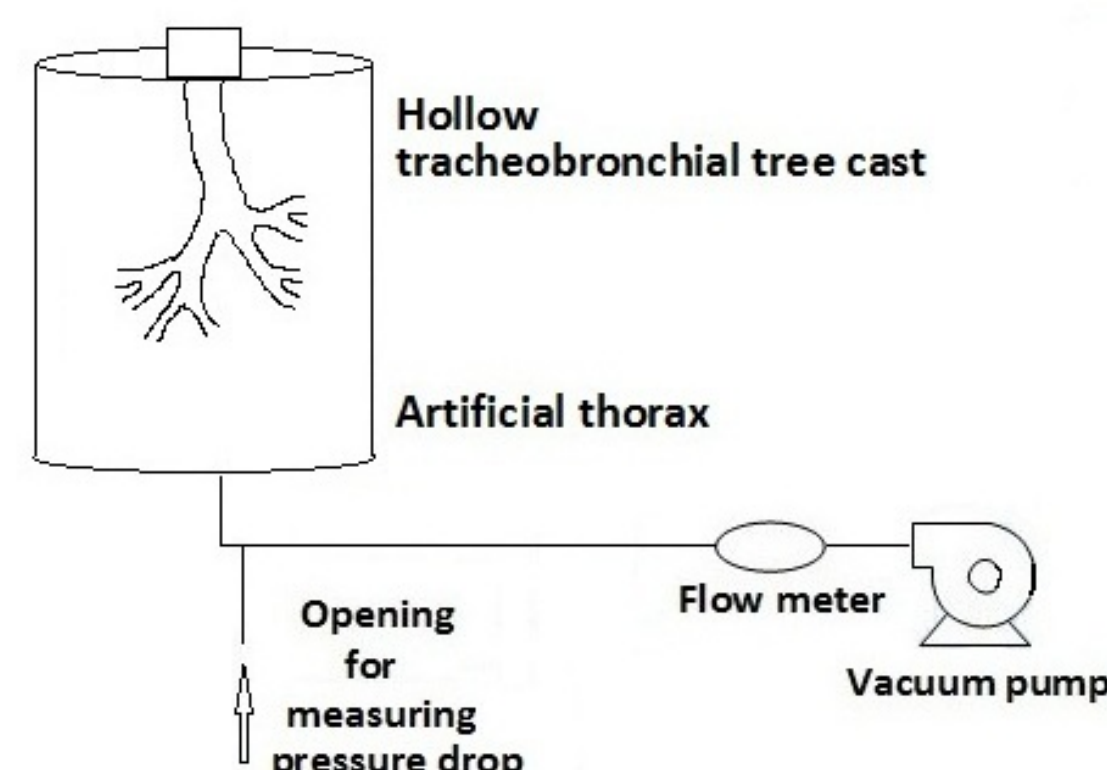

FIGURE 1. Experimental apparatus used to measure pressure drop in the airway replicas.

TABLE 1. Analytical resistance models.

Model	Hydraulic Resistance, R
Katz[1]*	$R_{Katz} = \frac{8}{\pi^2 D^4 g}[f\frac{L}{D} + K]$
Pedley[2]	$R_{pedley} = \frac{128 \cdot 1.85}{\sqrt{2}\pi^2 D^4}\left(\frac{L}{D}\right)^{0.5} Re^{-0.5}$
Modified Pedley[3+]	$R_{modified\ Pedley} = \frac{512}{\pi^2 D^4}\left(\frac{L}{D}\right)^{0.5}\frac{\gamma}{Re^{0.5}}$

*Expressions for the friction factor f and bifurcation minor loss coefficients K are found in Katz et al.[1]
+Values of γ in conducting airway generations are provided in van Ertbruggen et al.[3]

TABLE 2. Summary of child and adult subject information and airway diameters of child and adult replicas.

Age [years]	Subject Number	Sex	Height [cm]	Weight [kg]	Diameter Gen.0 (stdev) [mm]	Diameter Gen.1 (stdev) [mm]	Diameter Gen.2 (stdev) [mm]	Diameter Gen.3 (stdev) [mm]
4	10c	F	99	16	7.15(0.04)	4.7(1.19)	3.48(0.27)	2.2(0.23)
	14c	F	100	16	7.16(0.15)	6.47(2.77)	4.46(0.69)	2.23(0.76)
5	2c	M	117	23	7.05(0.09)	6.03(0.7)	6.00(1.4)	4.35(1.91)
	3c	M	112	20	7.99(0.51)	5.39(0.51)	4.93(0.49)	2.33(0.66)
	9c	M	113	20	7.56(0.01)	6.44(0.87)	5.26(0.01)	3.38(1.05)
6	5c	F	112	18	7.99(0.42)	5.36(1.14)	5.35(1.41)	3.55(1.00)
	6c	F	118	22	8.5(0.3)	6.75(1.32)	5.94(1.32)	2.9(1.47)
	12c	F	124	24	7.41(0.46)	6.45(2.72)	3.28(0.26)	3.23(0.90)
7	13c	F	121	20	9.78(1.32)	7.64(0.09)	6.48(1.23)	3.58(0.01)
8	11c	M	125	25	10.49(0.95)	7.43(2.26)	6.23(1.42)	3.02(0.35)
50	7a	M	178	113	14.57(2.04)	12.34(1.08)	6.79(1.62)	3.6(0.15)
	8a	F	155	99	12.4(0.01)	10.83(2.68)	6.53(2.27)	5.18(0.23)
55	3a	F	159	68	14.94(2.67)	14(2.15)	9.45(1.65)	7.46(0.80)
62	4a	M	168	91	14.47(2.09)	13.63(2.5)	7.8(1.04)	4.69(1.04)
80	5a	M	173	76	16.13(2.19)	14.27(2.3)	6.89(2.27)	4.47(1.87)

Subject numbers ending with "c" indicate child subjects, while those ending with "a" indicate adult subjects.
Generation 0 (Gen.0) is the trachea, Gen.1 are the main bronchi, Gen.2 are the bronchi, and Gen.3 are the segmental bronchi.

SUMMARY

For the adult replicas, the modified Pedley model proposed by van Ertbruggen et al.[3] most accurately predicted central conducting airway resistance for inspiratory flow rates ranging from 15 to 90 L/min. For child replicas, the Pedley[2] and Katz[1] models both provided good estimation of measured pressure loss at flow rates representative of resting tidal breathing, but under predicted measured values at high inspiratory flow rate (60 L/min).

These results are intended to provide guidance for selection of analytical pressure loss models for use in predicting airway resistance and ventilation distribution in adults and children.

REFERENCES

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2. Pedley, T.J., Schroter, R.C., Sudlow, M.F., 1970. Energy losses and pressure drop in models of human airways. Journal of Respiration Physiology. 9, 371-386.

3. van Ertbruggen, C., Hirsch, C., Paiva, M., 2005. Anatomically based three-dimensional model of airways to simulate flow and particle transport using computational fluid dynamics. Journal of Applied Physiology. 98, 970-980.

TRACHEAL REYNOLDS NUMBER

TABLE 3: Values of tracheal Reynolds number at different flow rates through the airway replicas.

$$Re = \frac{4\rho Q}{\pi D_{trachea}\mu}$$

| Subject ID#	Q (L/min) = 2	Q (L/min) = 5	Q (L/min) = 10	Q (L/min) = 15	Q (L/min) = 30	Q (L/min) = 60	Q (L/min) = 90
Subject 3a	---	---	---	1436	2872	5744	8616
Subject 4a	---	---	---	1483	2965	5931	8896
Subject 5a	---	---	---	1331	2661	5322	7984
Subject 7a	---	---	---	1473	2946	5893	8839
Subject 8a	---	---	---	1730	3460	6920	10380
Subject 9c	378	946	1892	2838	5676	11353	---
Subject 6c	337	842	1684	2526	5052	10104	---
Subject 5c	358	895	1790	2685	5371	10742	---
Subject 13c	292	731	1462	2193	4386	8773	---
Subject 2c	406	1014	2029	3043	6087	12174	---
Subject 3c	358	895	1790	2685	5370	10739	---
Subject 11c	273	682	1364	2046	4093	8185	---
Subject 10c	400	1000	2000	3000	6000	11999	---
Subject 12c	386	965	1930	2895	5790	11580	---
Subject 14c	400	999	1998	2997	5993	11987	---

AIRWAY RESISTANCE - ADULTS
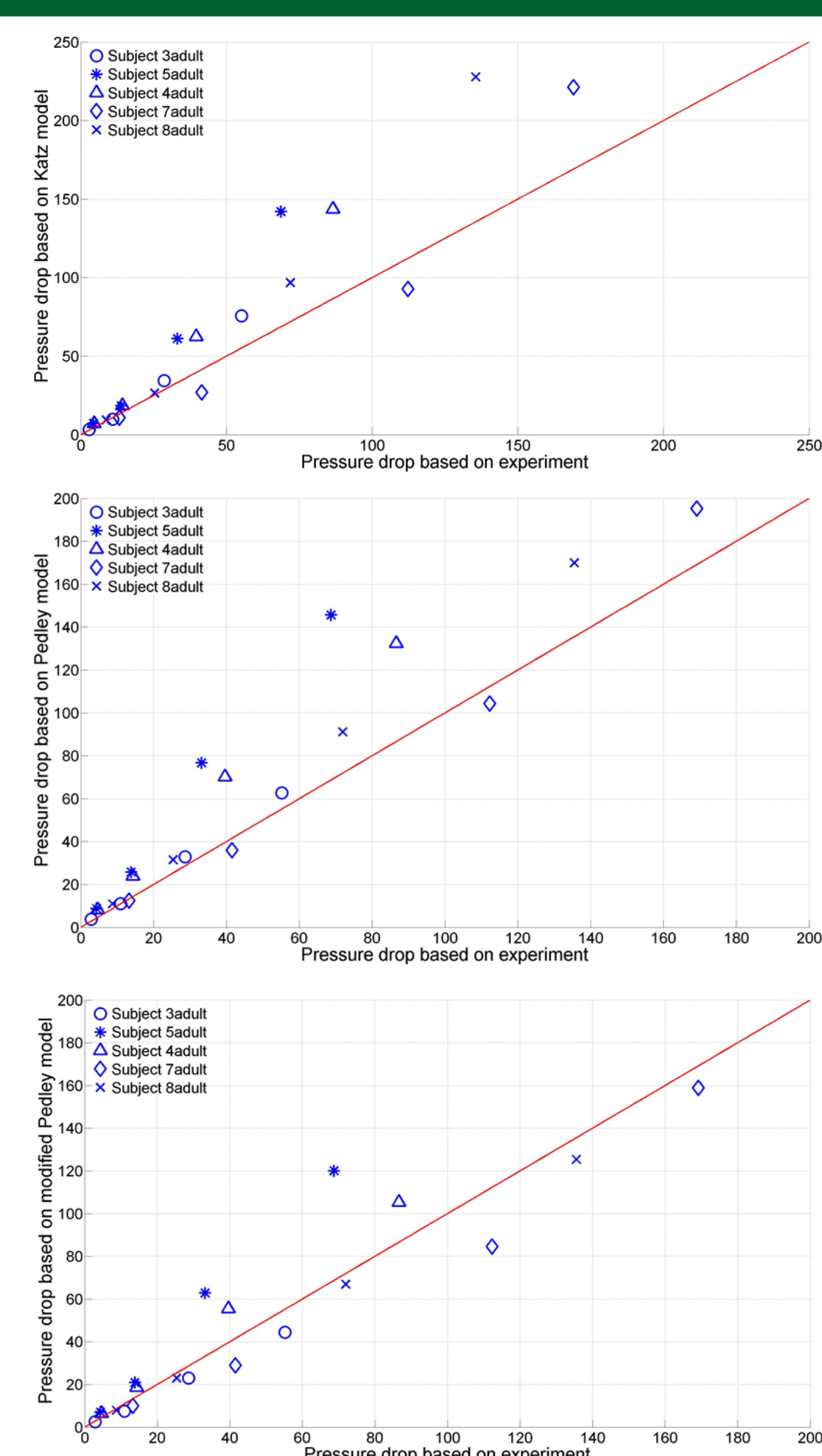
FIGURE 4. Pressure drop (Pa) predicted using analytical models is compared with that measured experimentally for adult central conducting airway replicas.

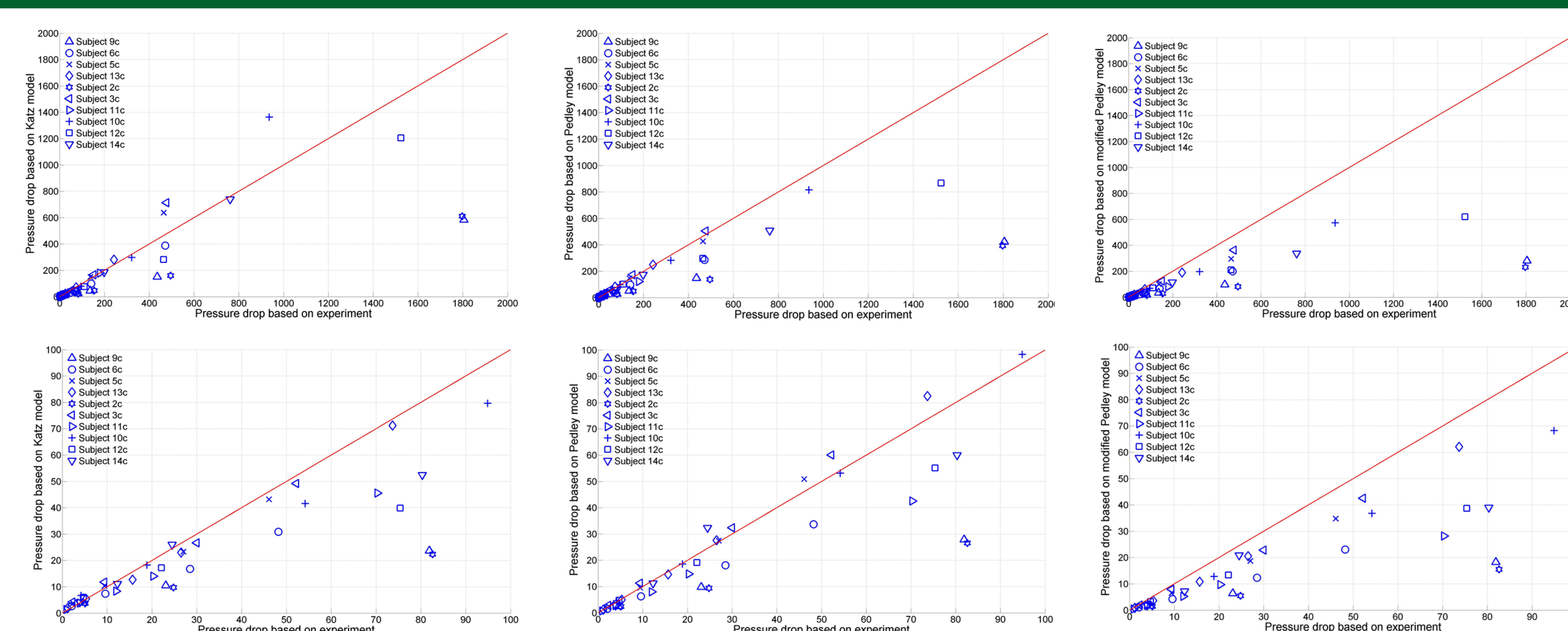## AIRWAY RESISTANCE - CHILDREN

FIGURE 5. Pressure drop (Pa) predicted using analytical models is compared with that measured experimentally for child central conducting airway replicas. Top row: the full range of measured pressure drop is shown. Bottom row: magnified view at low pressure drop.