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Publication Date

2021-02-01

DOI

10.1016/j.resp.2020.103564

Peer reviewed

1 **Airflow dynamics and exhaled-breath temperature following cold-water**
2 **ingestion**

3

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12 Running Head: Airflow dynamics following cold-water ingestion

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18 Declarations of interest: None.

19 **ABSTRACT**

20

21 **Introduction.** Drinking cold water evokes decreases in spirometric indices of lung function. We studied
22 whether this could be explained by changes in exhaled-breath temperature (EBT), airflow dynamics,
23 and spirometer measurement sensitivity. **Methods.** In a randomized/crossover design, 10 healthy adults
24 consumed 1,000 mL refrigerated water (2.1 ± 0.64 °C) or water at room temperature (19.4 ± 0.5 °C), with
25 EBT assessed at baseline and at 5,10,15 and 30-min post-ingestion. The influence of EBT on
26 pneumotachograph measurement characteristics was modelled using computational fluid dynamics
27 (CFD). **Results.** At 5-min post-ingestion, EBT was lower ($p<0.001$) following the ingestion of cold
28 water versus water at room-temperature (31.7 ± 1.1 vs. 33.0 ± 0.9 °C), and remained lower until 30-min
29 post-ingestion. At a flow of $8\text{ L}\cdot\text{s}^{-1}$, a decrease in EBT of 2.1 °C (observed following cold-water
30 ingestion) was modelled to underpredict lung volume by 0.7%. **Conclusions.** Cold water reduces EBT
31 below baseline but effects pneumotachograph measurements only negligibly; thus, decreased lung
32 function following cold-water ingestion likely has a physiological explanation which warrants further
33 study.

34

35 **Keywords:** airflow; lung function; spirometry.

36 **1.0 INTRODUCTION**

37

38 Spirometry is a common pulmonary function test (PFT) used in the diagnosis and monitoring of
39 respiratory disorders (Miller *et al.* 2005; Graham *et al.* 2019). In addition to providing standardized
40 criteria for maneuver quality, the ATS/ERS suggest that optimal and repeatable results are more likely
41 if a patient abstains from vigorous exercise for 1 h, smoking or vaping for 1 h, large meals for 2 h, and
42 alcohol for 4 h before a given test. There are no clear guidelines pertaining to fluid ingestion as it relates
43 to spirometry, aside from the recommendation that “drinking water should be available” (Graham *et al.*,
44 2019).

45 Two recent studies from our group suggest that water, ingested up to 30 min before spirometry,
46 may negatively impact on lung function. In the first of these studies, 500 – 700 mL tap-water evoked
47 significant decreases in forced vital capacity (FVC, -2.3%) and forced expiratory volume in 1 second
48 (FEV₁, -2.9%) in healthy subjects (Turner *et al.* 2015). We observed no such changes with a volume-
49 matched food bolus, indicating that the decreases in lung function following fluid ingestion were
50 independent of gastric load, *per se*. In the second study, we showed that 1,000 mL of refrigerated water
51 (~3 °C) significantly reduced FVC, FEV₁, FEV₁/FVC, and forced expiratory flow measured between
52 25 and 75% of the exhalation (FEF₂₅₋₇₅) in the range of 5 – 10%. Furthermore, the decreases were
53 significantly greater than those observed with an equivalent volume of water at room-temperature
54 (Turner *et al.* 2016). We thereby concluded that ingesting a large bolus of water had the potential to
55 reduce lung function via a mechanism that was likely temperature-dependent.

56 We can conceive two potential physiological explanations for these findings. First, the
57 autonomic nervous system plays an important role in regulating airway function (van der Velden and
58 Hulsmann 1999). Ingesting cold water has been shown to increase vagal tone (Chiang *et al.* 2010),
59 which might trigger airway mucous production and bronchoconstriction in susceptible groups (Udem
60 and Kollarik, 2005). Second, cold air can evoke a pro-inflammatory hyper-responsiveness in the airway
61 (Cockcroft and Davis, 2006), and it is plausible that the ingestion of cold water may exert a similar effect

62 due to the trachea's close anatomical proximity to the upper-GI tract (laryngopharynx and oesophagus).
63 Both of these hypotheses are yet to be tested.

64 A third possible explanation for a decrease in spirometric values following cold-water ingestion
65 is a decrease in exhaled-breath temperature (EBT) (via indirect cooling of the upper-airway), and the
66 consequent effect of gas temperature on spirometer measurement (Miller and Sigsgaard, 1994). The
67 pneumotachograph is the most widely-used device in laboratory-based lung function testing (de Jongh,
68 2008). During an expiratory maneuver, a transducer measures pressure differentials (ΔP) across a
69 capillary tube bank. On the basis that pressure and laminar flow are proportional (Button, 2015), an
70 analogue ΔP signal is used to calculate flow, which is integrated to volume. The ΔP is dependent on
71 gas viscosity which increases with temperature (Miller *et al.* 2005). As a result, a potential source of
72 error is that a change in the temperature of expired gas (from ingesting cold fluids) may alter airflow
73 dynamics, and disrupt the flow-pressure relationship on which the pneumotachograph output is based.

74 There is also a large discrepancy between the ambient temperature (that at which the
75 pneumotachograph is calibrated) and that of the exhaled gas; this, in turn, would be expected to
76 influence the calculated flows and volumes. Accordingly, a BTPS correction factor (which assumes that
77 gas temperature in the measuring device is equivalent to body temperature; i.e., 37 °C) is applied to the
78 outcome variables. A second potential source of error, therefore, is a cold-water-induced decrease in
79 the exhaled gas temperature below the anticipated 37 °C, thereby invalidating one of the assumptions
80 of the BTPS equation.

81 To further elucidate the mechanical factors by which cold-water ingestion might influence
82 spirometry, several questions need to be addressed. First, is whether ingesting cold water reduces
83 exhaled-breath temperature (EBT) in healthy subjects. Second, is whether the reduction in EBT induced
84 by cold water ingestion is sufficient to influence airflow dynamics and, therefore, the measurement
85 characteristics of a commercially-available pneumotachograph. Data to this effect would edify
86 standardization guidelines for PFTs, and inform further mechanistic studies into the nature of lung
87 function decline following cold-water ingestion. Given that EBT is widely utilized as a means of
88 monitoring day-to-day perturbations in airway inflammation (Popov *et al.* 2017), data on cold-water
89 ingestion as a potential confounding factor in the assessment of EBT may also prove insightful.

90 Accordingly, the aims of this randomized, cross-over trial were to evaluate the effects of fluid ingestion
91 on EBT in healthy adults, and to use computational fluid dynamics (CFD) to model the effect of
92 perturbations in gas temperature (and pressure) on pneumotachograph measurements.

93 **2.0 METHODS**

94

95 **2.1 Subjects**

96 Ten healthy, recreationally-active adults (5 male/5 female) volunteered to participate (age = 36 ± 7 y;
97 mass = 87.4 ± 31.8 kg; stature = 1.74 ± 0.80 m). After providing written, informed consent, subjects
98 were instructed to attend the laboratory following an overnight fast, and to abstain from taking any fluid
99 the morning of their visits. The study was approved by the institution's Research Ethics Committee,
100 and performed in accordance with the 1964 Declaration of Helsinki.

101

102 **2.2 Experimental Overview**

103 Subjects attended the laboratory on three occasions separated by at least 24 h. At the first visit, they
104 performed basic anthropometry, baseline spirometry, and were accustomed to measures of exhaled-
105 breath temperature (EBT). At the second and third visits, subjects performed baseline tests of EBT,
106 after which they consumed a single bolus of cold- or room-temperature water with follow-up tests of
107 EBT performed periodically for 30 min. The order of trials was randomised and counterbalanced, and
108 performed at the same time of day to eliminate the influence of circadian variance. The effect of exhaled
109 gas temperature on measurement characteristics of the pneumotachograph was modelled using CFD
110 (see below).

111

112 **2.3 Spirometry**

113 Baseline pulmonary volumes, capacities, and flows were assessed via spirometry. Subjects performed
114 between three and eight FVC maneuvers into a two-way disposable mouthpiece connected to a portable
115 pneumotachograph (Alpha Touch; Vitalograph Ltd., Buckingham, England). Subjects were seated, had
116 the nose occluded, and verbal encouragement was given to ensure consistent efforts. Spirometry was
117 performed in accordance with ATS/ERS guidelines (Miller *et al.* 2005), and all values were expressed
118 in absolute terms and as percentages of predicted norms (Quanjer *et al.* 2012).

119

120 **2.4 Exhaled-Breath Temperature**

121 Exhaled-breath temperature was assessed during tidal breathing using a hand-held thermometer (X-
122 Halo; Delmedica Investments, Singapore) using protocols previously described (Popov *et al.* 2007).
123 Briefly, participants were required to inhale through the nose and exhale through the mouth into a one-
124 way antimicrobial filter. The EBT device comprised a metal core containing a high-precision thermal
125 sensor housed within a 300 mL thermo-insulated chamber. Participants were asked to maintain normal
126 tidal breathing until the metal core reached a thermal balance in the mixing chamber (3 – 6 min), at
127 which point peak-EBT was recorded. Following two baseline measures spaced 10 min apart to deduce
128 reproducibility, participants were given 10 min to consume 1,000 mL of refrigerated cold water ($2.1 \pm$
129 0.6 °C) or water at room temperature (19.4 ± 0.5 °C). Exhaled-breath temperature measures were
130 repeated at 5, 10, 15, and 30 min post-ingestion.

131

132 **2.5 Within- and Between-Day Reproducibility of Measures**

133 Within-day reproducibility of EBT was determined by comparing two sets of baseline measures
134 recorded before and after 10 min passive rest. Between-day reproducibility was determined by re-
135 assessing baseline values at the second visit > 24 h later. There were no systematic differences in
136 measurements ($p > 0.05$), and the between-occasion reliability was excellent (CV = 0.66%; SEM = 0.09
137 °C; ICC = 0.84). Using similar procedures and identical apparatus to the present study, we recently
138 published strong within- and between-day reproducibility of our spirometric assessments (all CV < 5%;
139 all SEM < 5%; all ICC > 0.94) (Tiller *et al.* 2019).

140

141 **2.6 Computational Fluid Dynamics**

142 Computational fluid dynamics was used to model the influence of exhaled-breath temperature on
143 spirometer measurements. The numerical calculation of flow was accomplished through solution of
144 continuity, Navier-Stokes, energy and turbulence model equations (Versteeg and Malalasekera, 1995).
145 Calculations were performed using commercially-available software (Fluent version 17.1.0; ANSYS,
146 Pennsylvania, U.S.A.). A geometric representation of the pneumotachograph and associated equipment,
147 suitable for simulation, was first created with a 22.5° rotational periodic geometric assumption using
148 computer-aided design (Fig. 1). This was subsequently discretized into 15.3 million polyhedral

149 elements, and the geometry represented with finite volumes in which flow calculations were iteratively
150 performed.

151 With the body temperature of the pneumotachograph held at a constant 20 °C (i.e., that at which
152 it was calibrated), the effect of various gas temperatures (20, 22, 24, 26, 28, 30, 32, 34 °C) on the
153 measured pressure drop (ΔP) across the capillary tube bank was simulated at fixed physiological flow
154 rates of 1, 4, 8, 12, and 16 L*s⁻¹. Physical gas properties were specified using temperature-dependent
155 polynomials. A pneumotachograph operates on the principle that pressure drop and laminar flow
156 through the body are proportional. For a known ΔP signal, it is possible to calculate flow rate as a factor
157 of time, and thereby interpolate volume. However, because ΔP is affected by temperature of the gas
158 passing through the device, a discordance between the calibration gas temperature and the exhaled gas
159 temperature will introduce discrepancies in the calculated flow (that is, unless a temperature correction
160 has been applied). Through the simulation process (based on a representative flow-volume curve in a
161 healthy subject with normal lung function), a series of ΔP -flow curves were obtained for each gas
162 temperature. From these curves, it was possible to calculate the discrepancy in reported flow and volume
163 that would result from a pneumotachograph calibrated at room temperature (20 °C). Accordingly, we
164 determined the effect of changes in gas temperature alone, as evoked by cold-water ingestion, on
165 predicted pneumotachograph flow/volume metrics.

166

167 **2.7 Data Analysis**

168 Descriptive and inferential statistics were calculated using SPSS 24 for Windows (IBM; Illinois,
169 U.S.A.). Reproducibility was assessed using coefficient of variation (CV), standard error of
170 measurement (SEM), and intra-class correlation coefficients (ICC). Exhaled breath temperature
171 following the ingestion of cold- and room-temperature water was compared using a two-factor
172 (condition \times time) repeated-measures ANOVA, with a critical alpha level of 0.05. The assumption of
173 equal variance was assessed via Mauchly's Test of Sphericity and, if violated ($p < 0.05$), a Greenhouse-
174 Geisser correction was applied. On significant interactions, follow-up pairwise comparisons were
175 performed using a Bonferroni-adjusted alpha level of 0.01. Effect size (Cohen's d) was used to quantify

176 the magnitude of the difference between group means (0.2 = small; 0.5 = medium; 0.8 = large effect)
177 (Cohen, 1977). Data were presented as mean \pm standard deviation (SD).

178 **3.0 RESULTS**

179

180 **3.1 Spirometry**

181 Lung function was within normal limits: FVC = 103 ± 18 %Pred; FEV₁ = 87 ± 18 %Pred; FEV₁/VC =
182 85 ± 8 %; peak expiratory flow = 106 ± 22 %Pred.

183

184 **3.2 Exhaled Breath Temperature**

185 Exhaled-breath temperature at baseline and in response to the ingestion of cold- and room-temperature
186 water is shown in Table 1.0. Baseline EBT was not different between the two experimental visits ($p =$
187 0.269 , $d = 0.25$). Mean drink temperature was 2.1 ± 0.6 °C in the cold-water condition (range 1 – 3 °C)
188 and 19.4 ± 1.5 °C in the room-temperature condition (range 17 – 21.5 °C). Relative to baseline, EBT at
189 5 min post-ingestion had decreased significantly with both cold water ($p < 0.001$, $d = 2.57$) and room-
190 temperature water ($p = 0.005$, $d = 0.94$), and in both cases remained below baseline until the final
191 measurement at 30 min ($p < 0.01$). When comparing between the conditions, there were main-effects
192 showing a lower EBT with cold water ($F[1,9] = 62.90$, $p < 0.001$), and a condition \times time interaction
193 ($F[2.21,36] = 10.72$, $p = 0.001$). Pairwise comparisons revealed that EBT was significantly lower
194 following the ingestion of cold water relative to room-temperature water at 5, 10, and 15 min ($p < 0.001$;
195 Table 1.0). Differences at 30 min were worthy of note, but did not reach statistical significance ($p =$
196 0.059).

197

198 **3.3 Computational Fluid Dynamics**

199 The influence of gas temperature on pressure differentials across the tube bank is shown in Table 2. The
200 magnitude of the pressure drop increased congruent with flow rate and, at each of the five flow rates (1,
201 4, 8, 12, and 16 L*s⁻¹), ΔP was lower at higher gas temperatures. From these data, we were able to
202 model the influence of EBT perturbations on ΔP and the subsequent expiratory flow-volume curve. In
203 a pressure transducer calibrated with an ambient gas of 20 °C, an EBT of 33.8 °C (baseline) and 31.7
204 °C (post- cold-water ingestion) would result in the underprediction of volume by 5.2 and 4.5%,
205 respectively (Fig. 2). At an example flow rate of 8 L*s⁻¹, a decrease in gas temperature from 33.8 to

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206 31.7 °C attenuated ΔP by 3.2 Pa (0.8%). Thus, in this scenario, a cold-water-induced decrease in EBT
207 of 2.1 °C results in a difference between predicted volumes of 0.7%.
208

209 **4.0 DISCUSSION**

210

211 The aims of this study were to evaluate the effects of fluid ingestion on EBT in healthy adults, and to
212 use computational fluid dynamics to model the effect of perturbations in gas temperature (and pressure)
213 on pneumotachograph measurement sensitivity. We made several observations: i) the ingestion of both
214 cold water and room-temperature water resulted in significant decreases in EBT, with values remaining
215 below baseline for at least 30 min; ii) cold water ingestion decreased EBT to a significantly greater
216 magnitude than water at room temperature; and iii) the decrease in EBT following cold-water ingestion
217 was calculated to influence the pneumotachograph flow-volume measurement by $< 1\%$. These data
218 have implications for the clinical assessment of both spirometry and EBT.

219

220 **4.1 Technical considerations**

221 There are several considerations that should predicate the interpretation of our data. First, as discussed
222 below, certain factors might confound the measurement of EBT, including food, exercise, cigarette-
223 smoking, and circadian variance (Carpagnano *et al.* 2016, 2017; Kralimarkova *et al.* 2012, 2014;
224 Svensson *et al.* 2012). To mitigate these factors, we recruited non-smokers, instructed our subjects to
225 attend the laboratory having abstained from food, fluid, and exercise on the morning of the test, and we
226 assessed EBT at the same time of day in both experimental trials (i.e., 08:00 – 09:00). We also
227 demonstrate excellent within- and between-day reliability of our EBT measures: no systematic
228 differences in measurements ($p > 0.05$); CV = 0.66%; SEM = 0.09 °C; ICC = 0.84. As such, we are
229 confident that our data reflect the *true* EBT responses to cold-water ingestion.

230 Second, our model of EBT and airflow dynamics is only relevant when assessing lung function
231 via the Fleisch or Lilly pneumotachograph (i.e., those deriving flow via pressure differentials across a
232 screen or capillary tube bank). Other frequently-used devices include wet/dry volume-measurement
233 spirometers, and flow measurement devices operating under different principles (e.g., mass flow
234 meters), and there are systematic differences in the data obtained among the various spirometers
235 (Brouwer *et al.* 2007; Gerbase *et al.* 2013; Stewart *et al.* 2003). As such, although pneumotachographs
236 are generally considered to be the best (Miller *et al.* 1997) and most widely-used (de Jongh, 2008)

237 means of measuring forced expiratory maneuvers, further studies are needed to assess the effects of
238 cold-water-induced changes in airflow dynamics with other devices.

239 Finally, it is worth noting that our airflow model is based on the standard, non-heated
240 pneumotachograph that is in widespread clinical use (Miller and Sigsgaard, 1994). Some devices
241 contain a heated element that conditions the expired air in order to reduce surface condensation in the
242 tube bank that may occur during repeated expiratory maneuvers, but this is unlikely to reduce
243 measurement inaccuracies that result from changes in gas temperature.

244

245 **4.2 Exhaled-breath Temperature and Computational Fluid Dynamics**

246 The bronchial microvasculature plays an important role in the response to airway disease (Paredi and
247 Barnes, 2009), and the assessment of EBT has become commonplace in monitoring day to-day
248 perturbations in airway blood flow resulting from inflammation and exacerbation (Popov *et al.* 2012).
249 Indeed, acute exacerbations in asthmatic patients (resulting from hyperreactivity and vascularization of
250 the bronchial smooth muscle) transiently increase EBT; by contrast, chronic airway damage and
251 reduced vascularization which characterize COPD results in lower baseline EBT values (Popov *et al.*
252 2012).

253 Several factors are thought to confound the measurement of EBT. Circadian variance was
254 shown to result in EBT fluctuations of ~ 1.33 °C (Carpagnano *et al.* 2017), while smoking a cigarette
255 and eating snack foods have been shown to influence baseline measurements by ~ 0.19 °C
256 (Kralimarkova *et al.* 2014) and ~ 0.48 °C (Kralimarkova *et al.* 2012), respectively. Following exercise,
257 asthmatics and healthy controls exhibited increases in EBT of < 1.0 °C, with no significant difference
258 between groups (Scvensson *et al.* 2012). To our knowledge, ours is the first study to evaluate the effect
259 of fluid ingestion on EBT measurement. The data show that a bolus of refrigerated water decreased
260 EBT to a far greater magnitude (-2.1 °C) than that observed from other confounders. Moreover, the
261 decrease had only partially recovered (to -1.0 °C) at 30 min post-ingestion (Table 1.0). Accordingly,
262 patients using EBT as a means of monitoring airway inflammation should abstain from drinking large
263 volumes of fluid, particularly cold fluid, for at least 30 - 60 min before a given assessment.

264 To evaluate the effect of cold-water ingestion on spirometer measurement, we first modelled
265 the broad effects of gas temperature on airflow dynamics in a standard, non-heated pneumotachograph.
266 The model assumed that the device was calibrated using an ambient gas at 20 °C. At an expiratory flow
267 of 8.0 L*s⁻¹, we calculated that an exhaled gas temperature of 33.8 °C (baseline EBT) would result in
268 a ΔP across the tube bank that is 22.4 Pa (5.5%) larger than that elicited by an ambient temperature
269 exhalate. The result would be a flow underprediction of 5.2% (Table 2). To accommodate this
270 considerable error, a BTPS correction factor is applied which assumes that gas temperature in the
271 measuring device is equivalent to body temperature (i.e., 37 °C). However, there are numerous studies
272 showing baseline EBT to be below 37 °C in various subgroups, including healthy controls (33.2 -
273 34.8 °C, Popov *et al.* 2007; Garcia *et al.* 2013; Svensson *et al.* 2012), asthmatics (33.7 - 35.5 °C, Popov
274 *et al.* 2007; Svensson *et al.* 2012, 2014; Garcia *et al.* 2013), and patients with COPD (34.0 - 34.6 °C,
275 Lázár *et al.* 2014). We presently report a baseline EBT in our healthy cohort of $\sim 33.8 \pm 0.4$ °C, which
276 mirrors data from Svensson *et al.* (2012), and corroborates the general consensus. As such, to mitigate
277 unnecessary errors in spirometric measurement, we concur with others who suggest that the BTPS
278 correction factor for expiratory gas should be adapted to the actual gas conditions in the
279 pneumotachograph (Normand *et al.* 2007).

280 We next assessed the effects of a change in EBT on spirometer airflow dynamics. We showed
281 that a cold-water-induced decrease in EBT of 2.1 °C would alter the linear flow-pressure relationship,
282 and decrease the volume output by 0.7%. Our earlier studies show a decrease in FVC, FEV₁, and MEF₂₅₋
283 ₇₅ in the region of 5 – 10% following cold-water ingestion (Turner *et al.* 2015; 2016). These decreases
284 are of a far greater magnitude than can be explained by our current model of pneumotachograph airflow
285 temperature considerations. At present we can only speculate on the physiological mechanisms that
286 underpin lung function decline following cold-water ingestion. It was initially thought that cold-water
287 ingestion may evoke a pro-inflammatory hyperresponsiveness in the airway, in a similar fashion to that
288 observed with cold air (Cockcroft and Davis, 2006). However, Svensson *et al.* (2012) reported larger
289 post-exercise decreases in FEV₁ in those individuals with higher EBT, suggesting that EBT increases
290 under conditions of acute airway inflammation. We currently report decreases in EBT following cold-
291 water ingestion, thereby potentially discounting airway inflammation and/or hyperresponsiveness as a

292 causative factor. Further research into these mechanisms may have important implications for routine
293 pulmonary function testing guidelines.

294

295 In conclusion, we observed large and sustained decreases in exhaled breath temperature following the
296 ingestion of cold water. The magnitude of the decrease exceeds that seen with other confounding
297 variables and, as such, abstaining from fluid ingestion for at least 30 min prior to a test should be
298 integrated into standard EBT assessment guidelines. However, the decreases in EBT influenced
299 spirometer measurements only negligibly (<1%), suggesting that cold-water-induced decreases in
300 spirometric output likely have a physiological mechanism, which warrants further study.

301

302 **Acknowledgements**

303 The authors would like to thank the subjects who volunteered their time to participate in this research.

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426 **FIGURES & TABLES**

427

428 **Table 1.** Exhaled-breath temperature at baseline and following the ingestion of cold or room-
429 temperature water.

430

431 **Table 2.** The modeled influence of gas temperature on pressure changes (ΔP) across the
432 pneumotachograph tube bank.

433

434 **Fig. 1.** Modelled pneumotach geometry with a rotational periodicity of 22.5°. The geometry of the
435 pneumotach can be approximated as axially repeating, allowing the use of rotational periodic boundary
436 assumptions that reduce overall computational expense of the simulation.

437

438 **Fig. 2.** Modelled influence of gas temperature on a typical expiratory flow-volume curve. In a
439 pressure transducer calibrated with a gas of 20 °C (standard room temperature), an EBT of 33.8 °C
440 (baseline) and 31.7 °C (post- cold-water ingestion) result in an underestimation of the calculated
441 volume by 5.2 and 4.5%, respectively. The EBT decrease following cold-water ingestion (2.1 °C)
442 results in a 0.7% underprediction of volume.

443

444 **Table 1.** Exhaled-breath temperature at baseline and following the ingestion of cold- or room-
 445 temperature water.

	Cold (2.1 °C)		Room (19.4 °C)		* <i>p</i>	<i>d</i>
Baseline	33.8	± 0.4	33.7	± 0.5	0.269	0.25
+5 min	31.7	± 1.1*	33.0	± 0.9*†	<0.001	1.34
+10 min	32.6	± 0.6*	33.2	± 0.6*†	<0.001	1.06
+15 min	32.5	± 0.6*	33.3	± 0.5*†	<0.001	1.46
+30 min	32.8	± 0.5*	33.3	± 0.8*	0.059	0.74

446

447 Mean ± SD, n=10. *d* = Cohen's *d* effect size (0.2 = small, 0.5 = medium, 0.8 = large effect) (17).
 448 *significantly different versus respective baseline; †significantly different versus cold water.

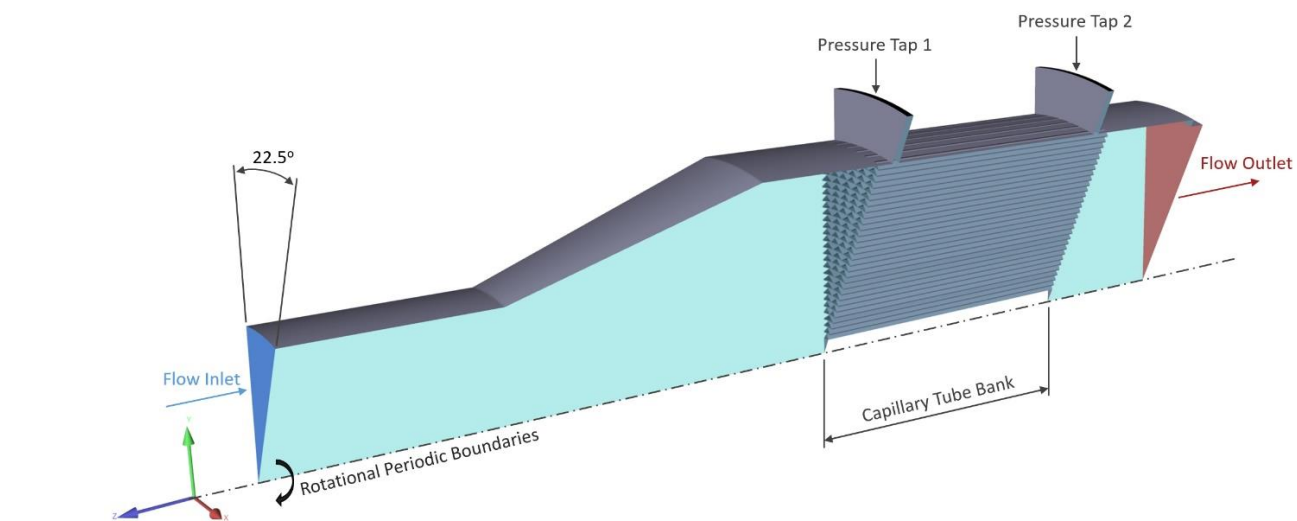
449

450 **Table 2.** The modeled influence of gas temperature on pressure changes across the
 451 pneumotachograph tube bank.
 452

453	Flow (L·s ⁻¹)	Pressure difference across pneumotachograph (Pa)		
		20 °C	28.5 °C (%Diff.)	34.5 °C (%Diff.)
454	1	-43.9	-42.6 (3.1)	-41.7 (5.3)
455	4	-197.9	-191.7 (3.2)	-187.6 (5.5)
456	8	-426.5	-413.1 (3.2)	-404.1 (5.5)
457	12	-664.2	-643.5 (3.2)	-629.5 (5.5)
	16	-907.4	-877.0 (3.5)	-858.0 (5.8)

458 %Diff. is relative to pressure at 20 °C.

459

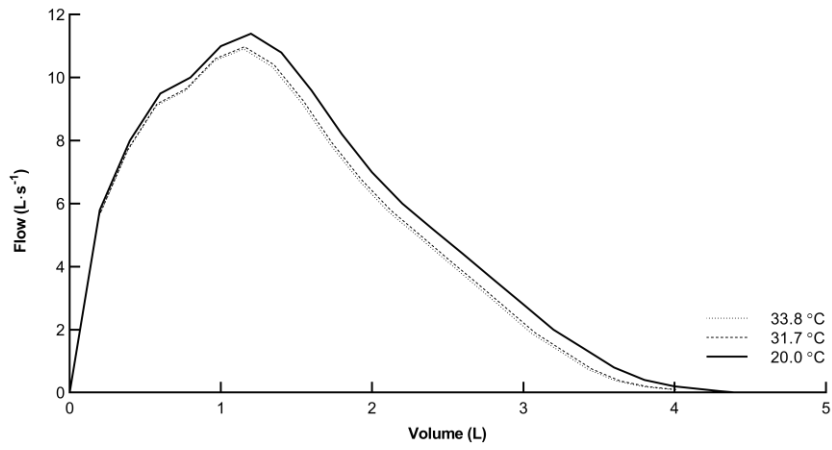


460

461 **Figure 1.**

462

Airflow dynamics following cold-water ingestion



463

464 **Figure 2.**