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Preschool Children's Inhalation Rates Estimated from Accelerometers—A Tool to Estimate Children's Exposure to Air Pollution

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ABSTRACT

Children are particularly sensitive to air pollution exposure, and their personal exposures may differ significantly from those of adults. One key factor for understanding the personal inhaled dose of air pollutants is the respiratory minute ventilation (V_e). To estimate the amount of particles circulated through the lungs, 24 h averages of V_e are often used. These averages poorly capture variations in V_e during the day, and between individuals. We here develop and implement a concept to assess individual V_e of children, with minimal impact on their natural activity and movement pattern by using ActiGraph GT3X+ accelerometers. Activity of 136 preschool children in the ages 3 to 5 years was logged using accelerometers while the children attended their preschools during a week. A linear regression equation is developed and used for estimating V_e from the accelerometer data retrieved for each individual child. The results show large variations in weekly average V_e between individuals, ranging from 0.33 to 0.48 L min^{-1} kg^{-1}. Over the days the averages of the individuals' 1st and 3rd quartiles were 0.28 and 0.48 L min^{-1} kg^{-1}, respectively. Outdoor activities resulted in a 17% higher V_e than indoor activities, which may be important to consider when estimating the inhaled dose of air pollutants since pollution levels and particle toxicities can be different indoors and outdoors. The observations motivate the use of individual values of V_e in exposure assessments and suggest that accelerometers are a suitable tool for estimating children's individual V_e in their natural environment. Combined with time resolved local air pollution monitoring, these measurements can provide the basis of a more precise estimate of children's inhaled dose of air pollutants.

Keywords: Minute ventilation, Inhalation rate, Physical activity, Children, Air pollution, Inhaled dose

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1 INTRODUCTION

The World Health Organization recognizes air pollution as one of the biggest threats to human health (WHO, 2021). The dose of air pollutants to the respiratory tract is a combination of, in principle, three factors: pollution levels that the individual is exposed to (concentration and exposure time), volume of air circulated through the lungs (minute ventilation/inhalation rate) and deposited fraction of the inhaled particles (Ashmore and Dimitroulopoulou, 2009; Wierzbicka *et al.*, 2014; Rissler *et al.*, 2017b; Deng *et al.*, 2019). Although all three factors are of importance for conducting health assessments of air pollution, minute ventilation/inhalation rate (often referred to as inhalation rate when averaged over the day) is a key factor for understanding the variation in inhaled dose over time and in between individuals and population groups (Rissler *et al.*, 2017a).

Children are at an increased risk of inhaling more air pollutants than adults. Compared to adults, children have a higher minute ventilation (V_e) if normalized to body mass (sitting down ~0.2 L min^{-1} kg^{-1} compared to ~0.1 L min^{-1} kg^{-1} for adults (Rissler *et al.*, 2017b))—a difference that is even more pronounced considering children's higher physical activity. For example, the Exposure Factors Handbook (U.S. EPA, 2011) reports values of ~2.0 L min^{-1} kg^{-1} for preschool aged children while ~0.6 L min^{-1} kg^{-1} for adults. Children also spend more time, active, outdoors during daytime periods when air pollution levels tend to peak (Schuepp and Sly, 2012). This is alarming since children are especially vulnerable to air pollution exposure as their lungs and cardiovascular system are still developing and damages in these systems during childhood might cause permanent impairments and accordingly lower their life expectancy (Salvi, 2007; WHO, 2021). In many industrialized countries, children aged 1–6 years spend much of their awake time at preschools. Therefore, the air pollution levels in the preschool's vicinity as well as the physical activity levels of the children while attending their preschool, and during indoor/outdoor play, are important factors when estimating the inhaled dose of air pollutants.

To calculate inhaled doses of air pollutants, tabulated values of inhalation rates averaged over the day or grouped on activities and stratified by gender and age are often used. As the inter- and intra-individual variation in activity level may be large, this generalization might cause large discrepancy between tabulated and actual inhaled volumes, especially considering that air pollution levels will vary over the day and in between local environments. Time resolved V_e can be assessed with high accuracy in laboratory settings. However, this often involves wearing a relatively large facemask or mouthpiece connected to a stationary equipment, which restricts both the location of the measurement and the subject's ability to move around (Kawahara *et al.*, 2011b; Tipparaju *et al.*, 2020). Thus, to assess breathing parameters and volumes that represent the true state during children's free play using such devices is difficult. Recently, some studies have focused on developing facemasks for monitoring V_e in free-living conditions for adults (Tipparaju *et al.*, 2020).

An alternative methodology to assess V_e was suggested in a study of preschool children by Kawahara *et al.* (2011a, 2011b, 2012). In their studies, pulse loggers and accelerometers were evaluated to estimate V_e based on the physical activity of the children. They report a high linear correlation between the accelerometer output and V_e (Pearson's r of 0.913 using a 3-axial accelerometer and 0.886 using a 1-axial accelerometer) (Kawahara *et al.*, 2011b). A similar methodology was also suggested and implemented by Rodes *et al.* (2012) for adults, where the estimated V_e was combined with local variations in the air pollution, also reporting a satisfactory linear correlation between accelerometer output and V_e.

Accelerometers are a common tool to assess physical activity and several studies have used them to study activity of preschool children (Raustorp *et al.*, 2012; Timmons *et al.*, 2012; Wu *et al.*, 2017; Nilsen *et al.*, 2019; Ng *et al.*, 2020), motivated by that physical activity is a key for good health and well-being of children, associated with development, growth, and a reduced risk of becoming overweight (Timmons *et al.*, 2007). Some of these previous studies have also related the accelerometer output to oxygen consumption ($\dot{V}O_2$), or similar measures such as energy expenditure, metabolic equivalents (METs) or physical activity ratio (PAR) (Pate *et al.*, 2006; Kawahara *et al.*, 2011b; Adolph *et al.*, 2012; Hanggi *et al.*, 2013; Butte *et al.*, 2014). One specific accelerometer type that is commonly used in research studies is the ActiGraph GT3X+ (Pate *et al.*, 2006; Butte *et al.*, 2014; Hildebrand *et al.*, 2014; Johansson *et al.*, 2015; Leppänen *et al.*, 2016; Migueles *et al.*, 2017). The relation between the ActiGraph GT3X+ output data and $\dot{V}O_2$/PAR for preschool children has been studied in two of the above mentioned studies (Pate *et al.*, 2006; Butte *et al.*, 2014), however, no studies have so far used this accelerometer to estimate V_e.

In this study, we used the 3-axial ActiGraph GT3X+ accelerometer to study the activity of 136 preschool children at 9 preschools. We present a linear regression equation between the ActiGraph GT3X+ accelerometer output and V_e and apply this to investigate variations in activity and V_e between: individuals, gender, preschool groups and during indoor and outdoor free play.

The present work is part of a larger study also including air quality monitoring, indoors and outdoors, at the preschools. The study has been reviewed and approved by the central Swedish Ethical Review Authority (dnr 2019-01031), in accordance with the Declaration of Helsinki.

2 METHODS

2.1 Study Design and Recruitment

Nine preschools participated in the study, whereof four in the city of Malmö (Sweden's third largest city) and the remaining five from rural and less urban areas (~20–100 km from Malmö). There was a diversity between the preschools in terms of the size of the preschool groups, and the size and quality of the preschool yards (for example vegetation, toys, and play equipment) and indoor areas. From each preschool, children aged 3 to 5 years wore accelerometers while attending their preschool during one workweek (Monday–Friday). The participation rate was approximately 38% (range: 17–48%) for children at the preschools. The guardians to the preschool children were informed of the study and approved their child's participation (written information and consent).

In total 163 children participated in this study and valid accelerometer measurements were obtained from 150 children. Only data from children that wore the accelerometer for two days or more were selected for the analysis and data from one child was excluded due to the child's high BMI (N = 136). The remaining children were evenly distributed between rural (N = 68) and urban (N = 68) preschools, although the number of children from the different preschools varied (Table 1). The relative participation of girls and boys were 49% and 51%, respectively. The average age (± 1 standard deviation [SD]) of the participating children was 4.5 ± 0.8 years and their average weight and height were 17.8 ± 2.8 kg and 106.6 ± 7.9 cm (corresponding to a BMI of 15.6 ± 1.4).

2.2 Data Collection and Analysis

The children wore a 3-axial ActiGraph GT3X+ accelerometer (Pensacola, FL, USA; sample rate 30 Hz) when at their preschool. The preschool teachers were instructed to place the accelerometers on the right side of the children's waist (attached with an elastic band) when they arrived in the morning. They also kept a logbook of when the children were indoors and outdoors during the days. For one preschool (R5, Table 1) the day began outdoors, and the accelerometers were attached to the children when the group went indoors (at 9.00 a.m. each day), resulting in a lack of measurements from this outdoor episode.

The average number of days the children wore the accelerometers varied between 3.2 and 4.4 days for the preschools (Table 1), reflecting that the children were not at the preschools every

Table 1. Study participants, accelerometer wear time and information on time spent indoors and outdoors. Values are presented as number of individuals [whereof girls] and mean ± 1 SD for children in respective preschool. R = rural preschools, U = urban preschools. Measurements were performed during spring for preschools 1 and 2 and during autumn for preschools 3–5, and in parallel at preschools R1 and U1 and so on.

	Number of individuals [girls]	Wear time (days)	Wear time (mean min day^{-1})		Outdoor (% of total time)
			Indoor	Outdoor	
R1	15 [9]	4.2	163	262	61
R2	11 [7]	3.7	202	223	54
R3	11 [7]	3.2	203	163	43
R4	19 [10]	3.8	187	258	58
R5	12 [4]	4.1	256	107	28–39[a]
U1	25 [10]	3.9	240	240	46
U3	26 [12]	4.4	288	69	19
U4	3 [1]	4.3	271	93	25
U5	14 [7]	3.3	281	156	35
Average	136 [67]	3.9 ± 1.0	234 ± 66	181 ± 87	41 ± 17

[a] For this preschool the day began outdoors. The children started wearing the accelerometer when going indoors. In the interval given, the lower limit corresponds to that all children arrived to the preschool at the time the groups went indoors (9.00 a.m.), while the upper corresponds to that all children arrived an hour earlier (at opening).

day. Additionally, many of the children were only present at the preschools for a few hours each day.

The accelerometer data was analysed in the software ActiLife (v. 6.13.4; ActiGraph LLC, Pensacola, FL, USA), using an epoch length of 5 s. To exclude events when the preschool teachers carried accelerometers around, wear time periods of less than 40 min were excluded. Accelerometer wear time was validated according to the model by Choi *et al.* (2011). The placement of the accelerometers, selection of registration time, epoch length etc. were based on findings presented elsewhere (Dencker *et al.*, 2012; Migueles *et al.*, 2017).

2.3 Physical Activity Distribution

Physical activity is usually divided into four intensity categories: sedentary (e.g., colouring or watching TV), light (playing with blocks or walking), moderate (climbing stairs or tossing a ball) and vigorous (running) (Tanaka *et al.*, 2007; Kawahara *et al.*, 2012). Different sets of accelerometer cut-points have previously been developed for classification into these physical activity categories. These cut-points are population-specific and strongly age dependent.

For the classification, the ActiLife software uses the number of counts per minute registered by the accelerometers, either in the vertical axis, VA, (up–down), or using the vector magnitude (VM), defined as $VM = \sqrt{x^2 + y^2 + z^2}$, where x, y and z are counts registered for each axis (vertical, longitudinal and lateral). The classification of the children's physical activity into intensity categories was done using the VA, since it is the most validated measure addressing the intensity of physical activity, with cut-points presented by Butte *et al.* (2014) for 3–5 year old children (Supplementary Material; Table S2).

The physical activity analysis was stratified based on the children's gender as well as on indoor and outdoor activities, derived from the preschool teachers' logbooks. Data was also stratified based on the preschool settings as "urban" or "rural".

2.4 Derivation of Minute Ventilation from Vector Magnitude

A linear regression equation is suggested to translate VM from the ActiGraph GT3X+ accelerometer to V_e. The regression is based on the relation between $\dot{V}O_2$ and V_e, well described by a linear relationship (Durnin and Edwards, 1955; Cooper *et al.*, 1987; Newstead, 1987; O'Donnell *et al.*, 2012; Hestnes *et al.*, 2017) up to the ventilatory threshold (Claxton, 1999), and a linear relationship between PAR and the VM given by the ActiGraph GT3X+. PAR is a "child-specific MET", calculated by dividing the energy expenditure for a specific activity by the estimated basal metabolic rate for children of the age of interest (Pate *et al.*, 2006; Kawahara *et al.*, 2011b; Adolph *et al.*, 2012; Hanggi *et al.*, 2013; Butte *et al.*, 2014). Linear correlations between accelerometer output and V_e has been reported and used in two previous studies deriving V_e for children and adults (Kawahara *et al.*, 2011a; Rodes *et al.*, 2012).

Butte *et al.* (2014) performed room calorimetry for minute-by-minute measurement of energy expenditure for preschool children and related the result to accelerometer counts (VM) of the ActiGraph GT3X+. The VM presented for the activity level cut-points (sedentary/light, light/moderate and moderate/vigorous) and their corresponding PAR show a linear relationship, given in Supplementary Material (Eq. (S2)). Also, a linear relationship was derived between PAR and V_e data published by Kawahara *et al.* (2012), shown in Supplementary Material (Eq. (S1)). By combining these two relationships, a linear regression equation translating the VM from the ActiGraph GT3X+ accelerometer into V_e was established according to:

$$V_e = 8.34 \cdot 10^{-5} \cdot VM + 0.246 \qquad (1)$$

where V_e is the minute ventilation (L min^{-1} kg^{-1}) at BTPS (body temperature, ambient pressure, saturated with water vapour) and VM is the vector magnitude (counts min^{-1}). The VM was chosen (prior to the VA) based on the slightly better correlation with V_e reported for a 3-axial accelerometer than for a 1-axial accelerometer (Pearson's r of 0.913 compared to 0.886) by Kawahara *et al.* (2011b).

The average VM reported by the ActiLife software was converted to the corresponding V_e, for each child. The time resolved accelerometer data was also analysed. The time resolution of V_e is limited by the epoch length chosen for the accelerometer data, in these analyses 15 s averages were used motivated by that adjustment of the breathing rate to an increase/decrease in activity is not instant. Furthermore, a maximum V_e of 17.25 L min^{-1} (0.97 L min^{-1} kg^{-1}) was applied based on the maximum V_e reported in Zapletal *et al.* (1987), extrapolating to an age of 5 years. This had no effect on the median values reported due to the short and few episodes at activity levels where it applies.

2.5 Statistical Analysis

Values are expressed as mean ± 1 SD, unless otherwise stated. The statistical tests and correlation analysis of the data was performed in IBM® SPSS® Statistics (v. 27). Differences between gender and children at rural and urban preschools were investigated with Student's independent samples t-test and differences between indoor and outdoor environments were investigated with Student's paired samples t-test. Pearson correlation was used to investigate linear correlations between percentage of time spent outdoors and VM. Significance was considered for three levels at $p < 0.05$, $p < 0.01$ and $p < 0.001$.

3 RESULTS

3.1 Physical Activity Analysis

The physical activity of the children was classified into the four activity categories (sedentary, light, moderate and vigorous) based on the accelerometers' vertical axis (VA) using the cut-points presented by Butte *et al.* (2014). The average percentage of time spent in each category was 60% sedentary, 28% light, 9% moderate and 4% vigorous (Table 2). The physical activity of the children was also stratified based on indoor or outdoor activities (Fig. 1 and Table 2). The logs for when the preschool children were outdoors or indoors show that an average of 41% of the preschool day was spent outdoors, however, the variation between the preschools was considerable (Table 1).

Both boys and girls were significantly more sedentary indoors compared to outdoors ($p < 0.001$). Accordingly, a lower percentage of time was spent in all the remaining physical activity categories indoors ($p < 0.001$), as seen in Table 2. The same trend is observed in the average of the VM, with a 54% higher average VM outdoors than indoors (Table 3). A small gender difference was observed, showing that the girls were more sedentary both indoors and outdoors compared to the boys. The girls also spent significantly less time in all the other physical activity categories both indoors and outdoors except for the vigorous activity outdoors, where no significant gender difference was found. Consistently, the average VM was less for girls compared to boys, but the difference was small and significant only during indoor activities ($p < 0.01$; Table 3).

When indoors, the children at rural preschools spent higher percentage of time in sedentary activity (68.2 ± 7.3 and 65.4 ± 7.7, $p < 0.05$) while lower percentage of time in moderate (6.1 ± 2.1 and 7.3 ± 2.3, $p < 0.01$) and vigorous (2.3 ± 1.0 and 3.3 ± 1.4, $p < 0.001$) activity compared to the children at urban preschools. The same pattern was observed in the VM where the average

Table 2. Percentage of time spent in the four physical activity categories after analysis with the vertical axis cut-points from Butte *et al.* (2014). Values are presented as percentage of time (mean ± 1 SD) during time spent indoors, outdoors or both indoors and outdoors (Total).

	Sedentary (% of time)		Light (% of time)		Moderate (% of time)		Vigorous (% of time)		Total (% of time)			
	Indoor	Outdoor	Indoor	Outdoor	Indoor	Outdoor	Indoor	Outdoor	Sedentary	Light	Moderate	Vigorous
Girls	69.2 ± $6.9^{***,\#}$	53.1 ± $9.4^{**,\#}$	22.3 ± $4.5^{**,\#}$	31.5 ± $5.3^{***,\#}$	6.0 ± $2.0^{***,\#}$	10.6 ± $3.6^{*,\#}$	2.5 ± $1.2^{*,\#}$	4.8 ± $3.3^{\#}$	62.1 ± 7.1^{**}	26.2 ± 4.2^{**}	8.1 ± 2.3^{**}	3.6 ± 1.8
Boys	64.4 ± $7.6^{***,\#}$	48.6 ± $7.7^{**,\#}$	25.0 ± $5.0^{**,\#}$	34.8 ± $4.6^{***,\#}$	7.5 ± $2.3^{***,\#}$	11.9 ± $3.7^{*,\#}$	3.1 ± $1.3^{*,\#}$	4.6 ± $3.0^{\#}$	58.2 ± 7.3^{**}	28.7 ± 4.8^{**}	9.3 ± 2.6^{**}	3.8 ± 1.8
All	66.8 ± $7.6^{\#}$	50.8 ± $8.9^{\#}$	23.7 ± $5.0^{\#}$	33.2 ± $5.2^{\#}$	6.7 ± $2.3^{\#}$	11.3 ± $3.7^{\#}$	2.8 ± $1.3^{\#}$	4.7 ± $3.1^{\#}$	60.1 ± 7.5	27.5 ± 4.7	8.7 ± 2.5	3.7 ± 1.8

Significant difference between girls and boys is noted as *($p < 0.05$), ** ($p < 0.01$), *** ($p < 0.001$); Significant difference between indoor and outdoor environments is noted as $^{\#}$ ($p < 0.001$).

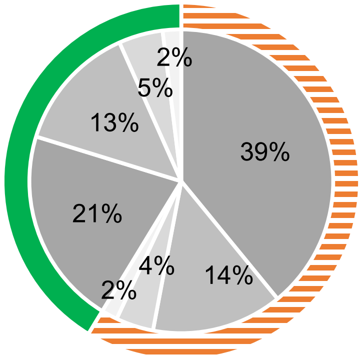

Fig. 1. Physical activity presented as percentage of total time, divided into time spent indoors (striped) and outdoors (filled). Each grey nuance represent time spent in the four physical activity categories, where dark grey represents sedentary and the lighter greys light, moderate and vigorous activity.

Table 3. Vector magnitude and minute ventilation, calculated with Eq. (1) from the vector magnitude, for time spent indoors and outdoors separately as well as together (Total). Minute ventilations are given at BTPS, and are expressed as both absolute (L min^{-1}) and normalized to body weight (L min^{-1} kg^{-1}). Values are presented as mean ± 1 SD.

	Vector magnitude (counts min^{-1})			Minute ventilation (L min^{-1} kg^{-1})			Minute ventilation (L min^{-1})		
	Indoor	Outdoor	Total	Indoor	Outdoor	Total	Indoor	Outdoor	Total
Girls	1294 ± 317$^{**,\#}$	2052 ± 647$^{\#}$	1632 ± 400	0.35 ± 0.03$^{**,\#}$	0.42 ± 0.05$^{\#}$	0.38 ± 0.03	6.4 ± 1.1$^{\#}$	7.6 ± 1.6$^{\#}$	6.9 ± 1.3
Boys	1461 ± 362$^{**,\#}$	2178 ± 519$^{\#}$	1754 ± 388	0.37 ± 0.03$^{**,\#}$	0.43 ± 0.04$^{\#}$	0.39 ± 0.03	6.4 ± 1.4$^{\#}$	7.5 ± 1.6$^{\#}$	6.9 ± 1.5
All	1378 ± 349$^{\#}$	2116 ± 587$^{\#}$	1694 ± 398	0.36 ± 0.03$^{\#}$	0.42 ± 0.05$^{\#}$	0.39 ± 0.03	6.4 ± 1.2$^{\#}$	7.5 ± 1.6$^{\#}$	6.9 ± 1.4

Significant difference between girls and boys is noted as ** ($p < 0.01$); Significant difference between indoor and outdoor environments is noted as $^{\#}$ ($p < 0.001$).

VM was significantly lower for the children at the rural preschools when indoors (1297 ± 310 and 1460 ± 369 counts min^{-1}, $p < 0.01$). No significant difference between the two groups was observed during outdoor activities, although the majority of the rural preschools spent more time outdoors.

To investigate to what extent the amount of time spent outdoors affected the physical activity, a correlation analysis was performed between the percentage of time spent outdoors and total physical activity (VM total), as well as VM outdoor and VM indoor (Supplementary Material; Fig. S2). A significant correlation was found for the total activity (VM total), with a joint increase in physical activity and percentage of time spent outdoors (Pearson's $r = 0.19$, $p = 0.03$). No correlation was found between the percentage of time outdoors and physical activity level outdoors (VM outdoor), while there was a trend of lower physical activity indoors (VM indoor) with increasing percentage of time spent outdoors (Pearson's $r = -0.16$, $p = 0.07$). To further analyse the effect of time spent outdoors on the activity, a correlation analysis was made separating the children into two groups with children spending less or more than 50% of the preschool day outdoors. For the children in the group that spent shorter periods outdoors (< 50% of the day) the correlation between time spent outdoors and total activity as well as activity outdoors was stronger than for the whole group.

3.2 Minute Ventilation

The resulting mean V_e, estimated from Eq. (1), for the children was 0.39 L min^{-1} kg^{-1} or 6.9 L min^{-1}. The mean V_e was significantly higher during the time children spent outdoors compared to indoors ($p < 0.001$), which was anticipated from the activity analysis since V_e is linearly related to VM. The absolute difference between the V_e indoors and outdoors was 0.06 L min^{-1} kg^{-1} or 1.1 L min^{-1}, representing a 17% higher V_e outdoors (Table 3). There were some variations in average VM and thus in the resulting V_e between the different preschools (Supplementary Material; Table S3).

Table 4. Median vector magnitude of all children in the respective physical activity category during the measurement period and corresponding values of the minute ventilation calculated with Eq. (1).

Physical activity category	Vector magnitude[a] (counts min^{-1})	Median vector magnitude (counts min^{-1})	Minute ventilation (L min^{-1} kg^{-1})	Minute ventilation[b] (L min^{-1})
Sedentary	$<$ 820	197	0.26	4.7
Light	820–3908	1971	0.41	7.3
Moderate	3908–6112	4668	0.64	11.3
Vigorous	$>$ 6112	7648	0.88	15.7

[a] According to cut-points presented in Butte *et al.* (2014).
[b] Calculated using the weight 17.8 kg (average from the current study).

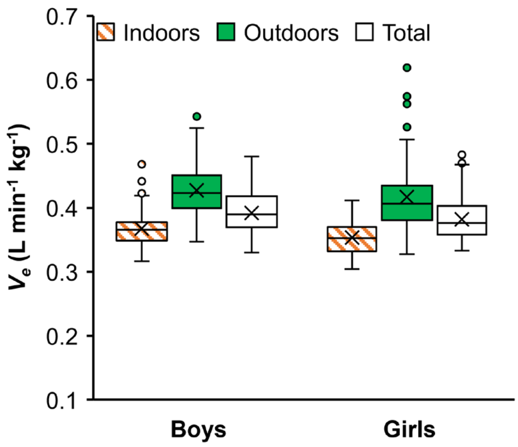

Fig. 2. Minute ventilation, V_e, indoors (striped), outdoors (filled) and total (white) for boys and girls. The boxes represent the first and third quartiles, the lines in the boxes represent medians, x represent mean, whiskers represent minimum and maximum values and single points represent outliers. The quartiles were calculated inclusive of the median.

The children's individual weekly average V_e ranged from 0.33 to 0.48 L min^{-1} kg^{-1}, showing large individual differences. An even larger difference in average V_e between the individuals was observed for outdoor activities, where the average V_e ranged from 0.33 to 0.62 L min^{-1} kg^{-1}. As for VM, a trend with slightly lower V_e (when normalized to body mass) was observed for the girls (Fig. 2 and Table 3). This difference was however only significant for the time indoors.

There were considerable variations in V_e during the week for the individuals, with occasions of V_e close to that of resting (0.25 L min^{-1} kg^{-1}) up to short events with very high V_e (up to 0.97 L min^{-1} kg^{-1} as specified by the applied maximum). The average of the individual's 1st and 3rd quartiles were 0.28 and 0.48 L min^{-1} kg^{-1}, respectively. The average V_e during the time the children spent in each of the four physical activity categories ranged from 0.26 L min^{-1} kg^{-1} for the sedentary category to 0.88 L min^{-1} kg^{-1} for the vigorous category (Table 4).

4 DISCUSSION

4.1 Deriving Minute Ventilation from Accelerometer Data for Exposure Assessments

As mentioned in the introduction, there are three main factors determining the personal deposited dose of air pollution in the respiratory tract: *i*) pollution levels that the individual is exposed to, *ii*) V_e (air circulated through the lungs) and *iii*) deposited fraction of the inhaled particles.

Another important factor, included in the variations of V_e (*ii*), is the activity level of a person. Due to an increased metabolic rate at higher activities, the activity level will directly impact how much air is inhaled, and thus also the inhaled amount of air pollutants. There are also variations in V_e between individuals and population groups, such as between children and adults, and healthy and diseased (Ofir *et al.*, 2008; Löndahl *et al.*, 2012; Borel *et al.*, 2014). Additionally, there are differences in the lung deposited fraction of particles between individuals and between adults and children (Rissler *et al.*, 2017a), and a change in deposited fraction of particles with activity. However, the differences in deposited fraction do not alter the dose to any extent near that of V_e.

In urban environments, there may be large temporal and spatial variations in air pollution levels. When applying daily inhalation rates (i.e., daily average V_e) there is a risk of underestimating the inhaled dose if the personal activity is high in environments where the air pollution levels are elevated. Furthermore, there is a large variation between the activity level of individuals. Thus, the optimal way to assess the personal inhaled dose of air pollution would be to combine the personal variation in V_e with measurements of local air pollution levels. There is an ongoing rapid technical development for monitoring air pollution exposure using small and cheap devices, allowing individual exposure monitoring. However, there are yet no established ways to assess V_e or inhalation flow rates of individuals (and children) in their natural environment, without affecting their activity.

In this study, we therefore suggest and implement a methodology to estimate V_e for preschool children based on their physical activity registered by accelerometers. We do not claim this method to be as precise as those directly monitoring the inhaled/exhaled flow rates in a laboratory setting. However, the method may be a useful and less intrusive alternative that would allow for time resolved estimations of V_e under daily activities, and in combination with actual measures of ambient air pollution levels, to be used for estimating the inhaled dose of air pollutants.

Two earlier studies have suggested and used accelerometers for estimating V_e—one for adults (Rodes *et al.*, 2012) and one for preschool children (Kawahara *et al.*, 2011a, 2011b, 2012). Neither of these studies used the same type of accelerometer as in the current study. Since different accelerometers use different sensors and data algorithms, the earlier reported relations between accelerometer output and V_e could not be applied directly to the data from the ActiGraph GT3X+. Although the suggested regression equation derived herein is specific for data retrieved by the ActiGraph GT3X+ accelerometer, the principle can be applied to other accelerometer types.

Two studies have related the ActiGraph GT3X+ accelerometer output to measures of children's activity levels, such as $\dot{V}O_2$, heart rate, energy expenditure and PAR (Pate *et al.*, 2006; Butte *et al.*, 2014). There were three major reasons for using the data from Butte *et al.* (2014) when translating the accelerometer output to a more physical measure. Firstly, it includes children of a similar age as the current study and as in the study by Kawahara *et al.* (2012), from which the generic relation between PAR and V_e of preschool children was used. Secondly, Butte *et al.* (2014) report PAR as a measure of physical activity, which is the same measure as reported by Kawahara *et al.* (2012). Although the cut-points in PAR between the activity categories were not explicitly used herein for the translation from VM to V_e, it is worth noting that both these studies used similar cut-points (Supplementary Material; Tables S1 and S2). Thirdly, the baseline in $\dot{V}O_2$ (oxygen consumption at rest) reported by Butte *et al.* (2014) (~6.5 mL min^{-1} kg^{-1}) is close to that reported by others (Tanaka *et al.*, 2007; Kawahara *et al.*, 2012; Hildebrand *et al.*, 2014) while Pate *et al.* (2006) have a significantly higher baseline (~9 mL min^{-1} kg^{-1}). Using the data from the study by Pate *et al.* (2006) translating VM to $\dot{V}O_2$ together with the relation between $\dot{V}O_2$ and V_e from the study by Kawahara *et al.* (2012) would therefore likely lead to an overestimation of V_e.

4.2 The Estimated Minute Ventilations

Our results showed considerable intra- and inter-individual variation in V_e, as well as a consistent difference in V_e for activities indoors and outdoors. These differences indicate that it is important to consider the individual values of V_e when estimating exposures. Furthermore, the results highlight that V_e can vary in different environments (indoors and outdoors), which should be considered when for example estimating health effects of various types of air pollution—as indoor and outdoor particles have been reported to have different toxicities (Long *et al.*, 2001; Oeder *et al.*, 2012a, 2012b).

The strengths with the method is the possibility to get time resolved V_e and to be able to study variations on a group and individual level, however, an important step of evaluating the method is to compare the average V_e predicted from this study with inhalation rates from previous studies.

Table 5. Minute ventilations from our study and established 24 h inhalation rates commonly used in exposure assessments.

	Inhalation rate (m^3 day^{-1})	Minute ventilation (L min^{-1} kg^{-1})	Minute ventilation (L min^{-1})
Current study			
Average for all children (N = 136), 4.5 years, 17.8 kg			
Indoor		0.36 ± 0.03	6.4 ± 1.2
Outdoor		0.42 ± 0.05	7.5 ± 1.6
Total		0.39 ± 0.03	6.9 ± 1.4
Exposure Factors Handbook (U.S. EPA, 2011)			
Recommended long-term exposure values for inhalation (males and females)			
2 to < 3 years (mean)	8.9		6.2
3 to < 6 years (mean)	10.1		7.0
Swedish Environmental Protection Agency, Report 5859 (Liljelind and Barregård, 2008)			
3–5 years	8.3		5.8
15 kg child	7.6	0.35	5.3

The average V_e, resulting from the here implemented method, is comparable to daily values reported earlier (Table 5). The Exposure Factors Handbook reports a value of 7.0 L min^{-1} for preschool-aged children, while the Swedish Environmental Protection Agency (Naturvårdsverket) reports somewhat lower values between 5.3–5.8 L min^{-1} (when normalized to body weight 0.35 L min^{-1} kg^{-1}) (Liljelind and Barregård, 2008). More examples are presented in Supplementary Material; Table S5 with references. The average values reported here (6.9 ± 1.4 L min^{-1} and 0.39 ± 0.03 L min^{-1} kg^{-1}) are slightly higher/in the higher end of those daily averages typically reported, likely explained by that the measurements were performed during daytime activities (~7 h day^{-1}) when the children attended their preschools. During this time, the activity level, and thereby V_e, is expected to be higher than the daily averages.

The V_e values for the four physical activity categories can be compared with those reported in the Exposure Factors Handbook for 3–6 year old children (U.S. EPA, 2011). The value for the sedentary activities is similar to that reported herein (0.25 L min^{-1} kg^{-1} in the Exposure Factors Handbook and 0.26 L min^{-1} kg^{-1} in this study). For the other activity categories, the values presented in the Exposure Factors Handbook are higher: 0.63, 1.2 and 2.1 L min^{-1} kg^{-1} compared to 0.41, 0.64 and 0.88 L min^{-1} kg^{-1} in this study, for light, moderate and vigorous activity, respectively. The explanation might be that there are differences in the division of activity categories. The categorisation does not influence the estimated daily inhalation rates as long as the same criteria are used when reporting time spent in each physical activity category and V_e for a specific category. The values are further similar to those given by Kawahara *et al.* (2012) (Supplementary Material; Table S1) and correspond well with the mean maximal V_e extrapolated from Zapletal *et al.* (1987) for a 5 year-old child (0.97 L min^{-1} kg^{-1} with a weight of 17.8 kg).

4.3 Physical Activity Analysis

Our findings of a higher physical activity outdoors compared to indoors, and that the physical activity correlate to the percentage of time spent outdoors, are in line with what has been reported earlier by Hinkley *et al.* (2008) and Raustorp *et al.* (2012), who concluded that children who spend more time outdoors had an overall higher activity compared to children who spend less time outdoors. Furthermore, we find that the positive correlation between the average physical activity and relative time spent outdoors was most pronounced for the group of children where less than 50% of the day was spent outdoors. This has to our knowledge not been reported earlier. These results could suggest that when the children reach above a certain threshold of time spent outdoors, their activity reaches a level that is not changed during the extra time given outdoor. It further seemed as if the activity indoors decreased with increasing percentage of time spent outdoors. This could be part of the explanation for our results of lower average physical activity indoors for children in the rural preschools, as they generally spent higher percentages of time outdoors. However, behind this observation there are more potentially influencing factors, not included in the scope of this study, such as size of the preschool group, quality of the indoor environment and number of children per surface area or per teacher. The observed gender differences in the physical activity, with girls being generally less active than the boys both indoors and outdoors, has also been reported in previous studies (Hinkley *et al.*, 2008; Nilsen *et al.*, 2019; Ng *et al.*, 2020).

4.4 Study Limitations

In this study we use a relationship between the ActiGraph GT3X+ output and physical measures of energy expenditure derived from a previous study of preschool children, performed in a controlled laboratory setting using established methods (Butte *et al.*, 2014). In that study an accuracy of 68–70% is reported. This can be explained by individual variation in the metabolic rate at rest and for the various activities. Furthermore, the accelerometer is unable to capture isometric exercise (physical activity involving static muscle contractions). Based on the reported accuracy it seems that the largest uncertainty in translating the accelerometer output to V_e lies in the correlation between accelerometer output and PAR/$\dot{V}O_2$, rather than in the relation between V_e and PAR/$\dot{V}O_2$. However, the research field of applying accelerometers to study physical activity and relate the accelerometer output to measures of the metabolic rate is well established and widely implemented. Even if not widely used for estimating V_e, the $\dot{V}O_2$ is known to be directly proportional to V_e below the ventilatory threshold.

Although the equation used translating VM to V_e includes uncertainties, we want to stress that most estimations of daily inhalation rates do, and that the use of accelerometers provides a unique tool to monitor the time resolved variation in V_e.

5 CONCLUSIONS

We used ActiGraph GT3X+ accelerometers to study the activity of 136 preschool children while attending preschool during a week, and suggest and implement a method for estimating personal and time resolved V_e of children aged 3 to 5 years from the retrieved accelerometer data. This method allows for time resolved estimates of V_e and provides a possibility to study variations on a group and individual level. The algorithm used is based on earlier studies performed in controlled laboratory settings. We conclude that the derived relation between VM and V_e generates estimates of average V_e that are well in line with values reported earlier, suggesting that the method is suitable.

Our results highlight the importance to study and consider variations in V_e for individuals over time, between individuals, as well as in different environments such as indoors and outdoors, when assessing preschool children's exposure to air pollution. We show that there are large variations in V_e for the individuals over the day, where the 1st and 3rd quartile were 0.28 and 0.48 L min^{-1} kg^{-1}, respectively. We also analysed the collected activity data and show that the children were more active outdoors compared to indoors (average V_e was 17% higher during outdoor activities than during indoor activities) and that the average VM for each child correlates with the relative time spent outdoors—and is stronger up to a certain threshold of time spent outdoors.

Even though activity leads to increased inhalation rates and higher exposure to air pollution, we want to emphasize that recent literature suggest that the benefits of activity outweigh the drawbacks of a higher exposure (Tainio *et al.*, 2021). The current study is aimed at understanding the exposure of children in different settings and variations between individual children to provide a good basis for air quality guidelines that are safe also for active children.

We suggest the use of accelerometers as a suitable tool for assessing children's personal V_e in their natural environments without altering their activity. The observations motivate the use of personal and time resolved V_e in air pollution exposure assessments of individuals; when combined with time resolved local air pollution measurement, this method could provide the basis of more precise estimates of the inhaled dose for individual children compared to applying daily averages of V_e.

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SUPPLEMENTARY MATERIAL

Supplementary material for this article can be found in the online version at https://doi.org/10.4209/aaqr.220067

REFERENCES

Adolph, A.L., Puyau, M.R., Vohra, F.A., Nicklas, T.A., Zakeri, I.F., Butte, N.F. (2012). Validation of uniaxial and triaxial accelerometers for the assessment of physical activity in preschool children. J. Phys. Act. Health 9, 944–953. https://doi.org/10.1123/jpah.9.7.944

Ashmore, M.R., Dimitroulopoulou, C. (2009). Personal exposure of children to air pollution. Atmos. Environ. 43, 128–141. https://doi.org/10.1016/j.atmosenv.2008.09.024

Borel, B., Leclair, E., Fabre, C., Thevenet, D., Beghin, L., Gottrand, F. (2014). Mechanical ventilatory constraints during incremental exercise in healthy and cystic fibrosis children. Pediatr. Pulmonol. 49, 221–229. https://doi.org/10.1002/ppul.22804

Butte, N.F., Wong, W.W., Lee, J.S., Adolph, A.L., Puyau, M.R., Zakeri, I.F. (2014). Prediction of energy expenditure and physical activity in preschoolers. Med. Sci. Sports Exerc. 46, 1216–1226. https://doi.org/10.1249/MSS.0000000000000209

Choi, L., Liu, Z., Matthews, C.E., Buchowski, M.S. (2011). Validation of accelerometer wear and nonwear time classification algorithm. Med. Sci. Sports Exerc. 43, 357–364. https://doi.org/10.1249/MSS.0b013e3181ed61a3

Claxton, D.B. (1999). The measurement of oxygen uptake kinetics in children, Doctoral thesis. Sheffield Hallam University.

Cooper, D.M., Kaplan, M.R., Baumgarten, L., Weiler-Ravell, D., Whipp, B.J., Wasserman, K. (1987). Coupling of ventilation and CO_2 production during exercise in children. Pediatr. Res. 21, 568–572. https://doi.org/10.1203/00006450-198706000-00012

Dencker, M., Svensson, J., El-Naaman, B., Bugge, A., Andersen, L.B. (2012). Importance of epoch length and registration time on accelerometer measurements in younger children. J. Sports Med. Phys. Fitness 52, 115–121.

Deng, Q., Ou, C., Shen, Y.M., Xiang, Y., Miao, Y., Li, Y. (2019). Health effects of physical activity as predicted by particle deposition in the human respiratory tract. Sci. Total Environ. 657, 819–826. https://doi.org/10.1016/j.scitotenv.2018.12.067

Durnin, J.V., Edwards, R.G. (1955). Pulmonary ventilation as an index of energy expenditure. Q. J. Exp. Physiol. Cogn. Med. Sci. 40, 370–377. https://doi.org/10.1113/expphysiol.1955.sp001137

Hanggi, J.M., Phillips, L.R., Rowlands, A.V. (2013). Validation of the GT3X ActiGraph in children and comparison with the GT1M ActiGraph. J. Sci. Med. Sport 16, 40–44. https://doi.org/10.1016/j.jsams.2012.05.012

Hestnes, J., Hoel, H., Risa, O.J., Romstol, H.O., Roksund, O., Frisk, B., Thorsen, E., Halvorsen, T., Clemm, H.H. (2017). Ventilatory efficiency in children and adolescents born extremely preterm. Front. Physiol. 8, 499. https://doi.org/10.3389/fphys.2017.00499

Hildebrand, M., VT, V.A.N.H., Hansen, B.H., Ekelund, U. (2014). Age group comparability of raw accelerometer output from wrist- and hip-worn monitors. Med. Sci. Sports Exerc. 46, 1816–1824. https://doi.org/10.1249/MSS.0000000000000289

Hinkley, T., Crawford, D., Salmon, J., Okely, A.D., Hesketh, K. (2008). Preschool children and physical activity: A review of correlates. Am. J. Prev. Med. 34, 435–441. https://doi.org/10.1016/j.amepre.2008.02.001

Johansson, E., Ekelund, U., Nero, H., Marcus, C., Hagstromer, M. (2015). Calibration and cross-validation of a wrist-worn Actigraph in young preschoolers. Pediatr. Obes. 10, 1–6. https://doi.org/10.1111/j.2047-6310.2013.00213.x

Kawahara, J., Tanaka, S., Tanaka, C., Aoki, Y., Yonemoto, J. (2011a). Estimation of daily inhalation rate in preschool children using a tri-axial accelerometer: A pilot study. Sci. Total Environ. 409, 3073–3077. https://doi.org/10.1016/j.scitotenv.2011.04.006

Kawahara, J., Tanaka, S., Tanaka, C., Hikihara, Y., Aoki, Y., Yonemoto, J. (2011b). Estimation of the respiratory ventilation rate of preschool children in daily life using accelerometers. J. Air Waste Manag. Assoc. 61, 46–54. https://doi.org/10.3155/1047-3289.61.1.46

Kawahara, J., Tanaka, S., Tanaka, C., Aoki, Y., Yonemoto, J. (2012). Daily inhalation rate and time-activity/location pattern in Japanese preschool children. Risk Anal. 32, 1595–1604. https://doi.org/10.1111/j.1539-6924.2011.01776.x

Leppänen, M.H., Delisle Nyström, C., Henriksson, P., Pomeroy, J., Ruiz, J.R., Ortega, F.B., Cadenas-Sanchez, C., Löf, M., Leppanen, M.H., Nystrom, C.D., Lof, M. (2016). Physical activity intensity, sedentary behavior, body composition and physical fitness in 4-year-old children: Results from the ministop trial. Int. J. Obes. 40, 1126–1133. https://doi.org/10.1038/ijo.2016.54

Liljelind, I., Barregård, L. (2008). Hälsoriskbedömning vid utredning av förorenade områden. Rapport / Naturvårdsverket: 5859. Naturvårdsverket, Sweden.

Löndahl, J., Swietlicki, E., Bengtsson, A., Rissler, J., Boman, C., Blomberg, A., Sandström, T. (2012). Experimental determination of the respiratory tract deposition of diesel combustion particles in patients with chronic obstructive pulmonary disease. Part. Fibre Toxicol. 9, 30. https://doi.org/10.1186/1743-8977-9-30

Long, C.M., Suh, H.H., Kobzik, L., Catalano, P.J., Ning, Y.Y., Koutrakis, P. (2001). A pilot investigation of the relative toxicity of indoor and outdoor fine particles: in vitro effects of endotoxin and other particulate properties. Environ. Health Perspect. 109, 1019–1026. https://doi.org/10.1289/ehp.011091019

Migueles, J.H., Cadenas-Sanchez, C., Ekelund, U., Delisle Nystrom, C., Mora-Gonzalez, J., Lof, M., Labayen, I., Ruiz, J.R., Ortega, F.B. (2017). Accelerometer data collection and processing criteria to assess physical activity and other outcomes: A systematic review and practical considerations. Sports Med. 47, 1821–1845. https://doi.org/10.1007/s40279-017-0716-0

Newstead, C.G. (1987). The relationship between ventilation and oxygen consumption in man is the same during both moderate exercise and shivering. J. Physiol. 383, 455–459. https://doi.org/10.1113/jphysiol.1987.sp016420

Ng, M., Rosenberg, M., Thornton, A., Lester, L., Trost, S.G., Bai, P., Christian, H. (2020). The Effect of Upgrades to Childcare Outdoor Spaces on Preschoolers' Physical Activity: Findings from a Natural Experiment. Int. J. Environ. Res. Public Health 17, 468. https://doi.org/10.3390/ijerph17020468

Nilsen, A.K.O., Anderssen, S.A., Ylvisaaker, E., Johannessen, K., Aadland, E. (2019). Physical activity among Norwegian preschoolers varies by sex, age, and season. J. Med. Sci. Sports 29, 862–873. https://doi.org/10.1111/sms.13405

O'Donnell, D.E., O'Donnell, C.D., Webb, K.A., Guenette, J.A. (2012). Respiratory consequences of mild-to-moderate obesity: Impact on exercise performance in health and in chronic obstructive pulmonary disease. Pulm. Med. 2012, 818925. https://doi.org/10.1155/2012/818925

Oeder, S., Dietrich, S., Weichenmeier, I., Schober, W., Pusch, G., Jorres, R.A., Schierl, R., Nowak, D., Fromme, H., Behrendt, H., Buters, J.T. (2012a). Toxicity and elemental composition of particulate matter from outdoor and indoor air of elementary schools in Munich, Germany. Indoor Air 22, 148–158. https://doi.org/10.1111/j.1600-0668.2011.00743.x

Oeder, S., Weichenmeier, I., Pusch, G., Schober, W., Pfab, F., Buters, J.T.M., Behrendt, H., Jörres, R.A., Schierl, R., Kronseder, A., Nowak, D., Dietrich, S., Fromme, H., Fernández-Caldas, E., Lintelmann, J., Zimmermann, R., Lang, R., Mages, J. (2012b). Airborne Indoor Particles from Schools Are More Toxic than Outdoor Particles. Am. J. Respir. Cell Mol. Biol. 47, 575–582. https://doi.org/10.1165/rcmb.2012-0139OC

Ofir, D., Laveneziana, P., Webb, K.A., O'Donnell, D.E., Lam, Y.M. (2008). Mechanisms of Dyspnea during cycle exercise in symptomatic patients with GOLD stage I chronic obstructive pulmonary disease. Am. J. Respir. Crit. Care Med. 177, 622–629. https://doi.org/10.1164/rccm.200707-1064OC

Pate, R.R., Almeida, M.J., McIver, K.L., Pfeiffer, K.A., Dowda, M. (2006). Validation and calibration of an accelerometer in preschool children. Obesity14, 2000–2006. https://doi.org/10.1038/oby.2006.234

Raustorp, A., Pagels, P., Boldemann, C., Cosco, N., Soderstrom, M., Martensson, F. (2012). Accelerometer measured level of physical activity indoors and outdoors during preschool time in Sweden and the United States. J. Phys. Act. Health 9, 801–808. https://doi.org/10.1123/jpah.9.6.801

Rissler, J., Gudmundsson, A., Löndahl, J., Nicklasson, H., Wollmer, P., Swietlicki, E. (2017a). Deposition efficiency of inhaled particles (15-5000 nm) related to breathing pattern and lung function: An experimental study in healthy children and adults. Part. Fibre Toxicol. 14, 10. https://doi.org/10.1186/s12989-017-0190-8

Rissler, J., Nicklasson, H., Gudmundsson, A., Wollmer, P., Swietlicki, E., Löndahl, J. (2017b). A set-up for respiratory tract deposition efficiency measurements (15–5000 nm) and first results for a group of children and adults. Aerosol Air Qual. Res. 17, 1244–1255. https://doi.org/10.4209/aaqr.2016.09.0425

Rodes, C.E., Chillrud, S.N., Haskell, W.L., Intille, S.S., Albinali, F., Rosenberger, M. (2012). Predicting adult pulmonary ventilation volume and wearing compliance by on-board accelerometry during personal level exposure assessments. Atmos. Environ. 57, 126–137. https://doi.org/10.1016/j.atmosenv.2012.03.057

Salvi, S. (2007). Health effects of ambient air pollution in children. Paediatr. Respir. Rev. 8, 275–280. https://doi.org/10.1016/j.prrv.2007.08.008

Schuepp, K., Sly, P.D. (2012). The developing respiratory tract and its specific needs in regard to ultrafine particulate matter exposure. Paediatr. Respir. Rev. 13, 95–99. https://doi.org/10.1016/j.prrv.2011.08.002

Tainio, M., Jovanovic Andersen, Z., Nieuwenhuijsen, M.J., Hu, L., de Nazelle, A., An, R., Garcia, L.M.T., Goenka, S., Zapata-Diomedi, B., Bull, F., Sa, T.H. (2021). Air pollution, physical activity and health: A mapping review of the evidence. Environ. Int. 147, 105954. https://doi.org/10.1016/j.envint.2020.105954

Tanaka, C., Tanaka, S., Kawahara, J., Midorikawa, T. (2007). Triaxial accelerometry for assessment of physical activity in young children. Obesity 15, 1233–1241. https://doi.org/10.1038/oby.2007.145

Timmons, B.W., Naylor, P.J., Pfeiffer, K.A. (2007). Physical activity for preschool children — how much and how? Appl. Physiol. Nutr. Metab. 32, S122–S134. https://doi.org/10.1139/H07-112

Timmons, B.W., Leblanc, A.G., Carson, V., Connor Gorber, S., Dillman, C., Janssen, I., Kho, M.E., Spence, J.C., Stearns, J.A., Tremblay, M.S. (2012). Systematic review of physical activity and health in the early years (aged 0-4 years). Appl. Physiol. Nutr. Metab. 37, 773–792. https://doi.org/10.1139/h2012-070

Tipparaju, V.V., Xian, X., Bridgeman, D., Wang, D., Tsow, F., Forzani, E., Tao, N. (2020). Reliable breathing tracking with wearable mask device. IEEE Sens. J. 20, 5510–5518. https://doi.org/10.1109/jsen.2020.2969635

U.S. Environmental Protection Agency (U.S. EPA) (2011). Exposure Factors Handbook: 2011 Edition (Final Report). Inhalation Rates., U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-09/052F.

World Health Organization (WHO) (2021). WHO global air quality guidelines: particulate matter ($PM_{2.5}$ and PM_{10}), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide. World Health Organization, Geneva. https://apps.who.int/iris/handle/10665/345329

Wierzbicka, A., Nilsson, P.T., Rissler, J., Sallsten, G., Xu, Y., Pagels, J.H., Albin, M., Österberg, K., Strandberg, B., Eriksson, A., Bohgard, M., Bergemalm-Rynell, K., Gudmundsson, A. (2014). Detailed diesel exhaust characteristics including particle surface area and lung deposited dose for better understanding of health effects in human chamber exposure studies. Atmos. Environ. 86, 212–219. https://doi.org/10.1016/j.atmosenv.2013.11.025

Wu, X.Y., Han, L.H., Zhang, J.H., Luo, S., Hu, J.W., Sun, K. (2017). The influence of physical activity, sedentary behavior on health-related quality of life among the general population of children and adolescents: A systematic review. PLoS One 12, e0187668. https://doi.org/10.1371/journal.pone.0187668

Zapletal, A., Šamánek, M., Paul, T. (1987). Lung Function in Children and Adolescents. Methods, reference values, in: Herzog, H. (Ed.), Progress in respiration research (vol 22). Karger, Basel.