 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

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 $\sim0.2 \text{ L min}^{-1} \text{ kg}^{-1}$ compared to $\sim0.1 \text{ L min}^{-1} \text{ kg}^{-1}$ 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 $\sim2.0 \text{ L min}^{-1} \text{ kg}^{-1}$ for preschool aged children while $\sim0.6 \text{ L min}^{-1} \text{ kg}^{-1}$ for adults. Children also spend more time, active, outdoors during daytime periods when air pollution levels tend to peak (Scheu pp 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 (Rausorp 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 ($\text{VO}_2$), 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 $\text{VO}_2$/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 day.

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.

<table>
<thead>
<tr>
<th></th>
<th>Number of individuals [girls]</th>
<th>Wear time (days)</th>
<th>Wear time (mean min day⁻¹)</th>
<th>Outdoor (% of total time)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Indoor</td>
<td>Outdoor</td>
<td></td>
</tr>
<tr>
<td>R1</td>
<td>15 [9]</td>
<td>4.2</td>
<td>163</td>
<td>262</td>
</tr>
<tr>
<td>R2</td>
<td>11 [7]</td>
<td>3.7</td>
<td>202</td>
<td>223</td>
</tr>
<tr>
<td>R3</td>
<td>11 [7]</td>
<td>3.2</td>
<td>203</td>
<td>163</td>
</tr>
<tr>
<td>R4</td>
<td>19 [10]</td>
<td>3.8</td>
<td>187</td>
<td>258</td>
</tr>
<tr>
<td>U1</td>
<td>25 [10]</td>
<td>3.9</td>
<td>240</td>
<td>240</td>
</tr>
<tr>
<td>U3</td>
<td>26 [12]</td>
<td>4.4</td>
<td>288</td>
<td>69</td>
</tr>
<tr>
<td>U4</td>
<td>3 [1]</td>
<td>4.3</td>
<td>271</td>
<td>93</td>
</tr>
<tr>
<td>U5</td>
<td>14 [7]</td>
<td>3.3</td>
<td>281</td>
<td>156</td>
</tr>
<tr>
<td>Average</td>
<td>136 [67]</td>
<td>3.9 ± 1.0</td>
<td>234 ± 66</td>
<td>181 ± 87</td>
</tr>
</tbody>
</table>

²For 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 $VO_2$ 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:

$$V_e = 8.34 \times 10^{-5} \cdot VM + 0.246$$

where $V_e$ is the minute ventilation ($\text{L min}^{-1} \text{kg}^{-1}$) 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 \textit{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 \textit{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 \textit{et al.} (2014). Values are presented as percentage of time (mean ± 1 SD) during time spent indoors, outdoors or both indoors and outdoors (Total).

<table>
<thead>
<tr>
<th>Sedentary (% of time)</th>
<th>Light (% of time)</th>
<th>Moderate (% of time)</th>
<th>Vigorous (% of time)</th>
<th>Total (% of time)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indoor</td>
<td>Outdoor</td>
<td>Indoor</td>
<td>Outdoor</td>
<td>Indoor</td>
</tr>
<tr>
<td>Girls</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>69.2 ± 6.9</td>
<td>53.1 ± 6.9</td>
<td>22.3 ± 4.5</td>
<td>10.6 ± 3.6</td>
<td>2.0 ± 1.2</td>
</tr>
<tr>
<td>Boys</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>64.4 ± 5.0</td>
<td>48.6 ± 5.0</td>
<td>25.0 ± 4.5</td>
<td>11.9 ± 3.7</td>
<td>3.1 ± 1.3</td>
</tr>
<tr>
<td>All</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>66.8 ± 7.6</td>
<td>50.8 ± 7.6</td>
<td>23.7 ± 5.0</td>
<td>13.2 ± 4.7</td>
<td>2.8 ± 1.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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 a (\( p < 0.001 \)).
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.

<table>
<thead>
<tr>
<th></th>
<th>Vector magnitude (counts min⁻¹)</th>
<th>Minute ventilation (L min⁻¹ kg⁻¹)</th>
<th>Minute ventilation (L min⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Indoor</td>
<td>Outdoor</td>
<td>Total</td>
</tr>
<tr>
<td>Girls</td>
<td>1294 ± 317**#, 2052 ± 647#</td>
<td>1632 ± 400</td>
<td>1632 ± 400</td>
</tr>
<tr>
<td>Boys</td>
<td>1461 ± 362**#, 2178 ± 519#</td>
<td>1754 ± 388</td>
<td>1754 ± 388</td>
</tr>
<tr>
<td>All</td>
<td>1378 ± 349#</td>
<td>2116 ± 587</td>
<td>1694 ± 398</td>
</tr>
</tbody>
</table>

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).

<table>
<thead>
<tr>
<th>Physical activity category</th>
<th>Vector magnitude&lt;sub&gt;a&lt;/sub&gt; (counts min&lt;sup&gt;–1&lt;/sup&gt;)</th>
<th>Median vector magnitude&lt;sub&gt;a&lt;/sub&gt; (counts min&lt;sup&gt;–1&lt;/sup&gt;)</th>
<th>Minute ventilation&lt;sub&gt;b&lt;/sub&gt; (L min&lt;sup&gt;–1&lt;/sup&gt; kg&lt;sup&gt;–1&lt;/sup&gt;)</th>
<th>Minute ventilation&lt;sub&gt;b&lt;/sub&gt; (L min&lt;sup&gt;–1&lt;/sup&gt;)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sedentary</td>
<td>&lt; 820</td>
<td>197</td>
<td>0.26</td>
<td>4.7</td>
</tr>
<tr>
<td>Light</td>
<td>820–3908</td>
<td>1971</td>
<td>0.41</td>
<td>7.3</td>
</tr>
<tr>
<td>Moderate</td>
<td>3908–6112</td>
<td>4668</td>
<td>0.64</td>
<td>11.3</td>
</tr>
<tr>
<td>Vigorous</td>
<td>&gt; 6112</td>
<td>7648</td>
<td>0.88</td>
<td>15.7</td>
</tr>
</tbody>
</table>

<sup>a</sup> According to cut-points presented in Butte et al. (2014).

<sup>b</sup> 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<sup>–1</sup> kg<sup>–1</sup>, 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<sup>–1</sup> kg<sup>–1</sup>. 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<sup>–1</sup> kg<sup>–1</sup>) up to short events with very high $V_e$ (up to 0.97 L min<sup>–1</sup> kg<sup>–1</sup> as specified by the applied maximum). The average of the individual’s 1<sup>st</sup> and 3<sup>rd</sup> quartiles were 0.28 and 0.48 L min<sup>–1</sup> kg<sup>–1</sup>, 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<sup>–1</sup> kg<sup>–1</sup> for the sedentary category to 0.88 L min<sup>–1</sup> kg<sup>–1</sup> 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...
However, the differences in deposited fraction do not alter the dose to any extent near that of a similar age as the current study and as in the study by Kawahara translating the accelerometer output to a more physical measure. Firstly, it includes children of 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 $VO_2$, 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 $VO_2$ (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 $VO_2$ together with the relation between $VO_2$ 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.

<table>
<thead>
<tr>
<th></th>
<th>Inhalation rate (m³ day⁻¹)</th>
<th>Minute ventilation (L min⁻¹ kg⁻¹)</th>
<th>Minute ventilation (L min⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Current study</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average for all children (N = 136), 4.5 years, 17.8 kg</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Indoor</td>
<td>0.36 ± 0.03</td>
<td>6.4 ± 1.2</td>
<td></td>
</tr>
<tr>
<td>Outdoor</td>
<td>0.42 ± 0.05</td>
<td>7.5 ± 1.6</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>0.39 ± 0.03</td>
<td>6.9 ± 1.4</td>
<td></td>
</tr>
<tr>
<td>Recommended long-term exposure values for inhalation (males and females)</td>
<td>8.9</td>
<td>6.2</td>
<td></td>
</tr>
<tr>
<td>2 to &lt; 3 years (mean)</td>
<td>10.1</td>
<td>7.0</td>
<td></td>
</tr>
<tr>
<td>3 to &lt; 6 years (mean)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Swedish Environmental Protection Agency, Report 5859 (Liljelind and Barregård, 2008)</td>
<td>8.3</td>
<td>5.8</td>
<td></td>
</tr>
<tr>
<td>3–5 years</td>
<td>7.6</td>
<td>0.35</td>
<td>5.3</td>
</tr>
</tbody>
</table>

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/VO$_2$, rather than in the relation between $V_e$ and PAR/VO$_2$. 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 VO$_2$ 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 $V_e$. 
ACKNOWLEDGMENTS

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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


