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Evaluating artificial neural networks for predicting minute ventilation and lung deposited dose in commuting cyclists

Marguerite Nyhan [a,b,*], Aonghus McNabola [a], Bruce Misstear [a]

[a] Civil, Structural and Environmental Engineering Department, Trinity College Dublin, Ireland
[b] Massachusetts Institute of Technology, Cambridge, MA, United States

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ABSTRACT

Evidence linking personal air pollution exposure to adverse human health impacts is well reported in literature. Commuting in urban traffic micro-environments often leads to a large proportion of total daily exposure and uptake. Cyclists in particular, due to their elevated physical exertion levels and ventilatory parameters, experience higher uptakes of air pollution while commuting relative to less active commuters. A model for predicting minute ventilation of cyclist commuters in the field was developed, and PM_{10} lung deposited doses were predicted based on this. Sixty healthy volunteers were recruited. Minute ventilation, heart rate, personal air pollution exposure, local meteorological conditions, GPS acquired cycling speed and road topography were continuously monitored during sampling protocols. An artificial neural network (ANN) model for predicting minute ventilation was developed based on these variables and subject characteristics. Predicted values were regressed against measured minute ventilation. A Generalised Additive Model (GAM), a Partial Least Squares (PLS) model and three empirical minute ventilation models were tested in the same manner. The ANN, GAM and PLS predicted minute ventilation levels showed better agreement with measured minute ventilation values (R^2=0.82, 0.74 and 0.56 respectively) than the empirical models (R^2 values ranging from 0.36 to 0.43). The average percentage error of the ANN modelled minute ventilation ($2.5 \pm 20.2\%$) was smallest of all models tested. Lung deposited doses of air pollution were calculated using a human respiratory tract model. Doses calculated utilising ANN modelled minute ventilation demonstrated the best agreement with the lung deposited dose determined using measured minute ventilation. Cycling scenarios were investigated in terms of ANN modelled minute ventilation levels and PM_{10} lung deposited doses. This study presents a novel method of indirectly measuring cyclists' breathing rates in an urban outdoor setting and will have applications in assessing accurate air pollution uptake in cyclists in future research.

1. Introduction

Research in recent decades consistently indicates the adverse effects of outdoor air pollution on human health (Samet et al., 2000; Liao et al., 2004; Peters et al., 2004; Kaur et al., 2007; Brook et al., 2010; Gurjar et al., 2010; Nyhan et al., 2014). The World Health Organization estimates that air pollution contributes to 1.34 million premature deaths annually (WHO, 2008). Evidence has shown that fine particulate air pollution is especially associated with cardiovascular mortality and morbidity (Samet et al., 2000), while the adverse health effects of other air pollutants such as ultra-fine particles, oxides of nitrogen, ozone, carbon monoxide, volatile organic compounds and sulphur dioxide are also widely reported in literature (Brunkreef and Holgate, 2002; WHO, 2005; Knibbs et al., 2011). Studies have provided evidence for a link between air pollution and respiratory illnesses, and lung cancer (Nyberg et al., 2000).

Air pollution exposure while commuting in traffic micro-environments may lead to a high proportion of total daily exposure amongst cyclists in urban environments in developed countries due to elevated air pollution levels relative to other environments (Kaur et al., 2007; Nyhan et al., 2014). Cyclists in particular, due to their relatively higher physical exertion levels and subsequent breathing rates, experience higher uptakes of air pollution while commuting relative to less active commuters (train, bus and car passengers) (McNabola et al., 2008; Nyhan et al., 2014). Even so, encouraging populations to use sustainable transport modes (walking and cycling) is often

* Corresponding author. Current address: Senseable City Lab, Massachusetts Institute of Technology, Cambridge, MA, United States. Tel.: +1 6173244474.
E-mail address: mnyhan@tcd.ie (M. Nyhan).

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promoted as a viable method of reducing urban traffic density and subsequent air pollution levels, and improving public health through regular commuting exercise. Many large cities have initiated low-cost bicycle sharing schemes aimed at encouraging commuters to cycle for short trips instead of using motorised public transportation or private vehicles, and for normalising the image of cycling in cities (Goodman et al., 2014). Typically, the primary aim of these schemes is to reduce traffic congestion in urban centres which has the subsequent benefit of reducing air and noise pollution levels. To date, schemes have been implemented in over 300 cities worldwide including Copenhagen, Denmark (1995), Barcelona, Spain (2007), Paris, France (2007), Dublin, Ireland (2009), Mexico City, Mexico (2010), London, United Kingdom (2010) and New York, United States (2013). The largest scheme is the HZ bike scheme in the city of Hangzhou in China which was launched in 2008 and has a current fleet of approximately 65,000 bicycles (ICLEI, 2011).

Many studies have compared the differences between air pollution exposure across transport microenvironments (Adams et al., 2001; Tsai et al., 2008; De Nazelle et al., 2012, Huang et al., 2012; Nyhan et al., 2014). Further to this, most of these studies have assumed a constant elevated breathing rate for cyclists in comparison to other road users. Few studies have considered in detail the increased physical effort and minute ventilation (defined as the number of litres of air inhaled or exhaled per minute) that cyclists experience relative to other less active modes (O'Donoghue et al., 2007; McNabola et al., 2008; Int Panis et al., 2010; Zuurbier et al., 2010; Nyhan et al., 2014). Cyclists' ventilation rates can fluctuate greatly during commuting due to stopping and starting in congested traffic conditions, and due to the influence of road gradient and meteorological conditions on cycling effort required. Breathing rate also varies between individuals and depends on gender, fitness and lung capacity. To the authors' knowledge, only one previous study, by Int Panis et al. (2010), measured minute ventilation in the field for the purposes of determining air pollution uptake. That study, however, did not evaluate how cyclists' breathing rates vary with traffic conditions, road topography and meteorological conditions nor did it evaluate if a cyclist's breathing rate can be predicted using these measurements.

In studies examining air pollution exposure in transport micro-environments, O'Donoghue et al. (2007), Zuurbier et al. (2010) and Nyhan et al. (2014) determined inhaled doses of air pollution as the exposure metric. Inhaled doses of each pollutant are calculated by multiplying minute ventilation (litres of air inhaled or exhaled per minute) by the micro-environmental concentration of the pollutant by the travel time (or time exposed). Lung deposited doses of air pollution more accurately describe air pollution exposure metrics than ambient exposure or inhalation dose, however (Nyhan et al., 2014). A study by Int Panis et al. (2010) calculated lung deposited dose for each subject by multiplying the inhaled dose by a fixed deposition factor (Löndahl et al., 2009). Previous studies by McNabola et al. (2008), McCreddin et al. (2013) and Nyhan et al. (2014) have used the International Commission for Radiological Protection's (ICRP) Human Respiratory Tract (HRT) model for air pollution lung deposition calculations. However, accurate inhaled and lung deposited dose calculations depend on the availability of accurate breathing rate inputs.

Different methods have been applied to measure commuter breathing rates indirectly. For example, Zuurbier et al. (2009) used heart rate as a predictor of minute ventilation in cyclists for air pollution inhalation calculations. However, this research was conducted in an indoor laboratory setting. In real outdoor experiments, heart rate is affected by meteorological variables, stress, traffic and activity in the micro-environment of the cyclist. De Nazelle et al. (2012) predicted inhalation rates using average energy expenditure measured during trips in different modes. Hart (1998) and Satoh et al. (1989) carried out laboratory tests for determining minute ventilation based on subject characteristics and heart rate. Lin et al. (2011) used artificial neural networks (ANNs) to predict inspired minute ventilation in subjects during exercise step-tests carried out in a laboratory setting. These studies have not attempted to use ANNs to predict minute ventilation in cyclist commuters using values obtained in the field to build and calibrate predictive models. The advantages of indirect approaches to estimating minute ventilation in the field are that minute ventilation levels can be approximated using simple and low-cost equipment with no interference with the subject and the results can be combined with applications for determining air pollution uptake.

This study forms part of the Dublin Cycling Study, a project initiated by the Air Quality Research Group in Trinity College Dublin. The overall aim of the Dublin Cycling Study is to better quantify air pollution exposure and uptake of cyclist commuters relative to other modes of transport. An objective within this is to develop a dynamic model capable of predicting air pollution lung deposited doses based on air pollution levels, subject characteristics, GPS acquired data, road topography and meteorological conditions. The specific objective discussed here is to evaluate the possibility of using an ANN model to predict minute ventilation in cyclists in the field, and thus estimate lung deposited doses of air pollution based on this.

2. Methodology

2.1. Protocol

This study was conducted in Dublin, the capital city of the Republic of Ireland. The test centre was located and all field tests took place in the city centre. Two inner-city fixed study routes were chosen herein referred to as routes 1 and 2. Both routes were in the form of a loop so that cyclists started and ended at the testing centre. The routes included some increasing and decreasing road gradients.

Subjects were recruited through advertisements posted across Dublin City. Sixty healthy male and female volunteers were recruited for the purposes of the study. Subjects satisfied the criteria of being (1) between 18 and 60 years of age; (2) being resident, commuting and working within the greater Dublin area; and (3) commuting to and from home to work on a regular basis by bicycle. Being a regular cyclist commuter was defined as cycling for at least 90 min each week over a period of at least 6 months prior to the study taking place.

Each volunteer presented themselves at the study centre which was based on Trinity College Dublin main campus in Dublin city centre. Each test subject protocol lasted approximately 2 h. Firstly subjects were seated for 30 min and then were fitted with a heart rate monitor and portable breathing rate apparatus. Baseline heart rate and ventilation parameters (described in Section 2.3) were immediately assessed. Following this assessment, subjects were driven as a car passenger on one of the two designated routes and then asked to cycle the same trip on a bicycle. The purpose of the car trip was to familiarise the participants with the route. Minute ventilation and personal air pollution exposure data was also collected as part of the study protocol during the car trip for future analyses comparing exposure and uptake of air pollution while car commuting and cycling. The time between the car and the bicycle trips was kept to a minimum and was typically less than 10 min. The car trip always preceded the bicycle trip so that the effect of increased physical exertion while cycling would not affect heart rate and ventilation measurements while in the car. A pair-wise study design (where the car and cycling effort was