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Developing Demand Driven Ventilation Criteria for Airborne Infection Control in Congregate Spaces

Tobias van Reenen[1,*], Jan-Hendrik Grobler [1]

[1] Council for Scientific and Industrial Research, Pretoria, South Africa

[*]*Corresponding email: tvreenen@csir.co.za*

SUMMARY

This article presents the case that 12 air changes per hour (ACH) does not provide adequate control against the amplification of disease in different indoor congregate settings. It proposes an occupancy and risk-based algorithm for determining ventilation rates for spaces with a high airborne disease transmission risk. The method modifies the Wells-Riley airborne disease transmission model with the indoor space's local disease amplification rate to estimate a ventilation limit in terms of space, disease, risk and population. This proposed ventilation capacity sizing strategy is subsequently economical, adaptable and application-specific in ways deficient in prescriptive ACH limits.

While acknowledging that proximity effects increase individual exposure risk, the modelling conducted shows that far-field exposure is dominant in large congregate settings. It was found that the per-person ventilation demand tends to a definable lower limit as occupancy increases. This reveals how ACH is not a universally comprehensive metric.

KEYWORDS

Ventilation Rate, Environmental Control, Congregate Settings, Tuberculosis, Airborne Transmission

1. INTRODUCTION

Evidence for the Institutional Guidance Framework

The US Centers for Disease Control and Prevention (US-CDC) and the World Health Organisation (WHO) have published TB infection-control guidelines based on a 3-tiered approach (Jensen et al., 2005):

(1) administrative controls or work practice,
(2) environmental controls, and
(3) personal protection

The WHO strongly recommends adequate ventilation as a fundamental environmental control for preventing indoor transmission of airborne infections even though it describes the evidence for the prescribed ventilation rates as weak (WHO, 2009b, 2019). The WHO TB policy for congregate settings has defined the minimum ventilation rate for high risk spaces as 12 air changes per hour (ACH) or 80 L/s·person for a 24m³ room (WHO, 2009a). These guidance values appear to be derived from 12 ACH prescribed by the American Institute of Architects (AIA) and US-CDC Guidance (Ninomura et al., 2013; The American Institute of Architects, 2010; WHO, 2007). This metric describes the number of times the whole room air volume is replaced in an hour.

The 2004 US-CDC guideline for environmental infection control in healthcare facilities defines 12 ACH as the ventilation magnitude with the "*peak particle removal efficiency*" (CDC & Healthcare Infection Control Practices Advisory Committee, 2003). Thereby, the 12 ACH criterion is presented as a rational solution, allowing for economizing ventilation equipment capacity and cost. This US-CDC guide references Streifel as the source of the 12 ACH limit (Streifel, 2011). The current edition of that book does not adequately reference the origin of the limit.

The presentation of 12 ACH as a limit approaching peak particle removal efficiency does not withstand prima facie scrutiny since particle removal efficiency as a ratio increases with a decreasing ventilation rate, presenting no local maximum or inflection point. Therefore, this criterion does not adequately address economic concerns nor acceptable limits of transmission risk.

The Wells-Riley probability of transmission model suggests that occupancy density determines transmission risk. The question then arises whether per person ventilation rates would be a more appropriate metric for specifying ventilation capacities in various high risk airborne transmission rooms and congregate settings, as found in healthcare facilities.

The 2009 WHO TB policy was the only guidance found to address occupancy numbers when defining ventilation rates for airborne infection control in healthcare buildings. The 2012 International Mechanical Code (ICC, 2012) took occupancy into account for ventilating healthcare spaces but these criteria have been omitted again in later revisions (ICC, 2017).

To prescribe a minimum per person ventilation rate, a defendable level of transmission risk needs to be defined.

Limits for Demand Driven Ventilation

It is shown above that, with mixing ventilation, there is no contaminant removal efficiency peak and that increasing ventilation cannot drive transmission rates to zero or a local minimum. There can therefore be no ethical lower limit for airborne transmission. It is therefore proposed that minimum ventilation rates can only be prescribed which prevent a congregate space from inflating the prevalence of a disease within the population using that space.

The basic reproduction number (R_0) for a disease can be simply defined as the number of secondary infections that arise from each existing case. When the basic reproduction number (R_0) for a transmission model of a disease is less than 1, the disease-free equilibrium is stable. Where $R_0 > 1$ the equilibrium is unstable and the disease can invade a population. The threshold value of a compartmental disease transmission model is therefore R0 = 1 (Van Den Driessche & Watmough, 2002). Following Rudnick and Milton (Rudnick & Milton, 2003) the number of transmissions (D) per stay of infectious persons (I) is defined as the environmental reproduction number (R_{0E}). When limiting the environmental reproduction number to less than 1, the disease's incidence rate within the resident population will not be amplified by that environment. For this article, the boundary of the transmission model is the room under consideration for the period occupied daily.

The argument for 12 ACH as an economical ventilation rate for particle removal does not definitively address an acceptable transmission limit or the disease-free equilibrium of any disease's transmission rate within a population. It is therefore proposed that an appropriate

ventilation rate target would achieve the lower limit for transmission associated an R_{0E} of 1 or less.

Validation of Mixing Ventilation Model

It has been shown that separation between the source and the target of greater than 0.5m is fundamental in reducing airborne contaminant exposure levels. Duration of exposure is not well addressed by Kierat (Bolashikov et al., 2012), Liu (Liu et al., 2016) and Olmedo (Olmedo et al., 2012) when investigating the risk of proximity. Mezmarzedeh (Memarzadeh & Xu, 2012) shows that, with appropriate ventilation and architectural design, higher ventilation rates reduce time weighted exposure risk. Mezmarzedeh cautions that under low airflow rates, increasing proximity distance *"is not an effective way to reduce the risk regardless of the design"*.

To test the contribution of far-field transmission in large congregate settings, the authors conducted a brief CFD study which quantified the relative risk of near and far field transmission. A simulation was performed using Star-CCM+®. A transient model of 3 600 seconds in a large waiting room with an occupancy density of 1.5 m² per person was created. Sensible heat loads and air temperatures were set as per Olmedo et al (Olmedo et al., 2012). 100 seated persons facing front to back spaced in a 1.4 m x 0.6 m repeating array were placed in the room. A mixing ventilation model was created with high-level supply and low-level exhaust. A transient contaminant source of 4 000 PPM was placed in the room, coughing horizontally for five seconds and then breathing normally as described by Tang et al (Tang et al., 2013). The ratio of the re-breathed CO_2 was used as a risk index as per Rudnick (Rudnick & Milton, 2003).

The relative cumulative exposure risk in the breathing zones of each occupant was calculated as the product of contaminant concentration and exposure time (PPM·S). Three ventilation rates were simulated, namely 2, 6 and 12 ACH. Ventilation effectiveness (ε_v) was calculated for each scenario as defined by EN 13779: (CEN, 2007). All scenarios respectively presented good mixing.

Cumulative Transmission Risk	**2ACH**	**6ACH**	**12ACH**
Whole Room	707 603	308 159	230 245
Zone 1 (Seats adjacent to source)	131 622	68 138	57 716
Zone 2 (<4 seats from source)	420 801	185 864	143 017
Far-Field risk% (>1 seat from source)	**(81%)**	**(78%)**	**(75%)**

Table 1 Cumulative exposure (PPM·S) after 3 600 seconds in each zone

From the results in Table 1 it becomes clear that, under mixing ventilation, increased ventilation reduces cumulative exposure for both the whole room and far field transmission zones. It can be seen that increased ventilation has a more rapidly diminishing benefit within the near field zones than far field zones. With decreasing ventilation rates, the transmission risk in the far-field increasingly dominates the room's cumulative transmission risk. As occupancy density increases, proportion of persons in the far field transmission zone increases, increasing the contribution of far field transmission dynamics.

2. METHODS

It is shown that increased ventilation rates can reduce cumulative transmission risk for the large congregate settings. It is also shown that the ACH metric does not account for the effects of occupancy densities and duration of stay on indoor airborne contaminant levels and airborne infection rates. A per-person performance criterion could be derived using the Wells-Riley probability of infection model.

Using the Wells-Riley equation, it is possible to determine the relationship between occupant density, ventilation and disease transmission rates. This relationship can be used to describe new ventilation rates in these terms.

Determining Occupancy Based Ventilation Rates for Airborne Infection Control

Using the Wells-Riley model for calculating the probability of infection (Riley et al., 1978) for each susceptible person in a space, assuming the contamination concentration is at steady state, constant contaminant generation rates and fully mixed conditions, the probability of infection (*P*) is described as:

$$P = \frac{D}{S} = 1 - e^{\left(-\frac{Ipqt}{Q}\right)} \quad (1)$$

where *Q* is the room-air ventilation rate, *p* is the pulmonary ventilation rate per person, *I* the number of infectors, *t* the exposure duration, q the quantum generation rate, *D* the number of new cases and *S* the number of susceptible occupants in the room. Solving for the ventilation rate (*Q)* yields:

$$Q = Ipqt/ln\left(\frac{S}{S-D}\right) \quad (2)$$

Where the incidence of a disease such as TB is low in a population, the probability that any occupied spaces will contain more than one infectious person ($I > 1$) becomes similarly low. Based on the current TB prevalence rates in high burden countries and the detection and treatment rates of TB in these settings (WHO, 2015), it is unlikely that indoor congregate spaces would regularly have more than one infectious person with TB. Therefore, where the population of a room is represented by *n*, the number of susceptible persons is represented as *S* is:

$$S = n - 1 \quad (3)$$

Accepting $R_{0E} \leq 1$ as the transmission limit, it is possible to determine the minimum ventilation rate to achieve this. Setting $D = R_{0E}$, $I = 1$, substituting (3) into (2) and setting the ventilation (*Q)* as a rate per person (*n)* yields:

$$Q/_n = pqt/\ln\left[\left(\frac{n-1}{n-(1+R_{0E})}\right)^n\right] \quad (4)$$

The term $\left\{\ln\left[\left(\frac{n-1}{n-(1+R_{0E})}\right)^n\right]\right\}$ tends to R_{0E} as *n* increases. The relative error introduced by simplifying equation (4) may be acceptably low (<5%) when applied where indoor occupancy levels are 22 persons or above such as public waiting rooms.

∴When $n \geq 22$:

$$Q/_n \approx pqt/_{R_{0E}} \quad (5)$$

3. DISCUSSION

The application of equations (4) and (5) offer an opportunity to understand, defend or challenge the widely adopted 12 ACH ventilation criteria. It becomes quickly evident that in certain scenarios it is excessive, while in others it may be deficient.

Individual risk vs reproductive number.
The proposal by Hermans & Streifel (Hermans & Streifel, 1993) considers only individual chance of infection to calculate ventilation rates. Acceptably low individual risks can result a high reproductive number in large congregate settings while an acceptable reproductive number risk can result in high individual risk in low occupancy settings. Therefore, both individual and cumulative risks level need to considered and controlled when applying equations (4) and (5).

Assumption of quantum generation rate (q)
The US-CDC has used the recommended quantum generation rate of 60 /h as a reasonable worst-case estimate in the adoption of the interim recommendation of 12 ACH for airborne infectious isolation rooms by Hermans & Streifel (Hermans & Streifel, 1993). In the interest of a comparative assessment we shall adopt the same value for q.

Comparative Scenarios
Table 2 shows the comparative results of different scenarios for application to TB transmission control in a public health settings.

Scenario	*t (h)*	R_{0E} *(max)*	*n*	*Personal Risk % (max)*	*(L/s.p)*	*ACH*
Isolation Room @ 12 ACH eq (4)	0.49	1	2	5%	45	12
100 person waiting room @ 1.8 m²/p	1.63	1	100	5%	16	12
100 person waiting room @ 1.1 m²/p	4	1	100	5%	39	46
20 person waiting room @ 1.8 m²/p	4	0.19	20	5%	39	29

Table 2 Comparative scenario solutions

From Table 2 we can see how the room airflow volume required for controlling airborne infection changes with exposure-time and occupancy levels within constant limits of personal risk and $R_{0E,}$ and that a constant ACH design criteria does not deliver predictable levels of risk.

4. CONCLUSIONS
Since the proportional contribution of far field transmission in a room is affected, not only by ventilation rates, but also by the occupancy density, this methodology, which could adequately account for discrete scenarios deserves further investigation.

It is proposed that equation (4) and (5) be considered when designing ventilation for indoor spaces with airborne infection risk as this would result in a more consists and predictable airborne infection control outcomes. In addition, specifying ventilation capacity in terms of L/s per person will address much of the variability in occupancy and exposure time experienced between space types.

Using this methodology, the additive ventilation philosophy of ASHRAE 62.1 (Persily, 2015) could be developed further to apply to healthcare space types.

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