ANALYSIS OF RISK FORMING AIRFLOWS FOR CROSS-INFECTION IN AN ISOLATION ROOM

Ilse Schoenmakers[a], Wim Zeiler[b]

[a]*Arcadis Nederland, Rotterdam, The Netherlands, ilse.schoenmakers@arcadis.nl, www.arcadis.com*

[b]*Department of the Built Environment, University of Eindhoven, Eindhoven, The Netherlands, w.zeiler@bwk.tue.nl, www.tue.nl*

Keywords: isolation room, cross-infection, value of Air Changes Hour

Abstract Hospitals, need a lot of energy for their Heating Ventilation and Air Conditioning therefore it is important to look at possibilities to reduce the energy use. However, this of course has to be done without endangering the primary functions related to the patient's and staff safety. The HVAC energy consumption in isolation rooms is mainly caused by large volumes of air supply and are continuous supplying to the rooms, regardless the occupancy of the room. Resulting in over conditioned rooms, which leads to excessive energy consumption. It is concluded that the actual energy supply must be aligned to the energy demand. Solutions frequently used for this problem is HVAC setback using time schedules based on occupancy profiles. HVAC set back in isolation rooms require an unconventional approach, others than time schedules. A possible solution is manual HVAC setback for heating, cooling and ventilation. However, an important note to manual HVAC setback in ventilation rate is the increased risk of disease transmission through human failure. The risk of HVAC setback for heating and cooling is expected to be low. This research focusses on the amount of HVAC set back. The manner of setback is not investigated. The amount of HVAC setback depends on the type of occupancy in the room. For non-airborne infectious patients, a reduction of ACH to the guidance for single bedrooms (100 m^3/h per person = 2 ACH) is possible, provided that the comfort requirements are reached with these requirements. The ACH for isolation type of patients is doubtful. For not occupied rooms, the ACH need to be sufficient to maintain the space conditions for the time a patient need to be hospitalized. But also to keep the room at a low positive pressure in order to keep contaminants outside the room. According to the room model results it is concluded that the ACH for isolation patients can be reduced to < 6 ACH, however a more detailed model is needed which provides more certainty. The room model as defined in this research revealed that transmission of infectious particles through undefined cracks and gaps is most crucial (has most influences on transmission). Additionally, it is concluded that at low ACH the contamination concentrations are higher, however, more evenly distributed.

1 INTRODUCTION

Guidelines of HVAC operation, particularly the air ventilation rate, in air changes per hour (ACH), in isolation rooms are used during engineering design phases. Reviewing the Dutch guidelines of infection control in isolation rooms, interesting conclusions can be made. The recommend 6-7 ACH in the most recent infection prevention guidelines of the Netherlands [WIP, 2009] could be lowered [DBC, 2012]. A review on the amount of outside air required, is a function of, amongst others: exhaust through sanitary, leakage through air lock, duct leakage, wall and ceiling leakages and the level of pressurization required [Bhatia, 2012]. Other literature recommend specified and quantified minimum ventilation requirements in isolation rooms in relation to spread of infectious diseases [Li et al., 2007 and Atkinson et al., 2009]. In addition, the pressure differentials of anterooms in isolation rooms are discussed in the literature. Moreover, also the exact ventilation rate required in surrounding spaces adjacent to the airborne precaution rooms in order to reduce the risk of spreading airborne infectious diseases, is unknown. In 1994 the CDC notes a recommended pressure differential of 0.25 Pa, exhaust flow of 1.8 m^3/min or 10% greater than the supply to control the direction of airflow between rooms and adjacent areas such as corridors. In 2005 they raised the pressure differential to 2,5 Pa, compared to the current requirements of 5 Pa.

Table 1 – Type of isolation patients and type of isolation room required.

Country	Guideline ACH Existing structure	Requirement ACH New construction	Requiremend ΔP [Pa]	Source
United states	2014: 6	2014: 12	1994: 0.25 Pa	[AIA, 2001]
			2005: 2.5 Pa	[CDC, 2007]
Taiwan	-	-	8	[Tung, 2007]
Netherlands	-	6-7	5	[WIP, 2009]
Canada	1999: 6 – 9	1999: 12	-	[CSA, 2007]
	2007: 6	2007: 12	-	[CSA, 2007]

According to CDC standards, the measures of infection is control blocking any stage of infection pathway and is divided in three categories: administrative, personal protection, environmental and engineering. Administrative control involves keeping infectious people away from people who are susceptible to infections and ensuring correct usage of technical controls. Personal protection of nursing employees and visitors is achieved by using a surgical mask or respirator in order to prevent the distribution or inhalation of infectious pathogens. Pathogens leaving the breathing zone of an infectious patient are controlled by engineering and environmental interventions (in forms of isolation rooms), in order to prevent that the pathogens can enter the breathing zone of a vulnerable patient [Aliabadi et al., 2011].

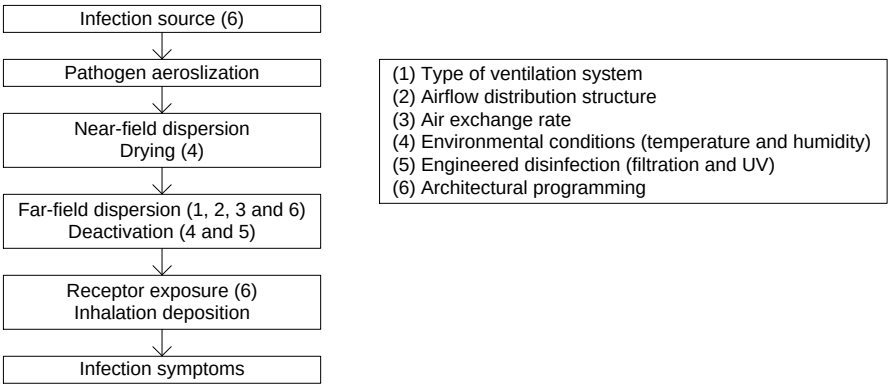

Figure 1 – Airborne infection process and influential environmental /engineering controls [Aliabadi et al., 2011].

As far as engineering and environmental interventions in isolation rooms is concerned, most research focuses on infection control of interzonal airborne infectious migration. Whilst, spread of infectious airborne transmission out of isolation rooms, can have more impact in a hospital environment. A larger number of susceptible individuals might be exposed to these infected particles. For airborne transmission, it is important to understand the pathway and influencing parameters, as designated in Fig. 1.

Infection source

Different types of host emission can generate infectious particles, for example: when a person sneeze, talks, coughs, exhales, etcetera. The amount of (infectious) particle generation and their infectiousness depend on important factors such as type of infection disease, patients' age and the moment in the clinical course of the disease. It is for example well known, that children with (for instance) tuberculosis are less infectious compared to adults and the infectiousness after treatment decreases [CDC,2011]. The amount of (airborne) particles generated per unit of time is called the generation rate.

Pathogen aerosolization and far-field dispersion

Aerosolization occur, if small pathogens remain suspended in the air and transmission over short or long ranges from person-to-person is possible by means of inhalation of infectious aerosols. Aerozolization and particle concentration in the air depend on several parameters as size, shape, velocity, humidity, temperature and airflow.

Receptor exposure

After pathogen aerosolization, the aerosols can be transmitted and inhaled. Particles < 100 µm are considered inhalable. The time of exposure to the source and the particle concentration in the air, is related to the maximum number of particles that might be inhaled. The number of particles necessary to cause an infection, called the infection dose (ID_{50}) depends on the type of infectious disease and the susceptibility of person

who is exposed to the infectious source. Amongst children diseases, MRSA, Mycobacterium Tuberculosis and Varicella (chickenpox) are the most common airborne infection diseases. Literature reveals that inhalation of fewer than ten Mycobacterium Tuberculosis bacteria may cause an infection [Philippe et al., 2006]. For Varicella <100 virus particles may cause an infection [Hawker et al., 2005].

The necessary ACH determines to a large extent the energy consumption. In this article a room model is defined, which enables to assess the representative minimum ACH to provide minimal isolation while using as less energy as possible. This room model accesses the risk of infection transmission at different values of ACH, in case of an airborne infectious isolation patient in the isolation room. To make it more specific the model was applied to a case study building

2 CASE STUDY BUILDING: ERASMUS MC SOPHIA

Erasmus MC Sophia (children's hospital of EMC as illustrated in Fig. 2) includes 26 type B isolation rooms, which are located at the 1st, 2nd and 3th floor of the Sk-building (Fig. 3). The building departments in which these rooms are located vary in care intensity: from general medical care to intensive care. The 3th floor houses intensive care functions of neonatology, with limited access. The 1st and 2nd floor houses the oncology/haematology (ON/HE) and medium care/high care (MC/HC) departments, and include 16 isolation rooms which form the case study for this research.

Figure 2 – West facade of Erasmus MC Sophia complex in Rotterdam.

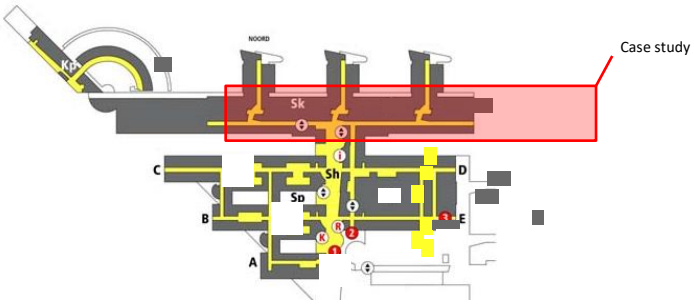

Figure 3 – Map of Erasmus MC Sophia complex in Rotterdam. The red market area represents the building in which the case study rooms are located (Sk-building).

Of the sixteen isolation rooms, four rooms are equipped with a High Efficiency Particle air Filtration (HEPA) system and a pressured air lock as illustrated in Fig. 4 (hereafter referred as type 1). Two of these rooms are located at the ON/HE department, the other two are located at the MC/HC department. The other twelve rooms only have a pressurized air lock (Fig. 5), hereafter referred as type 2 rooms.

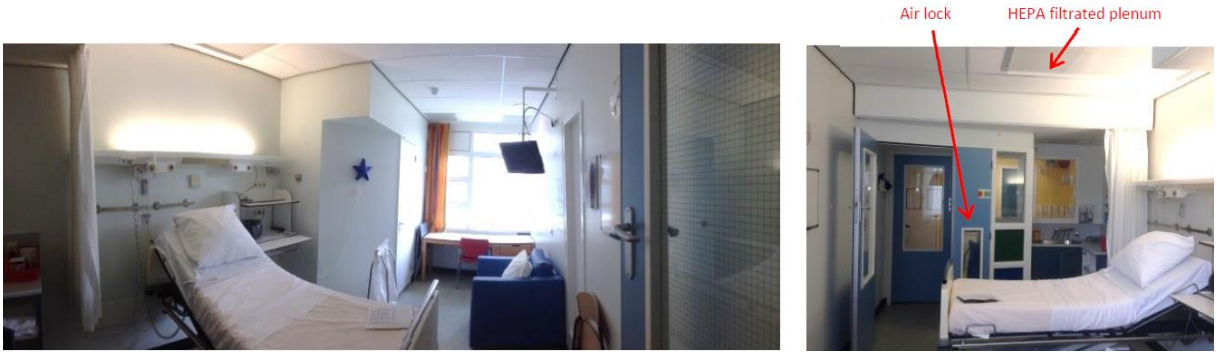

Figure 4 – Isolation room (type 1) at the oncology/hematology (ON/HE) department, provided with a High Efficiency Particle air Filtration (HEPA) system and a pressured air lock.

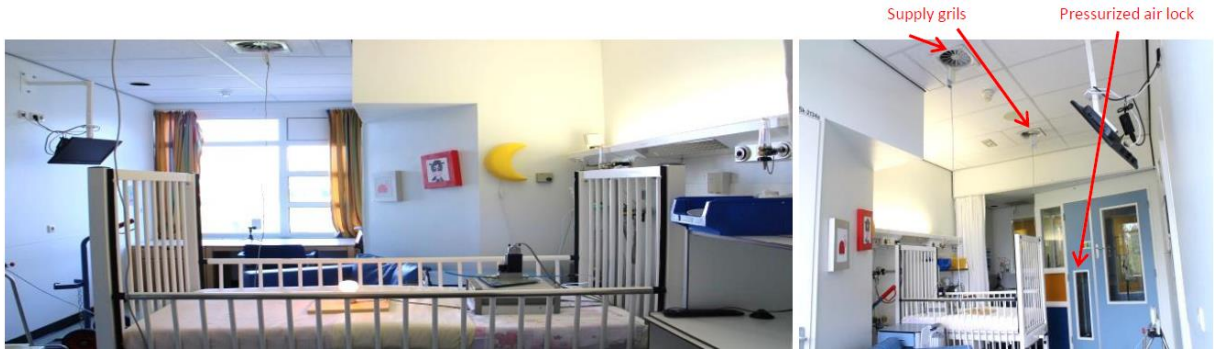

Figure 5 – Isolation room (type 2) at the medium care/high care (MC/HC) department, provided with a pressurized air lock.

3 METHODOLOGY: ROOM MODEL TO DETERMINE MINIMUM VENTILATION

The theoretical approach takes into account the airborne infectious control, including the risk of airborne transmission dispersion to adjacent rooms. The ideal situation for this infection control implies:
(A) a sufficiently low contamination concentration in the room, or;
(B) no overflow of air from contaminated areas to clean areas.

This situation is illustrated in Fig. 6, where:
(A) The ACH has such an efficiency, that the concentration in the room is sufficiently low;
(B) There is no air movement from the anteroom to the corridor through a sufficient high and stable pressure differences. Absence of users activity, and no air exchange ($\varphi = 0$) between isolation room and adjacent rooms, as $\Delta p = 0$, according to $\varphi = C * \Delta P^n$ (volume flow through cracks and gaps).

As in real situations, there is user's activity (with pressure drops and instability of pressure differences) and undefined airflow through cracks and gaps, there is a possibility of infection transmission through a volume flow containing contamination. In order to define a minimum ACH, the risk on airborne infectious particle transmission

during user's activity is investigated at different values of ACH. The infectious particle transmission at a critical point (as indicated with 'P' in Fig.7) is defined as:

$$Infectious\ particle\ transmission < acceptable\ particle\ tranmission$$

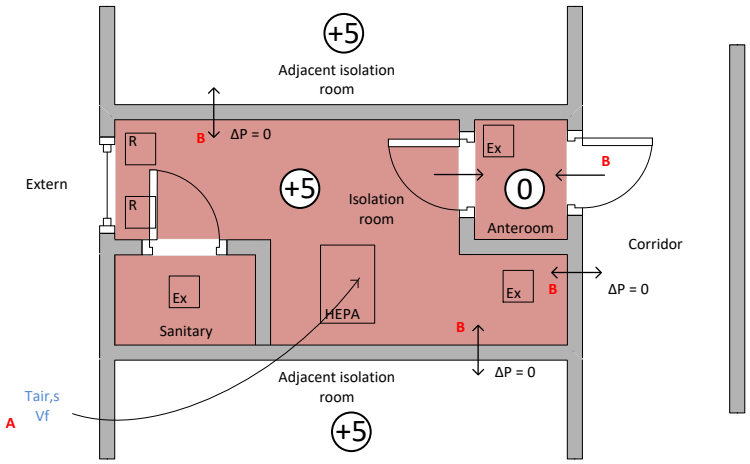

Figure 6 – Ideal situation of infection control in type 1 and type 2 rooms.

Acceptable particle transmission

From the literature in it was shown that combined AIIR/PE rooms are used for protection of the patient and environment at the same time. For both of these isolation types, an acceptable infectious particle transmission respectively concentration is defined.

The amount of pathogens (number of infectious particles) necessary to inhale in order to contract a disease is used as limitation for the transmission of particles to the critical points 'P'. This limitation number of pathogens is variable, depending on the type of disease and susceptibility of the person at point 'P'. For an estimation of this number, the infection dose (ID_{50}) is considered. This value is defined for the three most common infectious diseases in EMC Sophia: M. tuberculosis, MRSA and Varicella (chickenpox), illustrated in Table 2. For protective environments, the allowable number of infectious particles in a room is determined, indicated as colony forming units (CFU) per air volume ($V\ in\ m^3$). For type 1 rooms, a maximum of 15 CFU/m³ is recommended according to literature of [Bowden et al., 2010].

Table 2 – Quantity of pathogens necessary to cause an infection (infection dose) for two most common diseases in Erasmus MC Sophia: tuberculosis, MRSA and Varicella.

Disease	Infection dose
Mycobacterium Tuberculosis	<10 bacteria [Philippe et al., 2006]
Varicella (chickenpox)	<100 virus particles [Hawker et al., 2005]

Infectious particle transmission

The value of contaminated particles at 'P' depends on two parameters; the magnitude of the concentration and the risk forming airflow, and is represented by the following equation:

$$Infectious\ particle\ transmission = C_i * \varphi_{risk} \quad (1)$$

- $C_i =$ $particle\ concentration\ in\ room [particles/m^3]$;
- φ_{risk} $= risk\ forming\ airflow\ [m^3/s]$;

Contamination concentration (C_i)

The isolation rooms' HVAC system consists of air supply and exhaust. As the amount of air supplied equals the exhaust, the contamination concentration in the room reaches equilibrium (maximum concentration). This mechanism is illustrated in Figure 7, and is explained by a steady state ventilation-contamination equation (2).

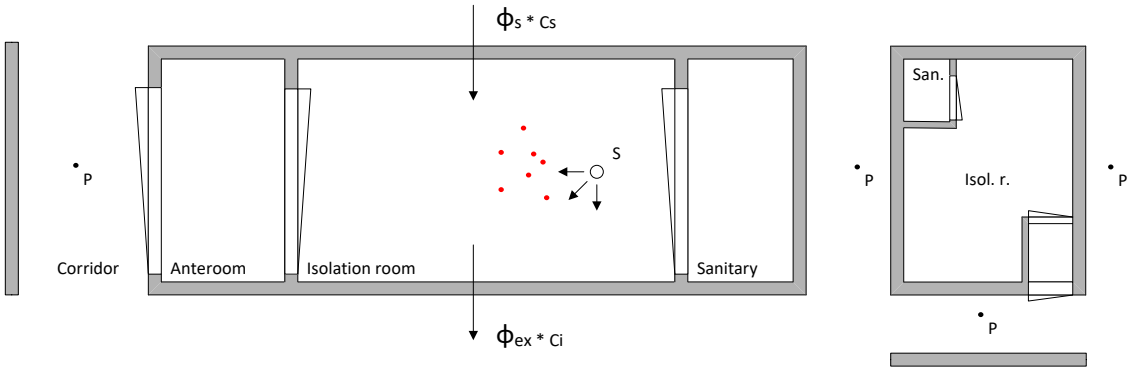

Figure 7 – Model and model boundaries for determining the infectious particle transmission.

The equation is based on a fully mixed situation, meaning that the contamination concentration is equal at any point in the isolation room and that an infectious particle has an equal chance of being anywhere within the space, regardless at which time or what position the infectious particle was generated.

The calculation is performed for both type 1 and type 2 (case study) rooms. The calculation assumes one identified infectious patient (infectious point source S with an emission rate $E\ in\ particles/s$) in the enclosed space, including a defined air supply respectively exhaust/leakages ($\varphi_s\ resp.\ \varphi_{ex}\ in\ m^3/s$).

In type 1 rooms a part of the extracted air is 'recycled', filtrated, and mixed again with air from the AHU, before it goes back again into the room (reducing heating power). The recirculation volume is indicated with ($\varphi_r\ in\ m^3/s$). The model assumes that the concentration of infectious contamination in the outside air ($C_s\ in\ particles/m^3$) is 0. The steady state equation for the contamination concentration can be written as:

$$\sum \varphi_s * C_s + \sum S - (\varphi_r * C_r)^* = \sum \varphi_{ex} * C_i \quad (2)$$

with $\sum \varphi_s = \sum \varphi_{ex}$ *and* C_s
C_r = *Contaminated particle concentration recirculated* $[particles/m^3]$;
**Only applicable to HEPA filtrated isolation rooms*

Airborne infectious contamination concentration in room:

$$C_i = \frac{S-(\varphi_r * c_r)*}{\varphi} in\ (particles/m^3) \quad (3)$$

with C_r is C_i * η_{filter}

$$\eta_{filter} = Filter\ efficiency\ [-] = 0{,}9997$$

Minimum 99,97% of particles > 0,3 µm removed by HEPA filtration. [Gammaitoni et el., 1997]

As the steady state equation does not take the room volume and time into account, a dynamic differential ventilation-equation was defined, representing the inertia of the system. As one airborne infectious person is present at time $t = 0$, in an enclosed space of volume $V\ in\ m^3 (44{,}5\ m^3)$, the contamination concentration can be expressed as function of time including the quanta production rate (infection source S), air supply volume per hour, recirculation volume and filtration efficiency. The dynamic ventilation-concentration equation can be written as:

$$dC_i = \frac{\varphi}{V} * \left(\frac{S-(\varphi_r * c_r)^*}{\varphi} - C_i\right) dt \quad (4)$$

$$C_i = \left(\frac{S-(\varphi_r * C_r)^*}{\varphi}\right) * \left(1 - e^{-\frac{\varphi * t}{V}}\right)$$

In fully mixed spaces, the worst case situation for risk on airborne transmission equals the maximum concentration at equilibrium. For this situation only the limit of equation 4 is required. But, to eliminate the possibility that the maximum concentration occurs after long time (than probably a lower ACH is possible), the dynamic ventilation concentration equation is used in the contamination concentration calculation.

Contaminating source (S)

The generation rate of airborne infectious particles (quanta), is used as contaminating source (S) to model the contamination concentration in a room. The quanta production rates of the most common and contagious diseases in EMC (M. Tuberculosis and Varicella) are illustrated in Table 3.

If patients do not undergo a procedure that induces the production of aerosols, the average generation rate of airborne contaminated infections (regardless the disease) is usually assumed to be < 1 infectious quanta/minute [Atkinson et al., 2009]. This value is assumed to be the worst case quanta generation rate. The generation rate of the common diseases is lower than this value (Table 3).

Table 3 – Quanta generation (E) of most common airborne infectious diseases in children hospitals (tuberculosis and Varicella), used as contaminating source (S) input in equation 3 and 4. The mean quanta production rate, is the rate of airborne infectious particles released by one person.

Disease	(E) Mean quanta production rate of quanta < 5 µm [quanta/h]	Standard deviation [quanta/h]		Reference
Mycobacterium tuberculosis	12,7	3,0	Stochastic	[Beggs et al., 2010]
	1-50	-	analysis	[Noakes et al., 2006]
	1,25 - 249	-	Measurement	[ASHREA, 2014]
	54,29	3,05	Estimation	[Chen et al., 2011]
	0-44	-	Estimation	[Escombe et al., 2007]
	0-60	0,25	Measurement	[Charney et al., 2006]
	1,25	-	Measurement	[Riley et al., 1962]
Varicella (chickenpox)	59	1,99	Estimated	[Chang et al., 2006]

Volume air supply φ_s, recirculation φ_r , exhaust and leakages φ_{ex}

The volume of air supply, exhaust and recirculation, as used in the contamination concentration calculation, is measured using flow finder and duct measurements (Fig. 8). The airflow volumes are measured at all supply, exhaust and recirculation grills in order to determine the contamination concentration in the rooms. The experiment is repeated for different values of ACH. An unknown parameter which is needed for the contamination concentration calculation is the exhaust volume of air leakages. This value is derived from the differences between air supply and exhaust, see Table 4.

Figure 8 – a) Flow finder and b) Pitot tube for measurement of: c) Air supply, d) Exhaust and e) Recirculation and exhaust grills.

Table 4 – Average volumes of air supply, exhaust and recirculated air after 10 measurements

	Type 1 room			Type 2 room		
Air volumes [m³/h]	9,1 ACH	6,0 ACH	2,2 ACH	12,0 ACH	7,2 ACH	3,1 ACH
Supply (φ_{sup})	403	266	99	535	321	136
Exhaust room ($\varphi_{ex,r}$)	151	140	43	293	161	50
Exhaust room to anteroom[1] ($\varphi_{cd,1}$)	60	14	125	72	52	19
Exhaust corridor to anteroom[1] ($\varphi_{cd,2}$)	75	121	10	33	53	86
Exhaust sanitary (φ_{san})	59	59	26	65	65	65
Air leakages[2] (φ_{cg})	133	53	20	105	43	2
Recirculation (φ_r)	191	191	191	-	-	-

[1] Air volume defined using pressure differential measurements.
[2] Air volume defined using equation (4)

For each value of ACH at each grill, the measurements are repeated ten times, after which the average value is calculated, as given in Table 4. The results of the calculated contamination concentration at different values of ACH (high, medium and low) and the worst case scenario for quanta generation (60 quanta/hour) are illustrated in Fig. 9 for type 1 rooms and for type 2 rooms. The contamination concentration is indicated in particles per cubic meter of air in the room. The contamination concentration in type 1 rooms is considerably lower than the concentration in type 2 rooms, as a result of the filtrated recirculated air volumes. Extracted air which is recycled, filtrated and mixed with outside air supplied back into the room reduces the heating power but at the same time the indoor air quality (CO2) becomes poor at high recycle rates. In both figures the concentration rises reaching the equilibrium (maximum concentration). The concentration in the sanitary also reaches equilibrium, but with a time delay. The concentration in the anteroom is lower than the maximum concentration in the isolation room, through air mixing with 'clean' air supply coming from the corridor. The (lower) maximum concentration in the anteroom is also reached with a time delay. For lower values of ACH (in both isolation room, sanitary and anteroom), the time at which the equilibrium is reached is significantly higher than for larger ACH. Note: the lower concentrations in the anteroom might be an advantage for the risk of infection transmission.

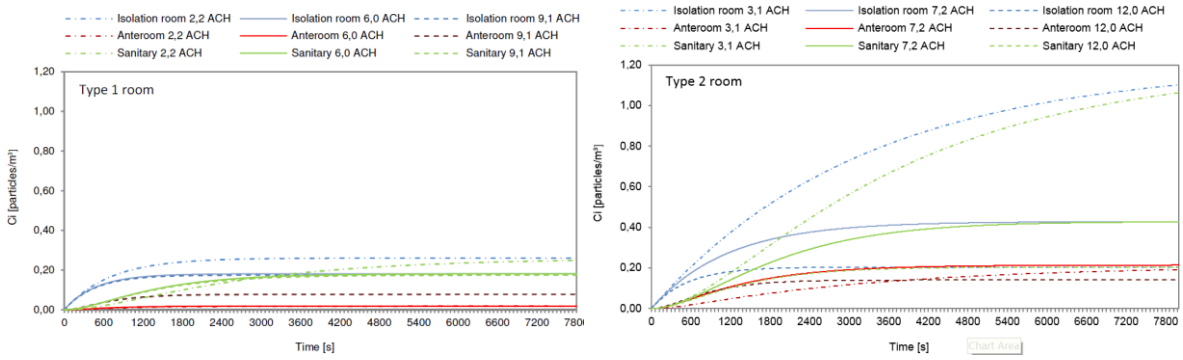

Figure 9 – Contamination concentration type 1 room and type 2, in worst-case scenario of quanta production rate (60 quanta/h).

Risk forming airflow (φ_{risk})

The WIP guidelines, which prescribe that the air change rate in isolation rooms is sufficient high (6 to 7 ACH), result in the assumption that the risk of disease spreading to adjacent areas would be very low to minimal. But as it is concluded that the required ACH, of isolation rooms is insufficient scientifically founded, and thus the risk of infection transmission is unknown, the risk of spreading diseases is defined as: 'the risk of airborne infectious particles spread to spaces adjacent to airborne isolation rooms' (according to the findings from the literature review).

With the risk forming airflow, the infectious particle transmission can predict the probability of airborne disease transmission (equation 1). And is defined as an uncontrolled air flow from contaminated areas to clean areas, through:

(1) Leakages through undefined cracks and gaps,;
(2) Instability and reversed pressure differences at the anteroom door location (through door openings/closures by users activity);
(3) Human motion;

(1) Air leakages through undefined cracks and gaps (φ_{cg})

Exfiltration of air from contaminated areas to clean areas through leakages is caused by an unbalance in the controlled air supply and exhaust in the room, caused by a variable flow. Changes in supply and exhaust will increasing or decreasing the room pressure and causes exfiltration/infiltration through undefined cracks and gaps, equal to differences in supply and exhaust. In order to estimate these undefined air leakages, the following equations are used:

$$\frac{d\varphi}{dt} = \sum \varphi_{in} - \sum \varphi_{out} - \varphi_{var} \quad (5)$$

$$\varphi_{var} = \varphi_{cg} = \varphi_s - \varphi_{ex,san} - \varphi_{ex,isol.r.} - \varphi_{cd} \quad (6)$$

In which the supplied air (φ_{sup}) minus the exhaust air at the sanitary ($\varphi_{ex,san}$) respectively the room ($\varphi_{ex,r}$), minus the clearly defined airflow through orifices (φ_{cd}), equals the air exfiltration or infiltration of the room. In order to define $\varphi_{c,g}$, the air supply and exhausts were measured (Fig. 8). The airflow through clearly defined orifices is determined using pressure differential measurements as described below.

Air movement through clearly defined orifices (φ_{cd})

Due to differences in air pressure between adjacent areas, air flows from higher pressure areas to lower pressure areas. If the differential pressure (ΔP), geometric coefficient of the gaps (c), and the empirical pressure exponent (n) are known, the gaps around a closed door can be modelled as an orifice. The differential airflow can be calculated according to the leakage function equation. This equation correlates the air leakage to the differential pressure, which produces the airflow [ASHREA, 2009]. This leakage function equation can be defined as:

$$\varphi_{cd} = c(\Delta P)^n \quad (7)$$

$with$

$\varphi = volumic\ rate\ flow\ through\ an\ orifice\ [m^3/s]$;
$c = flow\ coefficient\ [m^3/s * m^2 * (Pa)^n]$;
$\Delta p = Pressure\ differential\ across\ the\ orifice\ [Pa]$;
$n = 0{,}5 < n \leq 1\ [-] for\ turbulent\ air\ flow, 1{,}0\ [-] for\ laminar\ air\ flow.$

At different values of ACH, the pressure differences are measured at the two anterooms door locations, using pressure difference measurement equipment (Fig. 10). The class of the flow coefficient is assumed to be 'loose' $c = 7{,}0 * 10^{-4}\, m^3/s.m^2(Pa)^{0{,}65}$, and depends on the geometry of the orifice (air leakage areas) and is commonly around 0,65 (for sharp-edged orifices), according to [ASHREA, 2009].

Figure 10 – Pressure differences measurement. a) Anteroom door locations, b) differential pressure transducer, c) and d) differential pressure transducer connected to the magnehelic at the corridor, respectively room door location.

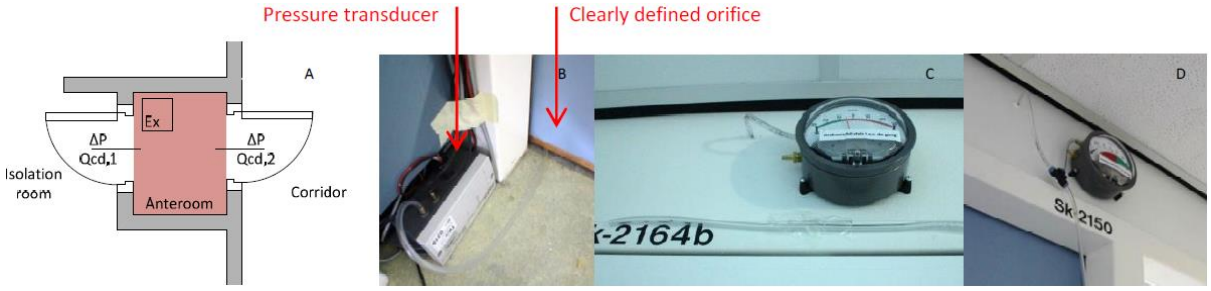

Table 5 – Air flow through undefined cracks and gaps at different values of ACH in type 1 rooms.

ACH	φ_{sup}	φ_{san}	$\varphi_{ex,r}$	$\varphi_{cd,1}$	$\varphi_{cd,2}$	$\boldsymbol{\varphi_{cg}}$
9,1	403	59	151	60	75	**133**
8,0	356	59	151	49	86	**97**
6,0	266	59	140	14	121	**53**
4,0	176	43	91	12	123	**30**
2,9	128	30	63	11	124	**24**
2,2	99	26	43	10	125	**20**

Table 6 – Air flow through undefined cracks and gaps at different values of ACH in type 2 rooms.

ACH	φ_{sup}	φ_{san}	$\varphi_{ex,r}$	$\varphi_{cd,1}$	$\varphi_{cd,2}$	$\boldsymbol{\varphi_{cg}}$
12,0	535	65	293	72	33	**105**
11,0	491	65	262	65	40	**99**
9,6	429	65	215	55	50	**94**
8,2	365	65	182	48	57	**70**
7,2	321	65	140	52	53	**64**
6,0	268	65	113	50	55	**40**
5,1	225	65	65	52	53	**20**
4,0	177	65	40	50	55	**4**
3,1	136	65	20	19	86	**2**

Table 5 and 6 illustrate the results of the defined air movement through undefined cracks and gaps, as a result of the air volume measurements (Figure 8 and Table 4) and the air movement through clearly defined cracks and gaps (equation 7). The results show higher air volumes through undefined cracks and gaps at higher values of ACH. The measured values of pressure differences have a bandwidth which is visible in for example Fig. 11, indicated with a 'Z'. For the calculations of airflow through clearly defined cracks and gaps the average value of the long term measurements is used (during closed door situations).

(2) Air movement through inversed or instability of pressure differences $(\boldsymbol{\varphi_{ip}})$

As users activity include opening and closing doors, a pressure differences of sufficient magnitude and stability is required in order to prevent inversed airflows. The current WIP requirements prescribe a pressure difference of 5 Pa in a situation with closed

doors. For the stability of the pressure differences, no requirements are described. The isolation room HVAC system has no pressure control and the amount of air supply and exhaust is constant. As the pressure difference changes during entering or leaving the isolation room, the stability becomes important and is investigated, using measurements. The measurements investigate if the air flow becomes inversed during opening/closing doors (through persons who entering or leaving the room). An inversed airflow is indicated with an inversed pressure difference.

The pressure differences measurements (as illustrated in Fig. 8) are also used for determining the risk forming airflow caused by inversed or instability of pressure differences due to users activity (through opening and closing doors). The measurements are performed in two rooms types at both the ON/HE and MC/HC department, for different values of ACH (low, medium and high). The measurement results are illustrated in Fig. 11 up to 14.

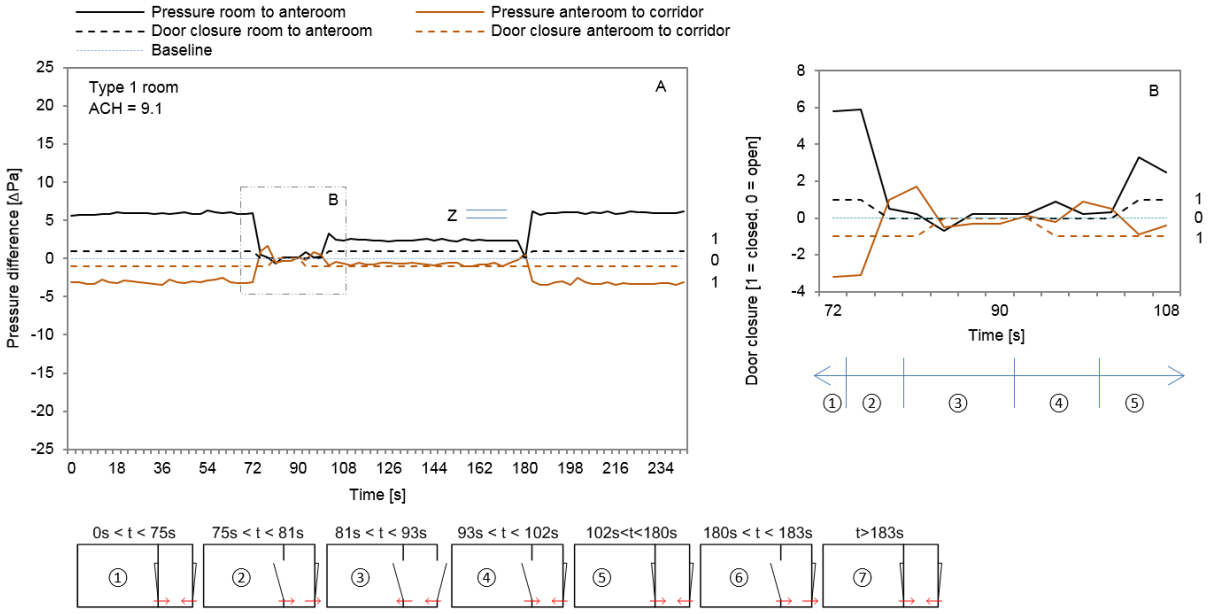

Figure 11 – Measurement results of pressure differences during isolation room usage of type 1 room at 9,1 ACH. A person moves from the room to the corridor and back to room.

Fig. 11 designates the measurement results of the pressure differences and pressure drop during opening and closing doors at 9,1 ACH in type 1 rooms. Opening of the door at the room-anteroom at 75s results in a pressure drop from 5,9 Pa to 0,5 Pa (room-anteroom), and stabilizes at 0,2 Pa. The pressure difference drops but remain positive (flow inright direction). At the same time there is an inversed pressure difference visible at the anteroom-corridor door location as illustrated with the red arrows in the overvieuw of door movements (from anteroom to corridor). During opening of the anteroom-corridor door at 81s, the pressure difference of the room-anteroom is inversed (-0,7 Pa), and stabilizes at 0,2 Pa. The pressure difference at the corridor –anteroom door location remains negative. It is remarkable that openings of doors at the room-anteroom location do not necessarily lead to inversed pressure

differences (t > 180s). The same measurements are performed during opening and closing doors at 6,0 ACH in type 1 rooms. These results are not reviewed in detailed as the results are comparable to each other. The results show that door openings do not lead to inversed pressure differences. However, door closure (room/anteroom) leads to inversed pressure differences and thus an inversed airflow. Fig. 12 designates the results of the pressure differences at the door locations and the pressure drop during opening and closure of doors of type 1 rooms at 2,9 ACH. Inversed pressure differences are visible during openings of the anteroom-corridor door location.

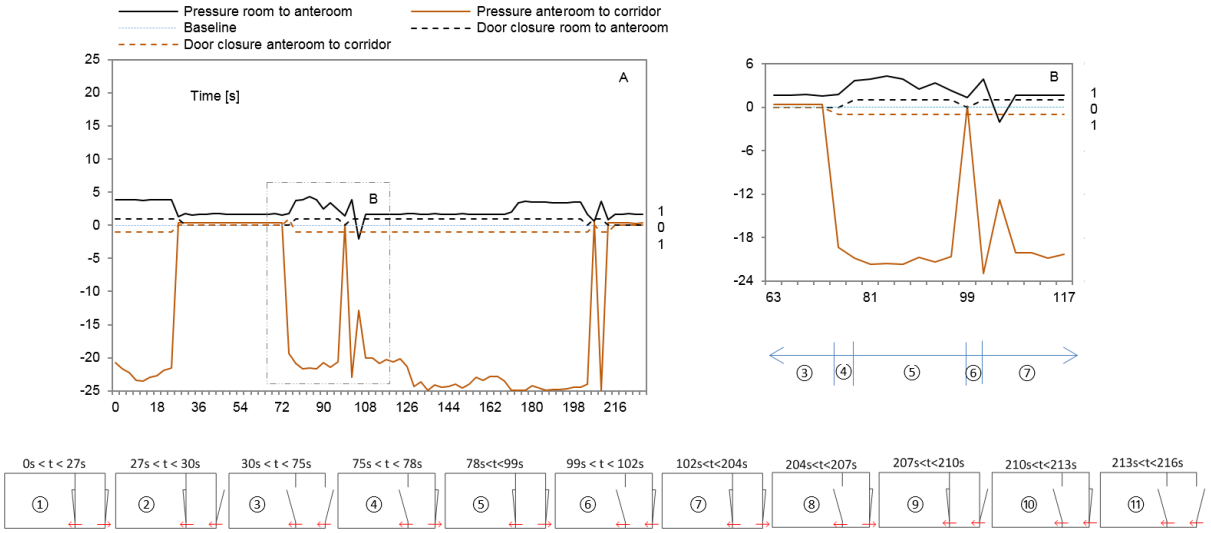

Figure 12 – Measurement results pressure differences type 1 room at 2,9 ACH

From the results of the measurements in type 2 rooms at different values of ACH in Fig. 13 it is visible that opening of a door (corridor-anteroom) leads to an inversed pressure difference. In Fig. 14 closing a door leads to inversed pressure difference.

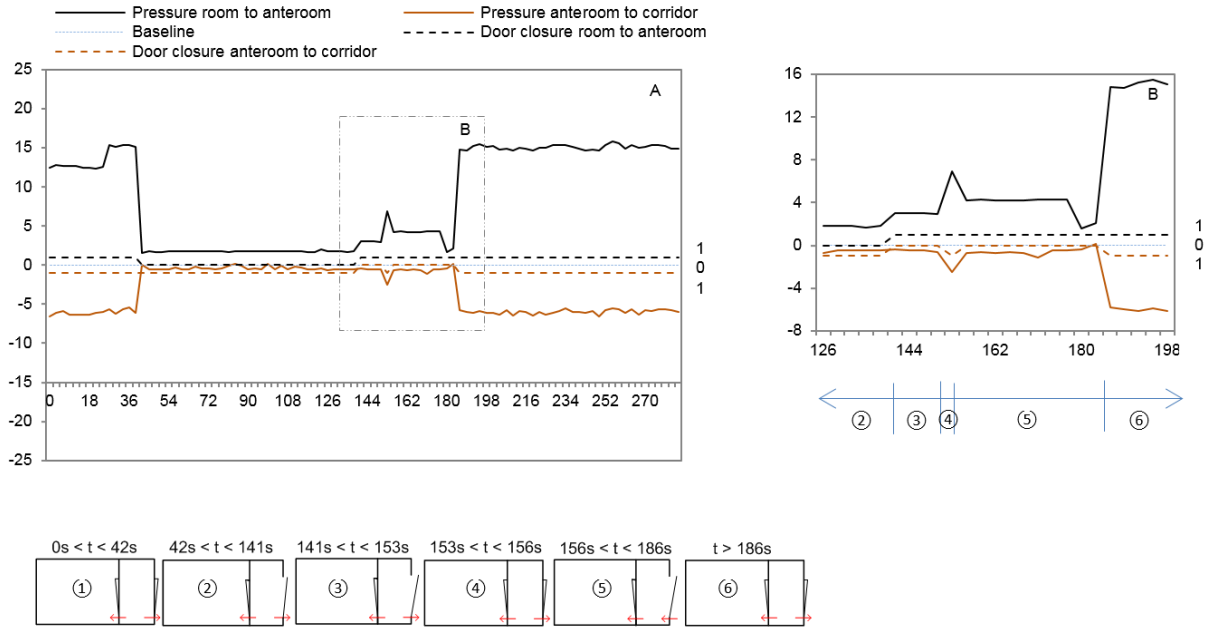

Figure 13 – Measurement results pressure differences type 2 room at 6,0 ACH. Human motion from corridor-room

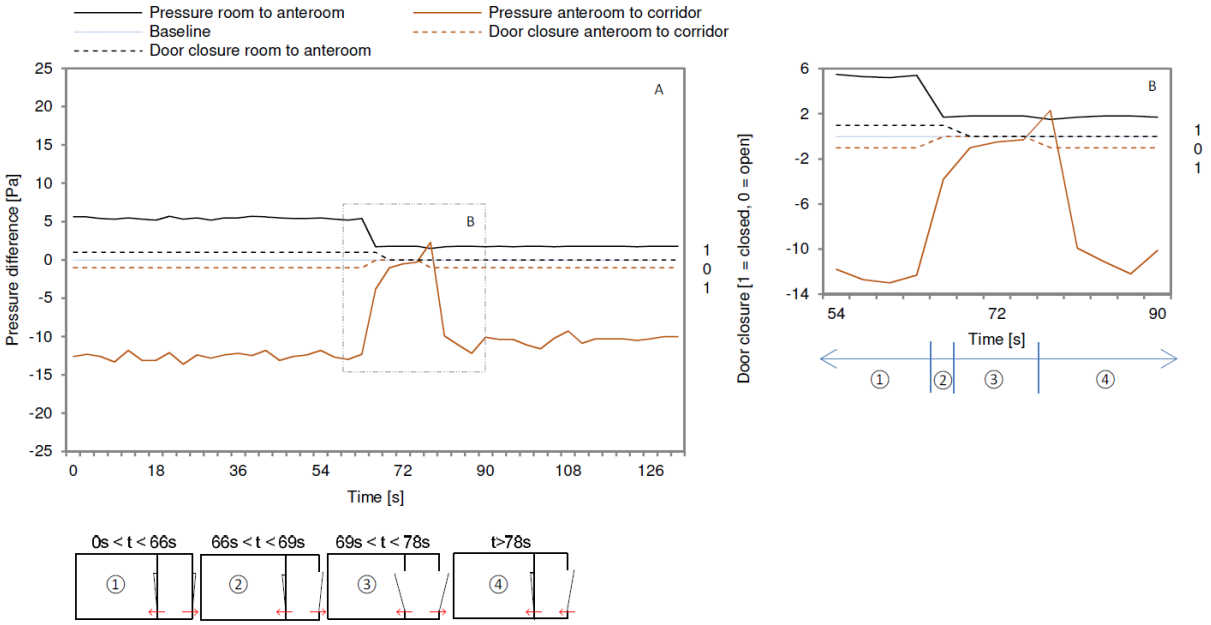

Figure 14 – Measurement results pressure differences type 2 room at 3,1 ACH. Human motion from corridor-room.

Although the differences in the magnitude of pressure differences at high and low values of ACH, the inversed pressure difference is not more of less at higher/lower value of ACH. At all values of ACH the pressure differences become inversed through users activity (opening and closure of doors and movement). The amount of inversed airflow is difficult to determine, but assuming that swinging doors lead to movement of air volumes, and thus air exchanges across the open door, if a door opens (Fig. 15), make it able to access the inversed air volume. The air is dragged into the region in which the door is swapped. Closing doors does not seem to lead to any significant air exchange between rooms [Tang et al., 2006]. The amount of air volume dragged during opening of a door, is calculated assuming that a person is leaving the room. A hinged door (in the case of the isolation rooms, $r = 1\ m$) opens from a closed to open position around 55°, resulting a door edge travel distance of $2\pi r * (55/360) = 0{,}96$ m. The time in which the door opens is assumed $2\ s$, resulting in an air flow with the speed of $0{,}48\ m/s$. The area of the door is $2{,}3\ m^2$, resulting in an air movement from the anteroom to the corridor of approximately $1{,}1\ m^3$.

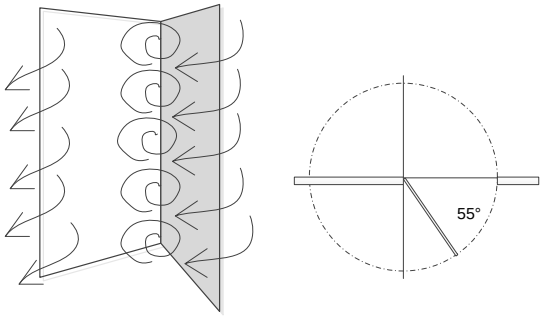

Figure 15 – Air exchange through opening of doors.

Note: air movements through door movement can be reduced using sliding doors, although this solution leads to less air exchange, they are a large source of pollution due to their mechanisms which are difficult to clean.

(3) Air movement through human motion (φ_{hm})

If people move, they displace air in front of them and carry an air wake forwardly (created by a pressure difference which drives (contaminated) air from two lateral sides into the wake). Air is transported from the room to the corridor by human motion through door openings. People walking through the doorway move a considerable volume of (infectious) air across the opening, which equals to a volume flux ($F\ in\ m^s/s$), calculated using the following equation [Tang et al., 2006]:

$$F = (c_{dr} * A * v) / 2 \quad (8)$$

- $c_{dr} = drag\ coefficient\ for\ a\ body\ [-]$;
- $A = cross\ sectional\ area\ of\ the\ body\ [m^2]$;
- $v = velocity\ of\ air\ flow\ [m/s]$;

It is assumed that the frontal area of a persons' body is approximately ($A = 0{,}35\ m\ x\ 1{,}7\ m = 0{,}595\ m^2$). The velocity of the air flow is assumed to be equal to the walking speed of the person ($v = 1{,}1\ m/s$). The drag coefficient equals 1,16 according to [Penwarden et al., 1978]. For this person the volume of air flux $\varphi_f = (1{,}16\ x\ 0{,}595\ x\ 1{,}1) / 2 = 0{,}38\ m^3/s$.

In addition, a moving person produces a wake which also transports air (containing infectious particles), see Fig. 16. This wake is assumed to be the volume of the persons' body ($0{,}35\ m\ x\ 1{,}7\ m\ x\ 0{,}2\ m = 0{,}119\ m^3$), resulting in a total air movement of $0{,}5\ m^3$.

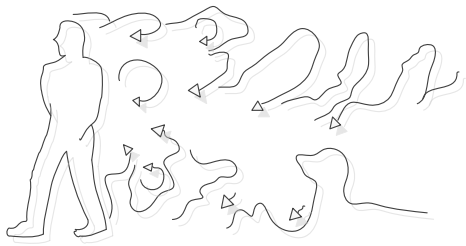

Figure 16 – Wake behind a body, produced by a moving person.

Note: at both large or small ACH, human motion affect airborne transmission, but at large ACH its effect is less important than at small ACH. If the ACH becomes smaller, the human motion becomes more important for spread of infections, as the concentrations in the rooms are higher (higher risk).

RESULTS

This paragraph describes and discusses the results of the room model as explained, calculated using equation 1. Fig. 17 illustrates the number of infectious particle transmission, and the acceptable particle transmission of both type isolation rooms, according to the following equations:

$$1)\ C_i * \varphi_{cg} < acceptable\ particle\ tranmission \quad (9)$$
$$2)\ C_i * \varphi_{ip} < acceptable\ particle\ tranmission$$
$$3)\ C_i * \varphi_{hm} < acceptable\ particle\ tranmission$$

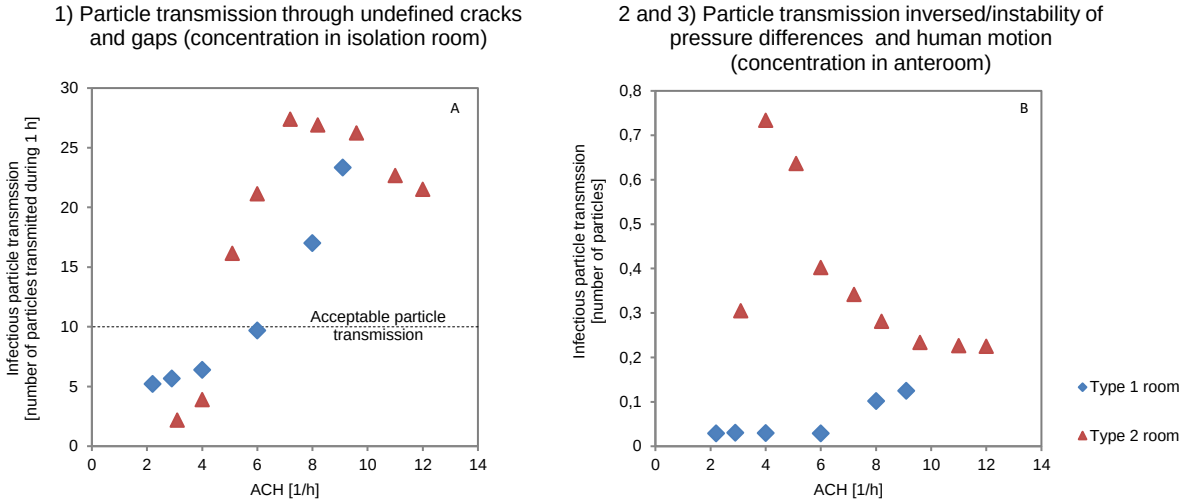

Figure 17 – a) Infectious particle transmission and acceptable particle transmission through contaminated airflow through 1) leakages through undefined cracks and gaps and b) through 2) instability and reversed pressure differences and 3) human motion through door openings.

A period of one hour (instead of seconds as described in equation 1) is determined for the particles transmission through cracks and gaps (Fig. 17a), as it is assumed that infectious particles flowing to an adjacent room where patients are hospitalized for many hours. In both type 1 and type 2 rooms the particle transmission is smaller than the acceptable particle transmission at low values of ACH (≤ 4 ACH). At these values of ACH, the contamination concentration is relatively high, however the risk forming airflow is relatively low.

In Fig. 17b the results of the particle transmission through inversed/instability of pressure differences, and the human motion are designated. Room type 1 has a relatively low contamination concentration at the anteroom at low values of ACH. These low concentrations are a result of larger pressure differences at the anteroom-corridor door location compared to the anteroom-room door location. Large volumes of uncontaminated air flow from the corridor to the anteroom, compared to small volumes of contaminated air from the room to the anteroom. At large values of ACH,

the volumes of contaminated air equals the volumes of uncontaminated air entering the anteroom, resulting in higher concentrations and thus larger risk of transmission if the pressure difference is reversed or instable, and/or human walking from the anteroom to the corridor.
The number of infectious particle transmission at 3 ACH for type 2 rooms does not correlate to the results of other values of ACH. The explanation for this deviating number of particle transmission is the contamination concentration in the anteroom. Through a higher pressure difference at the anteroom-corridor door location, compared to the anteroom-room door location, large amounts of uncontaminated air flows into the anteroom. Resulting in a low contamination concentration in the anteroom, and thus a low number of particles in the airflow of inversed pressure differences. The results of particle transmission through undefined cracks and gaps are only valid for rooms with a flow coefficient that is assumed to be 'loose'. Rooms which are more airtight have a lower risk on particle transmission, however in literature it is concluded that more airtightness leads to more instability of the pressure differences during opening or closure of doors and thus a higher risk on particle transmission at the door location [Brink, A., 2010].

CONCLUSION

The risk of infection transmission depends on the air volume and the contamination concentration. A lower air volume means less exfiltration of air, but a higher contamination concentration. The calculation of the infectious particle transmission need to be considered for defining the acceptable value of ACH.
The WIP requirements recommend $\varphi_{cg} < 0{,}05 * Q_s$ is often not feasible (in existing buildings) through openings alongside for example air, water, electricity or central heating ducts. From the results of the calculations of equation 7 it can be concluded that the rooms often in practice have a low air tightness.
There are differences in air tightness between rooms, however in al situations, a higher value of ACH result in a larger volume of airflow through undefined cracks and gaps.
The worst case situation of transmission of air (containing contamination) occurs if the airflow through undefined cracks and gaps flows in only one (critical) direction, to public areas (e.g. the corridor) or adjacent rooms (with patients who are susceptible). Air tightness (air leakages) is often difficult to detect and thus accessed by a calculation. The worst case is considered to eliminate uncertainties. In order to gain more accuracy of the air flows through undefined cracks and gaps, a blower door test or a leakages detection test can be used.
It is concluded that the particle transmission through undefined cracks and gaps is the most important/crucial factor for infectious particle transmission. It is recommended that isolation rooms are as airtight as possible to prevent air from being pulled in through these undefined cracks and gaps. Ideally, rooms should be sealed except for

the clearly defined gap(s). Additionally, a more airtight room and maintaining the same air supply conditions result in higher pressure differences at the door locations. According to this phenomena, a more airtight room at the same pressure differences at the door locations, result in less air supply and thus potentially energy reduction.
The ACH for isolation type of patients is doubtful. According to the room model results it is concluded that the ACH for isolation patients can be reduced to < 6 ACH, however a more detailed model is needed which provides more certainty. The room model as defined in this research revealed that transmission of infectious particles through undefined cracks and gaps is most crucial (has most influences on transmission). Additionally, it is concluded that at low ACH the contamination concentration is more evenly distributed. On the other hand, the concentration is higher. For not occupied rooms, the ACH need to be sufficient to maintain the space conditions for the time a patient need to be hospitalized. But also to keep the room at a low positive pressure in order to keep contaminants outside the room.

REFERENCES

American Institute of Architects (2001); The 2001 Guideline for Design and Construction of Hospital and Health Care Facilities. Academy of Architecture for Health, Facilities Guideline Institute with assistance from the U.S. Department of Health and Human Services and the National Institutes of Health.

Aliabadi A.A., Rogak S.N., Bartlett K.H., Green S.I., (2011, September); Preventing airborne disease transmission: Review of methods for ventilation design in health care facilities. Advances in Preventive Medicine, Volume 11 (2011), ID 124064.

ASHRAE (2009); Handbook Fundamentals SI Edition

ASHRAE (2014, January); Position Document on Airborne Infectious Diseases.

Atkinson J., Chartier Y., Pessoa-Silva C.L., Jensen P., Li Y., Seto W., (2009); Natural ventilation for infection control in health-care settings. World Health Organization publication/guidelines, 2009.

Beggs C.B., Stepherd S.J., Kerr K.G., (2010, August); Potential for airborne transmission of infection in the waiting areas of healthcare premises: stochastic analysis using a Monte Carlo model. BMC Infectious Diseases, Volume 10 (2010), 247.

Bhatia (2012); A basic design guide for clean room applications. PDH Centre An Approved Continuing Education Provider, 21 – 22.

Bowden R.A., Ljungman P., Snydman D.R., (2010); Transplant infections. Oxford Journals, Volume 19, 1342 – 1343.

Brink A. v.d., (2010); The dynamic behaviour of pressure in rooms with pressure hierarchy. Ventilatietechniek (2010), 54 – 143.

Centre for Disease Control and Prevention. Guidelines for preventing transmission of mycobacterium tuberculosis in health-care facilities. (MMWR 2005; 54 [RR-17]).

Charney, William (2006); Emerging infectious diseases and the threat to occupantional health in the U.S. and Canada. Public administration and public policy, 126.

Chen S.C., Liao C.M., You S.H., (2011, June); A probabilistic transmission model to assess infection risk from Mycobacterium tuberculosis in commercial passenger trains. Risk analysis, Volume (2011), 930-9.Chen S.C.,

Chang C.F. Liao C.M., (2006, March); Predictive models of control strategies involved in containing indoor airborne infections. Indoor Air, Volume 16 (2006), 469 – 481.

Dutch government, building requirements (2012, January); Dutch building code. Chapter 3: Technische bouwvoorschriften uit het oogpunt van gezondheid, Article 3.6.1, lid 2.

Escombe A.R., Oeser Cl., Gilman R.H., Navincopa M., Ticona E., Martinez C., Caviedes L., Sheen P., Gonzalez A., Noakes C., Moore D.A.J. Friedland J.S., Evans C.A., (2007, April); The Detection of Airborne

Transmission of Tuberculosis from HIV-Infected Patients, Using an In Vivo Air Sampling Model. Clinical Infectious Diseases, Volume 44 (2007), 1349 – 1357.
Hawker J., Begg N., Blair I., Reintjes R., Weinberg J., (2005); Communicable disease control handbook.
Li Y., Tang G.M. Yang J.W., Chao X., Lin C.Y.H., Lu J.Z., Nielsen J.W., Niu P.V., Qian J., Sleigh H., Su A.C., Sundell H.J.J., Wong T.W., Yuen P.L., (2007, February); Role of ventilation in airborne transmission of infectious agents in the built environment – a multidisciplinary systematic review. International Journal of Indoor Environment and Health, Volume 17 (2007), 2 – 18.
Philippe H., Fauville-Dufaux M., Breyer D., Vaerenbergh v. B., Pauwels K., Dai Do Thi C.,, Sneyers M., Wanlin M., Snacken R., Moens W., (2006, April); Biosafety Recoomendations for the Contained Use of Mycobacterium tuberculosis Complex Isolates in Industrialized Countries. Division of Biosafety and Biotechnology, Scientific Institute of Public Health, (2006), 2 – 17.
Tang J.W., Li Y., Eames I., Chan P.K.S., Ridgway G.L., (2006, August); Factors involved in the aerosol transmission of infection and control of ventilation in healthcare premises. Journal of Hospital Infection, Volume 64 (2006), 100 – 114.
Tung Y.C., Hu S.C., Tsai T.I., Chang I.L., (2007, May); An experimental study on ventilation efficiency of isolation room. Building and Environment, 44 (2009), 271 – 279.
WIP (2009), Balvers H.A., Mahieu C.J.E.J., Cornelissen H.J.M., TNO Bouw; Bouw- en inrichtingseisen isolatie-afdeling Ventilatie isolatiekamers.