

# Chapter 5

## Calculation of Air Change Rate

### 5.1 Outline

In order to dilute and effectively remove the bioaerosol in the negative pressure isolation ward, a certain amount of flow rate, i.e., the air change rate, is needed. According to the principle of air cleaning technology, the performance with larger air change rate is better. This has been proved and no further experimental verification is needed. For example, it is of no use to prove that the performance with the air change rate  $12 \text{ h}^{-1}$  is better than that with  $10 \text{ h}^{-1}$ , or the performance with  $10 \text{ h}^{-1}$  is better than that with  $8 \text{ h}^{-1}$ . But the relationship is not completely linear proportional. It does not mean that better performance will be obtained when the air change rate increases too much. There is an economic problem.

For the certain user such as hospital, too much air change rate cannot be beard. Then how much is it suitable? Just as that mentioned in Chap. 1, it is almost blank in the research and construction of isolation ward these years. Therefore, the related material is very rare. It is difficult to verify and summarize through practice, not to mention that the comprehensive practice is difficult to be found.

So usually the specification or suggestion from related literatures from U.S.A. are used as reference. For example, in ASHRAE manual in U.S.A., based on the requirement of thermal comfort, the air change rate in the isolation ward for the pulmonary tuberculosis patient is  $6 \text{ h}^{-1}$ . This is much less than that specified in other literatures, which is shown in Table 5.1.

Since there is no fundamental answer based on theory, the determination for the value of the air change rate is still controversial.

Then how could we determine the reasonable air change rate? Is it possible to use the isolation coefficient based on the biosafety cabinet to obtain the allowable microbial standard in the isolation, so that the problem for determining the air change rate in isolation ward can be solved? It is obviously infeasible. The safety limit outside the biosafety cabinet is determined under the condition that operator is standing in front of a biosafety cabinet with the isolation effect. But the bioaerosol

**Table 5.1** Related standards on the flow rates of the dilution air and the outdoor air

Standard	Specified flow rates of the dilution air and the outdoor air
“ <i>Guidelines for Preventing the Transmission of Mycobacterium tuberculosis in Healthcare Facilities</i> ” issued by CDC in U.S.A.	In new-built or renovated isolation ward for prevention of airborne transmission, the air change rate $>12 \text{ h}^{-1}$ and the outdoor air volume $>2 \text{ h}^{-1}$
ASHRAE manual (2003) “ <i>Health Care Facilities</i> ” [1]	In isolation ward, the flow rate of dilution air $>6 \text{ h}^{-1}$ (based on requirement for odor and thermal comfort)
UK “ <i>Guidance on the prevention and control of transmission of multiple drug-resistant Tuberculosis</i> ” [1]	In new-built or renovated isolation ward for prevention of airborne transmission, the flow rate of dilution air $\geq 12 \text{ h}^{-1}$ and the outdoor air volume $\geq 2 \text{ h}^{-1}$
CDC in U.S.A. “ <i>Guidelines for environmental infection control in health care facilities</i> ” [1]	In newly-built ward, the air supply volume $\geq 12 \text{ h}^{-1}$ . In existing ward, the air supply volume $\geq 6 \text{ h}^{-1}$ .
AIA in U.S.A. “ <i>Guidelines for design and construction of hospital and health care facilities</i> ” [1]	In isolation ward for prevention of airborne transmission, consulting rooms for emergency or radiotherapy, the flow rate of dilution air $\geq 12 \text{ h}^{-1}$ and the fresh air volume $\geq 2 \text{ h}^{-1}$
DHHS in U.S.A. “ <i>Guidelines for construction and equipment of hospital and medical facilities</i> ” [1]	In isolation ward for prevention of airborne transmission, the air supply volume $\geq 12 \text{ h}^{-1}$ and the fresh air volume $\geq 2 \text{ h}^{-1}$ . In the bathroom, laundry, waste disposal room, disinfection room, anteroom of isolation ward, the exhaust air volume $\geq 10 \text{ h}^{-1}$
ASHRAE 170-2013 “ <i>Ventilation of Health Care Facilities</i> ”	In new-built isolation ward for prevention of airborne transmission, the air change rate $\geq 12 \text{ h}^{-1}$ and the outdoor air volume $\geq 2 \text{ h}^{-1}$ . In the antechamber, the air change rate for exhaust air $\geq 10 \text{ h}^{-1}$
Australia “ <i>Guidelines for the classification and design of isolation rooms in health care facilities</i> ” [1]	In negative pressure isolation ward, the flow rate of dilution air should be the larger value between $12 \text{ h}^{-1}$ and $522 \text{ m}^3/\text{h}$
USA “ <i>Guidelines on the design and operation of HVAC systems in disease isolation areas</i> ” [1]	In newly-built isolation ward, disposal room and mortuary, the flow rate of dilution air $\geq 12 \text{ h}^{-1}$ . In the bathroom, the exhaust air volume $\geq 10 \text{ h}^{-1}$ . In the consulting room for infectious patient, the flow rate of dilution air $\geq 15 \text{ h}^{-1}$ and the fresh air volume $\geq 2 \text{ h}^{-1}$
“ <i>Guideline for Design and Operation of Hospital HVAC Systems</i> ” (HEAS-02-2004) established by Healthcare Engineering Association of Japan	In isolation ward, the total volume should of exhaust air be $12 \text{ h}^{-1}$

in the isolation ward disperses in the whole room. Therefore, it is difficult to provide the requirement in the isolation ward. Moreover, the bacterial generation rate cannot be determined based on one kind of disease.

In this chapter, one thought to calculate the air change rate in the negative pressure isolation ward will be proposed in a comprehensive way.

## 5.2 Two System Modes of Isolation Ward

### 5.2.1 Circulation Air System

In terms of air cleaning handling, the circulation air system is shown in Fig. 5.1. In the figure,  $N_t$  is the indoor particle concentration at time  $t$ , pc/L;  $N$  is the stable particle concentration indoors, pc/L;  $N_0$  is the initial particle concentration indoors, which is the particle concentration at time 0, pc/L;  $V$  is the volume of the cleanroom,  $m^3$ ;  $N$  is the air change rate,  $h^{-1}$ ;  $G$  is the particle generation rate per unit volume indoors,  $pc/(m^3 \text{ min})$ ;  $M$  is the concentration of atmospheric dust, pc/L;  $S$  is the ratio of the return air volume to the supply air volume.

When the purpose is to remove bioaerosols from indoor air, the implications of  $\eta$  in the figure are:  $\eta_1$  is the efficiency of the coarse filter (or the combination of air filter for the outdoor air) for bioaerosol (the particle counting efficiency, which is expressed with decimal);  $\eta_2$  is the efficiency of the middle filter for bioaerosol;  $\eta_3$  is the efficiency of the final filter for bioaerosol.

Under the steady-state condition, the calculation equation for the indoor bacterial concentration is:

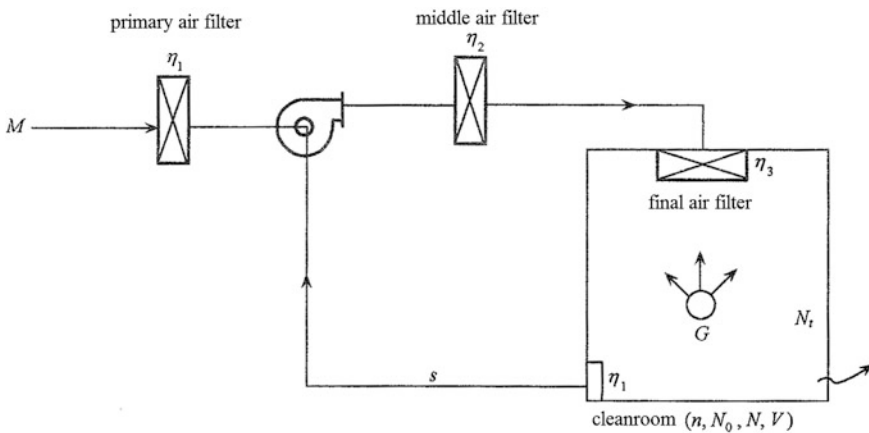


Fig. 5.1 Schematic diagram of circulation air system

$$N = \frac{60G \times 10^{-3} + Mn(1 - s)(1 - \eta_n)}{n[1 - s(1 - \eta_r)]} \tag{5.1}$$

When there is no specific bioaerosol from the supply air into the isolation ward,  $M = 0$ . When HEPA filter is installed on the return air grille or the air supply outlet, or both, the efficiency for bioaerosol reaches more than 99.999%. Equation (5.1) can be simplified as:

$$N = \frac{60G \times 10^{-3}}{n} \tag{5.2}$$

$$n = \frac{60G \times 10^{-3}}{N} \tag{5.3}$$

### 5.2.2 Full Fresh Air System

For the full fresh air system, there is only supplied air and exhausted air. The flow rate of exhausted air is larger than that of the supplied air. The schematic diagram is shown in Fig. 5.2. Because  $s = 0$ , we obtain

$$N = \frac{60G \times 10^{-3} + Mn(1 - s)(1 - \eta_n)}{n} \tag{5.4}$$

With the same method, Eqs. (5.2) and (5.3) can be also simplified. This means that no matter what kind of the system is, as long as there is no such kind of dust source or bacterial source in the atmosphere and HEPA filters are installed for the exhausted air or the return air, the equation to calculate the air change rate is the same.

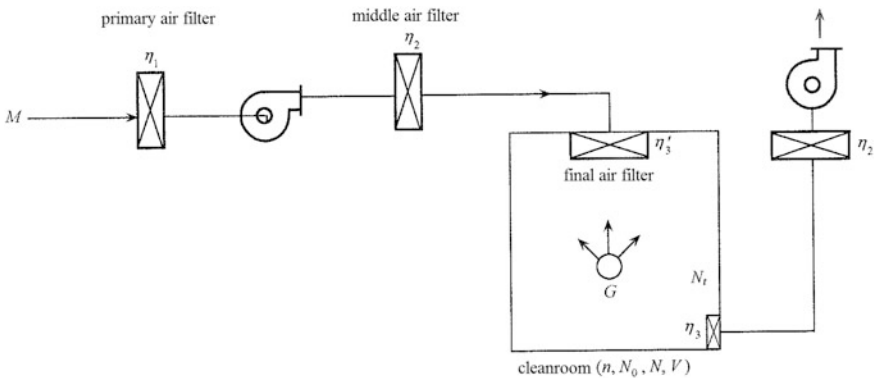


Fig. 5.2 Schematic diagram of the full fresh air system

From Eq. (5.3), two parameters must be known for calculating the air change rate, which are the bacterial generation rate indoors and the standard for the bacterial concentration.

### 5.3 Determination of Bacterial Generation Rate Indoors

#### 5.3.1 Bacterial Generation Rate from Ordinary Patients

In Eqs. (5.1)–(5.3), the value of  $G$  should be determined at first.  $G$  is the bacterial generation rate per unit volume. The bacterial generation rate per unit time should be known, so that under the assumption of the uniform distribution, the bacterial generation rate per unit volume indoors  $G$  could be obtained. Then after considering the non-uniform distribution, the air change rate  $n$  can be obtained with the non-uniform distribution coefficient  $\Psi$ .

As mentioned before, it is not comprehensive to use the data on the bacterial generation rate for individual disease which occurred occasionally. Based on the analysis on foreign literates [2], we could obtain the following information.

1. When people wear the asepsis clothes, the bacterial generation rate in the static state is 100–300 pc/(min people). When the common activity is carried out on body, the bacterial generation rate is 150–1000 pc/(min people). When people walk fast, the bacterial generation rate is 600–2500 pc/(min people).
2. When people wear the ordinary cloth, the bacterial generation rate is 300–62000 pc/(min people).
3. During the coughing process for once time, the bacterial generation rate is 70–700 pc/(min people). During the sneezing process for once time, the bacterial generation rate is 4000–60000 pc/(min people), which is slightly different from that in Fig. 1.3.
4. The ratio of the bacterial generation rate between the condition when people wear mask and that without mask is 1:7–1:14.
5. The ratio of the bacterial generation rate to the particle generation rate is 1:500–1:1000.

#### 5.3.2 Analysis of Bacterial Generation Rate from Respiratory System

In previous section, the bacterial generation rates during coughing and sneezing processes are given. But the information on bioaerosol size is not given. The frequency of sneezing per hour is unknown.

The data in detail was given in Fig. 1.3. When people sneeze for once time, the generation rate of aerosol with diameter 10  $\mu\text{m}$  is  $3 \times 10^5$  pc, which is larger than the value given in the previous section. The generation rates of aerosol with diameter 1 and 0.3  $\mu\text{m}$  are  $2 \times 10^4$  pc and 10 pc, respectively. When people cough for once time, the generation rates of aerosol with diameter 10, 1 and 0.3  $\mu\text{m}$  are  $1.5 \times 10^3$  pc, 30 pc and 1 pc, respectively.

However, the droplets generated during coughing and sneezing processes will evaporate quickly. The evaporation rate is related to the temperature, the vapor pressure of the droplet and the atmospheric pressure. The evaporation time of the droplet can be obtained with the following equation [3]:

$$t = - \left\{ \frac{D_p RT \rho_L}{2\alpha v (\delta P_1 - P) M_1} + \frac{RT \rho_L}{P_1 (\delta P_1 - P) M_1} \left[ \frac{D_p^2}{8} \cdot \frac{D_p}{2} \lambda + \lambda^2 \log \left( 1 + \frac{D_p}{2\lambda} \right) \right] \right\} \quad (5.5)$$

According to the calculation performed by Chen [4], the following values can be chosen for various parameters of water droplet.

$t$  is the time, s;  $D_p$  is the diameter of the droplet, which is  $9.53 \times 10^{-4}$  cm;  $R$  is the gas constant, which is  $8.317 \times 10^7$  erg/(mol K);  $T$  is the absolute temperature, which is 293 K (i.e., 20 °C);  $\rho_L$  is the density of the liquid, which is 1 g/cm<sup>3</sup> for H<sub>2</sub>O;  $\alpha$  is the evaporation coefficient, which is 0.04 for H<sub>2</sub>O;  $v = \left( \frac{RT}{2\pi M_1} \right)^{1/2}$  is the kinematic viscosity, cm<sup>2</sup>/s;  $M_1$  is the molecular mass of the liquid vapor, which is 18 g/mol for H<sub>2</sub>O;  $\delta$  is the degree of saturation, which is 0.3 (this means the relative humidity is 30%);  $P_1$  is the vapor pressure of the droplet (here it is the differential pressure of the water vapor), which is  $5.6 \times 1.33 \times 10^3$  dyn/cm<sup>2</sup>;  $P$  is the vapor pressure of the droplet, which is  $5.6 \times 1.33 \times 10^3$  dyn/cm<sup>2</sup>;  $D_1$  is the dispersion coefficient of the liquid vapor through the gas, which is 0.252 cm<sup>2</sup>/s;  $\lambda$  is the average mean free path of the molecular, which is  $6.53 \times 10^{-6}$  cm.

For the water droplet with diameter 9.5  $\mu\text{m}$ , it can be completely evaporated in 0.104 s. When the relative humidity is 60%, it only takes 0.193 s to evaporate completely.

According to the calculated results by foreign scholars, under the condition of relative humidity 70%, the water droplet with diameter 5  $\mu\text{m}$  will evaporate in 0.029 s [5], which is much faster than the above result.

On contrary to the water, the saline is the secretion from the parotid gland, the submandibular gland, the sublingual gland and the minor salivary glands. According to the analysis by Kou, water component occupies more than 99% of the saline. The solid component accounts for about 0.7%, where the organic compound and the inorganic compound occupy 0.5 and 0.2%, respectively [6]. Moreover, 0.85% of the body fluid is NaCl on average, which is also the standard value for the normal saline. Therefore, the maximum ratio of the NaCl in the saline is the level of the body liquid.

During the evaporation process, the droplet of the saline will be concentrated gradually until the phase change process occurs. In this case, the values of various parameters are not the same as that of the water droplet. Therefore, the time for evaporation will be prolonged.

As we know, the test aerosol used for HEPA filter and medical mask is the sprayed NaCl, which is generated from the NaCl solution with concentrate 2%. According to British test standard [7], Chinese literature [8] and the test standard for HEPA filter in China, the time of evaporation for sprayed NaCl droplet is 2 s.

Another problem is that the saline containing the salt component cannot evaporate to vanish completely as the water. The solute will stay airborne as the small salt particle. This means even when the saline droplet will evaporate thoroughly, it will become the extremely small particle. When the saline contains the bacteria, the particle with similar size of the bacteria will be left.

Because of the dehydration, bacteria will move and evaporate with the water molecular, which will change the property of the protein in the bacteria and may cause the death of the bacteria. Table 5.2 shows the recovery rate of the bacteria during the spraying process of droplet [9]. It is shown that the recovery rate of water during the spraying process is the maximum.

The solute particle left after evaporation of droplet may be larger than the size of the bacteria it contains, or may be smaller than the size of the bacteria. Suppose

**Table 5.2** Recovery rate of different bioaerosols

Type of aerosol	Component of spray fluid	Component of sampling fluid	Average recovery rate, %	Times of experiments
Phenolsulfonphthalein	Water	Water	86.9	2
Bacillus subtilis var. niger	Water	Water	73.4	3
Bacterium prodigiosum	2 gelatin aqueous solution	Gelatin dilution solution	25.1	6
Brucella	Tryptose sline containing 5% maltodextrin	Tryptose saline	25.9	5
Burkholderia pseudomallei	2% glycerol broth	Broth	16.6	15
Malleomyces Mallei	2% glycerol broth	Broth	10.1	18
Francisella tularensis	2% glycerol	1% gelatin saline	2.3	34
Meningitis pneumonia virus	Broth	Broth	9.5	7
Psittacosis virus (6BC)	Broth	Broth	18.1	19
Psittacosis virus (3Drg)	Broth	Broth	23.0	3

both the droplet and the solute particles are spherical, the relationship between their sizes can be expressed as follows [3],

$$d_P = d_D \left( \frac{c \rho_D}{\rho_P} \right)^{1/3} \quad (5.6)$$

Where  $d_P$  is the diameter of the solute particle,  $\mu\text{m}$ ;  $d_D$  is the diameter of the droplet,  $\mu\text{m}$ ;  $c$  is the percentage for the mass of the solute in the liquid droplet, which is set 0.85%;  $\rho_P$  is the density of the solute particle, which is  $2.164 \text{ g/cm}^3$  for NaCl;  $\rho_D$  is the density of the liquid droplet, which could be approximated as the density of water  $1 \text{ g/cm}^3$  since the value of  $c$  is extremely small.

Therefore, the size of the pure solute particle can be calculated as follows.

$$d_P = d_D \left( \frac{0.0085 \times 1}{2.164} \right)^{1/3} = 0.16 d_D$$

For the droplet with diameter  $10 \mu\text{m}$ , its smallest size is not smaller than  $1.6 \mu\text{m}$  after 2 s of evaporation. For the droplet with diameter  $5 \mu\text{m}$ , its smallest size is not smaller than  $0.8 \mu\text{m}$  after 2 s of evaporation. For the droplet with diameter  $1 \mu\text{m}$ , its smallest size is not smaller than  $0.16 \mu\text{m}$  after 2 s of evaporation. For the droplet with diameter  $0.5 \mu\text{m}$ , its smallest size is not smaller than  $0.08 \mu\text{m}$  after 2 s of evaporation.

By preliminary investigation, it is found that coughing will easily occur in the evening and in the morning when people get cold. In the morning, the average frequency of coughing is one time per 2 s. After getting up in the morning, it is five times per hour. When the maximum bacterial generation rate per hour is calculated based on this data (the frequency per hour is not always such large), the result will have a quite large deviation. After 2 s of evaporation, we obtain:

For the size  $1.6 \mu\text{m}$ ,

$$\frac{5 \times 2.5 \times 10^5 + 30 \times 1.5 \times 10^3}{60 \times 25} = 863 \text{ pc}/(\text{m}^3 \text{ min})$$

For the size  $0.8 \mu\text{m}$ ,

$$\frac{5 \times 6 \times 10^4 + 30 \times 200}{60 \times 25} = 204 \text{ pc}/(\text{m}^3 \text{ min})$$

For the size  $0.16 \mu\text{m}$ ,

$$\frac{5 \times 2 \times 10^4 + 30 \times 30}{60 \times 25} = 66.7 \text{ pc}/(\text{m}^3 \text{ min})$$



For the size 0.08 μm,

$$\frac{5 \times 30 + 30 \times 1}{60 \times 25} = 0.12 \text{ pc}/(\text{m}^3 \text{ min})$$

Now Eq. (5.6) is applied to analyze the final size of the sprayed droplet.

It is known that the percentage for the mass of NaCl in the sprayed droplet is 0.85%, and the main diameter of the droplets is 5 μm, the diameter of the solute particles after complete evaporation can be calculated as follows:

$$d_p = 5 \times \left(\frac{0.0085 \times 1}{2.164}\right)^{1/3} = 5 \times 0.16 = 0.8 \text{ μm}$$

This diameter value is close to that of the Bacillus subtilis as shown in Fig. 3.21.

## 5.4 Determination of Bacterial Concentration Standard Indoors

### 5.4.1 Outline

For obtaining the air change rate, the standard for the allowable bacterial concentration indoors must be known. But for different diseases, the pathogenic concentrations are obviously different. And for patients and medical personnel, the concentrations are also different.

Therefore, it is difficult to set the standard for the pathogenic dosage of indoor air with specific disease or microbes. Take the animal experiment as an example, when experiment with streptococcus and influenza virus as test aerosol on rabbit, results can be obtained as shown in Table 5.3 [10].

In our opinion, the influence of the pathogenic microbes generated during speaking and coughing process from patient on the patient himself should not be considered. This is why several patients with pulmonary tuberculosis can live in the same room. Therefore, it is of first priority to consider the influence on the medical personnel.

Fundamental protective measures are provided for the medical personnel entering into the isolation ward. The main measures are wearing N95 masks.

**Table 5.3** Median lethal dose of pathogenic microbes

Pathogenic microbes	Streptococcus			Influenza virus, PFU		
	Aerosol	Nasal drop	Respiratory infection	Aerosol	Nasal drop	Respiratory infection
Median lethal dose, LD <sub>50</sub>	10 <sup>4.95</sup> – 10 <sup>7.41</sup>	10 <sup>3.76</sup> – 10 <sup>4.13</sup>	10 <sup>3.87</sup> – 10 <sup>4.37</sup>	10 <sup>1.46</sup> – 10 <sup>1.86</sup>	10 <sup>1.06</sup> – 10 <sup>1.80</sup>	10 <sup>1.21</sup>

**Table 5.4** Efficiency of homemade polypropylene fibrous media for DOP, %

$\Delta P$	20.3 Pa	40.6 Pa	59.9 Pa	116.9 Pa	482.6 Pa
$v$	1.25 m/s	2.5 m/s	3.5 m/s	7.0 m/s	13.4 m/s
0.5 $\mu\text{m}$	–	–	–	–	99.83
0.4 $\mu\text{m}$	99.9994	99.995	99.984	99.83	99.59
0.3 $\mu\text{m}$	99.9991	99.990	99.970	99.71	99.12
0.2 $\mu\text{m}$	99.9950	99.970	99.920	99.41	98.37
0.15 $\mu\text{m}$	99.9960	99.870	99.780	98.48	97.78
0.10 $\mu\text{m}$	99.8800	99.660	99.370	98.62	96.26
0.08 $\mu\text{m}$	99.8500	99.560	99.270	96.52	95.39
0.05 $\mu\text{m}$	99.8400	99.400	99.170	95.54	93.80
0.03 $\mu\text{m}$	99.9700	99.860	99.710	98.92	–

In the early of May in 2003 during the epidemic of SARS, according to the TV report at Hong Kong, there were no people infected in a hospital where all the medical personnel wore N95 masks. However, for these hospitals where the ordinary masks were worn, many medical personnel were infected.

The filtration efficiency of N95 mask for particles with diameter 0.075  $\mu\text{m}$  reached more than 95%, which will be introduced in detail later. From Table 5.4 [11], the efficiency of the mask made of polypropylene fibrous media for particles with diameter 0.075  $\mu\text{m}$  (which is close to 0.08  $\mu\text{m}$  in the table) under the filtration velocity 13.4 cm/s is the lowest. It is safe when this value is set as the standard.

NIOSH standard 42CRF84 has pointed out that the N95 mask meets the standard requirement for mask to prevent the solid tuberculosis bacteria. N95 means the efficiency with the sodium flame method for particles with diameter 0.075  $\mu\text{m}$  is 95%, which meets the standard requirement for N-type. In China, it was misunderstood in some literatures that N95 means the efficiency for DOP with diameter 0.3  $\mu\text{m}$  is 95%. Moreover, there are also requirements for R-type mask with oil aerosol and P-type mask with both solid and liquid aerosol (they are based on the DOP efficiency).

After the epidemic of SARS, the standard GB2626 “Respiratory protective equipment. Non-powered air-purifying particle respirator” was revised. There are two types including KN-type and KP-type, which correspond with N-type and P-type in U.S.A. Detailed information is shown in Table 5.5.

**Table 5.5** Classification of masks in China

Classification level of air filtration unit	Test with NaCl	Test with oil aerosol
KN90	$\geq 90.0\%$	Not applicable
KN95	$\geq 95.0\%$	
KN100	$\geq 99.97\%$	
KP90	Not applicable	$\geq 90.0\%$
KP95		$\geq 95.0\%$
KP100		$\geq 99.97\%$

The test conditions in Chinese standard are the same as that in U.S.A. The concentration of NaCl is 2% with the median diameter  $0.075 \mu\text{m} \pm 0.02 \mu\text{m}$ . The flow rate is  $85 \pm 4 \text{ L/min}$ . There is no requirement for the size of the mask, but it is usually  $100 \text{ cm}^2$ . The corresponding filtration velocity is  $14.17 \text{ cm/s}$ .

### 5.4.2 Standard

Therefore, there are two aspects to consider the standard value of the bacteria indoors. One is from the medical personnel. The other is from the environment.

#### 1. From the medical personnel

##### (1) Standard for droplet nuclei with diameter $0.075 \mu\text{m}$

According to the previous section, the filtration velocity can be calculated based on the flow rate and the size of the mask, which is  $14.17 \text{ cm/s}$ . The corresponding maximum penetration particulate size is equivalent with  $0.075 \mu\text{m}$ . This means that the particle size  $0.075 \mu\text{m}$  corresponds to the minimum efficiency under the filtration velocity  $14.17 \text{ cm/s}$ . Therefore, test aerosol with diameter  $0.075 \mu\text{m}$  and the filtration velocity  $14.17 \text{ cm/s}$  are the most unfavorable conditions. When the efficiency under the most unfavorable conditions is met, the requirement under other conditions can be easily satisfied.

As mentioned before, there were no one infected when they wore N95 masks. From the aspect of most stringent requirement, there was no bioaerosol inhaled. If even one particle with diameter  $0.075 \mu\text{m}$  was inhaled, there is no possibility for other droplet nuclei to be inhaled (since the efficiency with other particles is higher than that with  $0.075 \mu\text{m}$ ).

When the medical personnel enter into the ward, it usually takes less than 0.5 h. When special treatment is needed, it may take more than 1 h. In this case, it can be assumed 1.5 h.

According to Chinese standard on medical masks, the requirement for the efficiency 95% is under the flow rate  $85 \text{ L/min}$ . We know that the common respiratory flow rate is between  $8 \text{ L/min}$  and  $80 \text{ L/min}$ . It is a much safer consideration for the standard to set such flow rate.

When the flow rate of respiratory air is  $85 \text{ L/min}$ , in the inhaled air within 1.5 h, the concentration of particles with diameter  $0.075 \mu\text{m}$  will not be larger than  $1/(90 \times 85) = 1.3 \times 10^{-4} \text{ pc/L}$ . Therefore, when the efficiency of mask reaches 95%, the concentration of particles with diameter  $0.075 \mu\text{m}$  should not exceed  $2.6 \times 10^{-4} \text{ pc/L}$ .

##### (2) Standard for droplet nuclei with diameter $0.075 \mu\text{m}$

From Fig. 1.3, it is known that the number of airborne droplet with diameter  $10 \mu\text{m}$  is the most. From the Sect. 5.3.2, the diameter of the airborne nuclei is  $1.6 \mu\text{m}$ .

The concentration of particles with diameter  $1.6 \mu\text{m}$  in the inhaled air should not exceed  $1.3 \times 10^{-4} \text{ pc/L}$ .

When the N95 mask is worn, the efficiency for  $1.6 \mu\text{m}$  is larger than that for  $0.075 \mu\text{m}$  by three orders of magnitude. Suppose the efficiency is 99.998% (please refer to Chap. 3), the concentration of particles with diameter  $1.6 \mu\text{m}$  in the inhaled air should not exceed  $6.5 \text{ pc/L}$ .

(3) Standard for ordinary microbes indoors

When particles are captured by masks, the microbial particles are filtered. For the isolation ward where air is supplied through HEPA filter, the particle concentration is based on the diameter  $\geq 0.5 \mu\text{m}$ . From Table 5.4, the efficiency of N95 mask for particles with diameter  $0.3 \mu\text{m}$  can be 99.12%. So the calculated efficiency for diameter  $\geq 0.5 \mu\text{m}$  is 99.97% [12].

The concentration of particles with diameter  $\geq 0.5 \mu\text{m}$  in the inhaled air should not exceed  $1.3 \times 10^{-4} \text{ pc/L}$ . So the concentration of particles with diameter  $\geq 0.5 \mu\text{m}$  indoors should not exceed  $0.433 \text{ pc/L}$ .

2. From the environment

From the environment, there should be no bioaerosol released from the isolation ward. For Three-Room-One-Buffer scheme, i.e., the ward-buffer-exterior or corridor, the final bacterial concentration, i.e., the inhaled bacteria during occupancy period which enters into the exterior room should be less than  $1 \text{ pc}$ . The period for passing through the exterior room is short. There is ventilation in the exterior room. The decayed concentration in 1 min will be more than a half. So the concentration within the first 1 min is considered.

When the flow rate of respiratory air is  $85 \text{ L/min}$ , in the inhaled air within 1.5 h, the concentration of particles with diameter  $0.075 \mu\text{m}$  will not be larger than  $0.012 \text{ pc/L}$ , so that the total number of inhaled bacteria can be less than 1. When the volume of the exterior room is  $25 \text{ m}^3$  (the less the volume is, the more stringent the bacterial concentration in the ward should be), the allowable bacterial number in the exterior room should not exceed  $0.012 \times 25 \times 10^3 = 300 \text{ pc}$ . In this case, the leakage flow rate into the exterior room during the opening of the door in the buffer room for once time is  $1.62 \text{ m}^3$  (please refer to the chapter about the buffer room), where the number of the microbes should not be larger than 300 pc. Given  $\beta_{3.1} = 40$ , the bacterial concentration in the isolation ward should be  $300/1620 \times 40 = 7.4 \text{ pc/L}$ . (When the volume of the exterior room is  $250 \text{ m}^3$ , the allowable concentration can be  $74 \text{ pc/L}$ ).

## 5.5 Calculation of Air Change Rate

### 5.5.1 Calculation Based on the Minimum Airborne Droplet Nuclei with Diameter 0.075 $\mu\text{m}$

With the assumption of uniform distribution, it can be calculated with Eq. (5.3), i.e.,

$$n = \frac{60G \times 10^{-3}}{N}$$

Where  $G$  is the generation rate of particles with diameter 0.08  $\mu\text{m}$  (it is equivalent to 0.075  $\mu\text{m}$ ) which are obtained after evaporation from the droplet with diameter 0.5  $\mu\text{m}$ . From the previous section, it is 0.12  $\text{pc}/(\text{m}^3 \text{min})$ .  $N$  is the allowable concentration of particles with diameter 0.075  $\mu\text{m}$  indoors. From the previous section, it is  $2.6 \times 10^{-3} \text{pc/L}$

Therefore, under the condition of uniform distribution, we obtain the air change rate:

$$n = \frac{60 \times 0.12 \times 10^{-3}}{2.6 \times 10^{-3}} = 2.8 \text{h}^{-1}$$

According to the non-uniform distribution theory, when the air change rate  $n = 3 \text{h}^{-1}$ , the non-uniform distribution coefficient  $\psi$  can be 4 [13]. So with the non-uniform distribution,  $n_v = 4n = 4 \times 2.8 = 11.2 \text{h}^{-1}$ . This means the air change rate should be  $11.2 \text{h}^{-1}$  at least.

### 5.5.2 Calculation Based on the Maximum Airborne Droplet Nuclei with Diameter from 10 $\mu\text{m}$ to 1.6 $\mu\text{m}$ After Evaporation

Suppose the generation rate of particles  $G$  with diameter 0.08  $\mu\text{m}$  is 863  $\text{pc}/(\text{m}^3 \text{min})$ , and  $N = 6.5 \text{pc/L}$ , the air change rate with uniform distribution assumption is  $n = \frac{60 \times 863 \times 10^{-3}}{6.5} = 8 \text{h}^{-1}$ .

According to the non-uniform distribution theory, when the air change rate  $n = 8 \text{h}^{-1}$ , the non-uniform distribution coefficient  $\psi$  can be 1.5 [13]. So with the non-uniform distribution,  $n_v = \psi n = 1.5 \times 8 = 12 \text{h}^{-1}$ . This means the air change rate should be  $12 \text{h}^{-1}$  at least.

### 5.5.3 Calculation Based on the Ordinary Microbial Particles Indoors

According to Sect. 5.3.1, when aseptic cloth (the cloth on patient should be washed and disinfected) is worn and ordinary activity is performed, the maximum the generation rate of particles  $G$  is 1000 pc/(min·people). We obtain

$$G = 1000/25 = 40 \text{ pc}/(\text{m}^3 \cdot \text{min}).$$

Based on the aforementioned data,  $N = 0.433$  pc/L. According to the uniform distribution, the air change rate is:

$$n = \frac{60 \times 40 \times 10^{-3}}{0.433} = 5.5 \text{ h}^{-1}$$

With the same method based on the non-uniform distribution theory, the non-uniform distribution coefficient  $\psi$  can be 2.25 according to the literature [13]. So with the non-uniform distribution,  $n_v = \psi n = 2.25 \times 5.5 = 12.4 \text{ h}^{-1}$ . This means the air change rate should be  $12.4 \text{ h}^{-1}$  at least.

### 5.5.4 Calculation Based on Environmental Standard

The largest value of the above three generation rates of particles  $G$  is 863 pc/( $\text{m}^3 \text{ min}$ ).  $N = 7.4$  pc/L. According to the uniform distribution, the air change rate is:

$$n = \frac{60 \times 863 \times 10^{-3}}{7.4} = 7 \text{ h}^{-1}$$

With the same method based on the non-uniform distribution theory, the non-uniform distribution coefficient  $\psi$  can be 1.75 according to the literature [13]. So with the non-uniform distribution,  $n_v = \psi n = 1.75 \times 7 = 12.2 \text{ h}^{-1}$ . This means the air change rate should be  $12.2 \text{ h}^{-1}$  at least.

Based on the calculation results of the air change rate based on the above four standards, we obtain:

Based on the least droplet nuclei with diameter  $0.075 \mu\text{m}$ , the calculated air change rate is  $11.2 \text{ h}^{-1}$ ;

Based on the most liquid droplets with diameter  $10 \mu\text{m}$ , the calculated air change rate is  $12 \text{ h}^{-1}$ ;

Based on the common indoor microbes, the calculated air change rate is  $12.4 \text{ h}^{-1}$ ;

Based on the environmental protection outside of the isolation ward, the calculated air change rate is  $12.2 \text{ h}^{-1}$ .

The air change rate under these four conditions is between 11 and  $12 \text{ h}^{-1}$ . This provides many rational understanding for the recommended valued in foreign standards shown in Table 5.1. This also provides the basis for the foreign standards.

Since the conditions during calculation are relatively stringent, and the requirement for the indoor average concentration of the isolation ward is not so important as that for protecting the medical personnel, it is reasonable to choose  $8\text{--}12 \text{ h}^{-1}$ . For the isolation ward containing patients with seriously diseases, the relative large value can be adopted. On the contrary, the relative small value can be chosen. By the aforementioned analysis, the requirement can be satisfied when the air change rate is  $10 \text{ h}^{-1}$ . However, it is small if the lower limit is set  $6 \text{ h}^{-1}$ .

In the air change rate, the outdoor air volume can be  $3\text{--}4 \text{ h}^{-1}$ , which is larger than that under the normal condition. “*Guideline for Design and Operation of Hospital HVAC Systems*” (HEAS-02-2004) established by Healthcare Engineering Association of Japan has pointed out that the outdoor air volume needed for the isolation ward should be larger than the average outdoor air volume, because the outdoor air needed for the sick people is much larger than that for the healthy people.

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