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Documentary Research of Human Respiratory Droplet Characteristics

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Abstract

Respiratory droplet characteristics are key to determine the droplet-borne pathogen transmission, which provide scientific basis for formulating the disease prevention from droplet transmission and control measures. Through studying the data information from existing documents, this paper gives the respiratory droplet characteristics, like size, concentration, velocity, etc. Meanwhile, droplet evaporation, droplet-borne pathogen activity and their transmission are discussed. The droplet size is no significant difference with human health level, gender and age. The size of droplets produced by health people is between 0.1 and 10 μm , it produced by patients is between 0.05 and 10 μm , and the patients' droplet concentration is higher. The coughed droplet concentrations change with the size into a peak rule. The velocity of the cough droplets is the biggest, the range of 10 to 25m/s, the transmission distance is more than 2m.

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1. INTRODUCTION

The spread of respiratory diseases has been a hot topic concerned by medical practitioners. Many researchers believe that droplet transmission is the principal means of airborne pathogen [1-3]. Patients produce droplets during

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breathing, speaking, coughing and sneezing. Pathogens attach to the droplets and transmit to the mouth, nasal and conjunctiva positions of susceptible populations within a close range and short time span. The susceptible population is infected and lead to the spread of the disease. Common droplet transmission diseases include the common cold, flu, tuberculosis, pathogen meningitis, etc.

The mass of evidence has been shown that the spread of respiratory disease is associated with the characteristics of human droplets during the last few decades. Although studying the droplet transmission looks to be a common matter and the volume of publications in this subject over past 50 years, it is necessary to explore future direction which needs more attention [4-7]. This paper is a literature review on the droplet characteristics produced from different respiratory activities, and it aims to taking effectively disease prevention from droplet transmission and control measures.

2. THE MECHANISM OF DROPLET FORMATION

Epidemiology [8, 9] shows that most respiratory infections indoor are caused by droplet or microbial aerosol transmission. Among different size respiratory droplets, those of the large size deposit to the ground in 1 meter [10-13] or vaporize into droplet nuclei, the other of the relatively small suspend in the air for long time. These smaller droplets may carry more pathogens.

Actually, droplet generation is simply stated as high-speed exhaling airflow skims over the mucus on respiratory tract. The mucus is stretched and broken away from mucosal cilia surface, and then form a series of droplets [14]. Different size of droplets will be produced because of the different airflow pressure and velocity from the different depth of respiratory tract. Further, the pathogens are in the mucus of the mucosal surface or ciliated epithelial cells of the respiratory tract [15], and the respiratory infection patients ejected droplets with pathogens to the surrounding air by talking, coughing and sneezing. The droplets will be evaporated, diffused, deposited or susceptible to individuals.

Different size droplets are inhaled and deposited on different sites in the respiratory tract [16-17]. According to Droplets of Air Quality Standards formulated by the U.S. National Air Pollution Control Administration, size $>10\mu\text{m}$ droplets almost completely deposit in the nasopharynx, about 10% in the range of 2 to $5\mu\text{m}$ droplets deposit in the bronchial parts, size $<2\mu\text{m}$ droplets mainly deposit in the alveolar tissue, about 50% droplets between 1 and $2\mu\text{m}$ deposit in the alveoli, that is, the smaller droplets are, the greater the amount deposit.

3. THE METHODS OF DROPLET TEST

There are much documented materials worldwide concerning the characteristics of human respiratory droplets using theoretical and experimental approaches. It can be found that some researchers use different experimental methods which lead to different results [18-20]. Moreover, there have been some literatures on droplet transmission in an enclosure space using simulation method. However, these studies only used droplets from nonhuman emission source, or used other non-aerosol materials, such as water, CO_2 , N_2O [21,22]. And the droplet size and quantity were set as constant values and it looked as the same for different individuals [23-26]. Therefore, it is necessary to reviewed the existing literatures and get characteristics of respiratory droplets, which provide scientific basis for the following study. In this paper, 25 relevant literatures are selected.

The studies before 1970s showed that human respiratory activities (breathing, talking, sneezing and coughing) will produce different quantity and size droplets by utilizing impaction and high-speed photography. The impaction method, which use the paper strip and the microscope slide, includes impaction upon solid and liquid surfaces [17,27-31]. Duguid used solid impaction to measure the respiratory droplets, the diameter of which was mainly in 4- $8\mu\text{m}$, the size distribution was approximately the same among sneezing, coughing and talking, and the largest amount of droplets was sneezing [28]. Jennison used high-speed photography to measure the size $\geq 5\mu\text{m}$ droplets from health people, but was unable to measure those of smaller. And the size of droplets were almost same, the amount of sneezing was larger than coughing [17]. The impaction method may cause particles to also spread, splash or finger and inevitably distort the true particle size if identified by microscopy. The Andersen sampler is belong to solid impaction, normally used to measure size and quantity of droplets carrying pathogen on an agar surface for later cultivation [32-39]. Fennelly studied distribution of the tuberculosis pathogen droplets from TB patients, and found that the size of droplets containing *Mycobacterium tuberculosis* was mainly $0.65\mu\text{m}$ to $3.3\mu\text{m}$. Moreover, it was

found that there were no significant correlation between the droplets size and cough frequency, age and gender, it was the first experimental study focused on the pathogen droplet characteristics [30]. Liquid impaction, operating similarly to solid impaction in terms of relying upon inertial mass, impacts into liquid agar surfaces. The studies shows that the influence of the evaporation, the limitation of the acquisition and the function of the droplet rebound relatively reduce the size and quantity of droplets collected by impaction [40-46].

Early studies showed that the size of droplets was approximately same, and the amount of sneezing droplets was the largest, coughing followed. Despite obvious poor precision instruments and incomplete capture of respiratory droplets, these studies have consequentially convinced that droplet transmission is the most dominant transmission mode of infectious aerosols, which promote the following theoretical and experimental study.

With the development of technology, the precision of instrument is gradually improved, optical instruments begin to be used, such as optical droplet counter (OPC), particle image velocimetry (PIV), aerodynamic droplet size (APS). Papineni and Rosental [18] studied respiratory droplet characteristics of health people by using OPC and analytical transmission electron microscope (AEM). Their study showed that the amount of coughing droplets was the largest and the amount of nose breathing droplets was the least. It was found by Chen [97], who used the APS and scanning electron mobility spectrometer system to study size and transmission of respiratory droplets of health people, that the size of the droplets mainly was in the range of 0.6-2 μm and about 90% -95% coughing droplet size was 2-10 μm . C.Y.H. Chao measured droplet size using the interferometric Mie imaging (IMI), and tested air velocity using PIV, and found that geometric mean diameter of coughing and speaking droplets was 13.5 μm and 16.0 μm respectively. And the droplet concentrations ranged of 2.4 to 5.2 cm^{-3} for coughing and 0.004–0.223 cm^{-3} for speaking. William G. use ultrasonic spirometer to study coughing droplet characteristics during patients influenza and in recovery period [33], found droplets concentration during suffering influenza was greater than in recovery period and existed a significant difference, but the droplets size was not [18-20].

There are much documented experiments using the optical instruments that can effectively measure size and concentration of fine droplets [47-55]. The PIV can observe the shapes of aerosol droplets. Actually, the differences between the test precision, test range and the output parameters of the instruments must affect the study results. The existing researches show that the transmission of respiratory diseases is associated with the droplet characteristics, especially, the droplet size and concentration are important for the control of pathogen spread.

4. THE RESULTS OF REASERCH

The droplet-borne pathogen transmission is related to not only the size and concentration of the droplet but also air temperature and humidity, the evaporation and sedimentation of droplets, the mortality of pathogens and so on.

4.1. The size of human respiratory droplet

According to documents, the size of airborne respiratory droplet is within 100 μm , and the size range of droplets in different experiments [18-20, 47-59] is approximately same, of course, it depends on the test instrument precision. It can be seen from Fig.1-Fig.3 that the size range of health people droplet is 0.1-8 μm . It is slightly larger than patients' 0.05-10 μm . The size of speaking droplets is 0.1-12 μm based on few of literatures. The size range of health people coughing droplet is 0.1-16 μm , it is larger than patients' 0.1-6 μm . The atomization process of male and female, has the difference due to the different respiratory mechanisms. For the size range of health people and patients, there is no significant correlation with gender. Zhu S, Yang S and Fennelly found the difference of droplet size have no statistical significance in different age groups [60-62, 98].

Moreover, the respiratory droplets can evaporate into droplet nuclei. The time of evaporation will affect their transmission distance. Wells [10] reported that a pure water droplet of 170 μm in dry air could fall height of 2m in 3s, as shown in Fig.4, and found that the droplet size after evaporation is only 1/5 of the initial diameter. Nicas [63] analyzed the component of human droplets, and found that the size of droplet nuclei after evaporation was about 1/2 of the initial diameter.

Droplet evaporation is also affected by relative humidity, is slower at higher relative humidity [10]. Relative humidity could affect the rate of evaporation and the final size of the droplet together with transmission trajectory [63-67]. Xie.X found evaporation time and movement trajectory were affected mainly by droplet size [68].

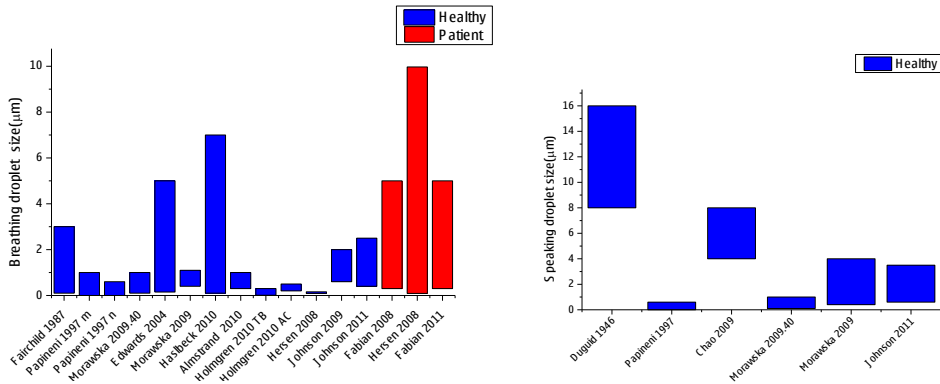


Fig. 1. Size range of human breathing droplet Fig. 2. Size range of human speaking droplet

(m—mouth breath; n—nose breath; TB—tidal breath; AC—airway closure)

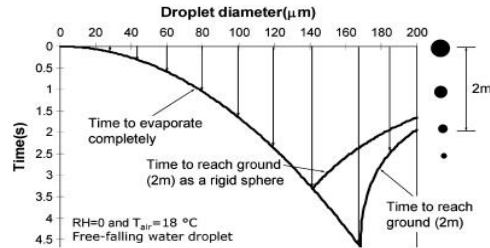
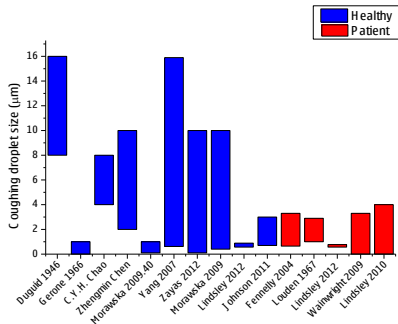


Fig. 3. Size range of human coughing droplet Fig. 4. The Wells evaporation-falling curve of droplet

4.2. The concentration of respiratory droplet

According to documents, it is obtained that some health people make more droplets than others, the coughing droplet concentration is the largest, speaking second, breathing least. It can be found from Fig.5~Fig.7 that the concentration range of droplets are 0.001-12cm⁻³(breathing), 0.001-1.2cm⁻³(speaking) and 0.001-5.5cm⁻³(coughing), respectively. The respiratory droplet concentration is definitely associated with medical parameters (breathing capacity, lung capacity), which are depended on the human height, weight, gender, age and health condition, etc.

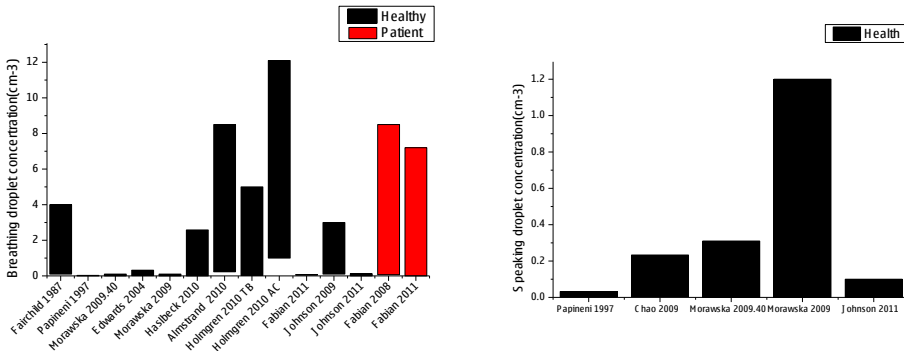


Fig. 5. The concentration range of breathing droplet Fig.6. The concentration range of speaking droplet

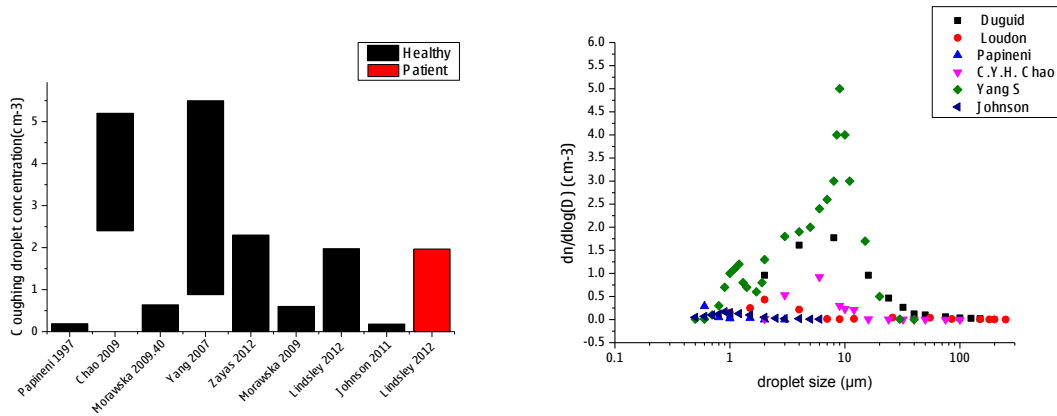


Fig. 7. The concentration range of cough droplet Fig. 8. The relation of cough droplet size and concentration

The coughing droplet concentration from patients is greater than in health people [20]. Couch et al. found that coughing was more frequent and more serious transmission during Coxsack-ievirus A infection [69-71]. For health people, there are different research results on the relation between the droplet concentration and human medicine parameters. Gustavo Zayas [60] found that droplet concentration was no statistical difference in age, sex, weight, height and body mass. Yang S [48] considered a significant difference of the droplet concentration for male and female, male produced higher concentrations than female. Yang S also got the difference between droplet concentration and age groups, the concentration from 30-50 age group were maximum. Johnson [72] pointed that there was a strong relation between the droplet concentration and age. So, these relevant topics need further study

It can be concluded from Fig.8 that the coughing droplet concentration varies with the size, the concentration reaches the peak at the size range of 8-10μm. But the concentration distribution studied by Yang S is slightly different, that was existing two peaks, the large droplet size was mainly 8 to 10μm, the small droplet nuclei size was 0.8 to 2μm. The ranges of droplet size and concentration in Fig. 8 are consistent.

As above, the coughing droplet size is 0.1 to 16μm and concentration range is 0.001 to 5.5 cm⁻³.

4.3. Droplet ejecting velocity and deposition

The human mouth or nose can be assumed a spout, the expelled droplet velocity is important for predicting the transmission distances and trajectories [90-96,99-102]. The breathing droplet velocity is relatively small, and lower than coughing and sneezing. The ranges of breathing droplet velocity is 0.1 to 1m/s, the transmission distance is about 1m; the speaking droplet velocity is 2-10 m/s; the coughing droplet velocity reaches 10-20 m/s and it transmits more than 2m, shown in Table 1. Gupta JK [73,74] gave the function of the velocity with human parameters, it could be used to calculate droplet transmission distance, it is the basis of controlling the disease spread.

Moreover, droplet deposition is an important dynamic behavior, and droplet velocity affect also its deposition time. The droplets can move from the high to the low concentration area. In 1941, Phelps & Buchbinder [67] used the droplets with green streptococcus to conduct a series of experiments, and showed that 50% of droplet nuclei disappeared in 3h due to deposition, the others deposited within 26h.

It should be noticed that microbial droplets deposit on the surface, but some will be raised to regenerate aerosols because of the wind, sweeping and various mechanical vibration. Hambræus pointed out that the diffusion coefficient for the regenerated aerosol was $3.5 \times 10^{-3} \text{ m}^2$. In a relatively stable room, the circulation of deposition and suspension will not stop as long as the microbial droplets remain active. Aerosols ($\geq 5 \mu\text{m}$) suspension has a close relation with the human activity, even a slight activity. The rate of secondary suspension was uncertain, and could affect the indoor droplet nuclei amount [75-77].

Table 1. The velocity and transmission distance of respiratory droplet

Author	Subject	Breathing	Speaking	Coughing
Zhu.S	Healthy	—	—	6—22m/s (average 11.2) transmission distance >2m
C.Y.H. Chao	Healthy	—	3.9m/s (average)	11.7m/s (average)
Shengwei Zhu	Healthy	—	—	22m/s transmission distance >2m
X. Xie	Healthy	1m/s transmission distance <1m	—	10m/s transmission distance >2m
J.K.Gupta	Healthy	Flow rate- a sinusoidal function with time	Flow rate- a constant related to body surface area	Flow rate-a combination of gamma-probability- distribution functions
Soon-Bark Kwon	Healthy	—	4.07m/s (male) 2.31m/s (female)	15.3m/s (male) 10.6m/s (female)

4.4. Droplet temperature, component and pathogen activity

Hoppe gave the exhalation temperature under different thermal environments, and found that the ambient temperature was the most influence parameter. The expelled droplet temperature can be approximated as body temperature when ignoring the effect of ambient temperature, health people and patients is slightly different [78,79].

Moreover, droplet component affect directly the type and number of pathogens. The human respiratory droplet is an aqueous solution containing inorganic ions, organic ions and glycoprotein [80], shown in Table 2.

Table 2.Component of respiratory droplet

Component	Na+	K+	Cl-	Lactate	Glycoprotein	H2O
Mass(g)	23	39.1	35.5	89	—	—
Concentration	91±8mM	60±11mM	102±17mM	44±17mM	76±18g/L	—
Component	Na+	K+	Cl-	Lactate	Glycoprotein	H2O

Droplets provide living space for the pathogens which cause respiratory disease. The droplet component and pathogens interact with each other. Pathogens exist in the droplets with the forms of single cells or spores, fungal spores or more virus and many cells, spores or virus polymer [58], and then are taken into the ambient environment with respiratory droplets.

The droplet-borne pathogen can grow, reproduce and decay during the whole biological process. The pathogen will reproduce by cell division in each 1/3-1/2h if the condition is appropriate[81]. The activity of pathogen is actually unstable, its survival rate will reduce with time going.

The decay can be used describe quantitatively the instability of microbial activity. Total decay of the microbial droplet include the physical and biological attenuation. The relation microbial decay with time is an exponential function[82-85].

The survival ability of pathogens is depend on droplet component. The small pathogens and viruses can survive only few of water and nutrients, and can live long in the air. The fungal spores is stronger due to itself relatively intact cell structure and different from other pathogen and viruses[86,87]. Larger pathogens such as bacteria can survive in larger droplets whereas the respiratory droplets from viral infection patients were much smaller [88,89].

5. CONCLUSION

The spread probability of respiratory disease depend on the droplet characteristics, which include droplet size, concentration, concentration distribution, droplet velocity, temperature, component, type of pathogen, activity of pathogen, etc. Droplet characteristics provide the basic data for studying indoor concentration distribution and control measures of respiratory diseases. Based on this documentary research, it can be get following conclusions.

It has shown that droplet pathogens do not exclusively airborne or droplet-borne transmission but both methods simultaneously. The size of human respiratory droplets is no significant difference with health level, gender and age. The size range of breathing droplet from health people is 0.1-8 μ m, patients is 0.05-10 μ m. For health people, the size of speaking droplet is 0.1-12 μ m, patients is not documented. The size range of coughing droplet is 0.1-16 μ m, patients is 0.1-6 μ m. So the size range of human respiratory droplet is roughly similar. But there are slightly size difference between health people and patients depend on their physical level.

The concentration range of human respiratory droplets is 0.001-12cm⁻³, and coughing is the largest, speaking second, breathing least. The ranges of droplets are 0.001-12cm⁻³ (breathing), 0.001-1.2cm⁻³ (speaking) and 0.001-5.5cm⁻³ (coughing), respectively. There are no definite conclusions about the relation of the concentrations and human medical parameters, which are directly depended on the human height, weight, gender, age and health condition, etc. These relevant topics need further study.

The respiratory droplet concentration varies with the size. The coughing concentration reaches the first peak at the size range of 0.8 to 2 μ m and the second peak at the size range of 8 to 10 μ m, but the former need further study and verify.

The range of breathing droplet velocity is 0.1 to 1m/s, the spread distance is about 1m; the speaking droplet velocity is 2-10 m/s; the coughing droplet velocity reaches 10-20 m/s and it can spread more than 2m. The function of the velocity with human parameters can use to calculate the droplet spread distance and the safe distance to control the disease spread.

The expelled droplet temperature can be approximated as body temperature if ignoring the effect of ambient temperature. The human respiratory droplet is an aqueous solution containing inorganic ions, organic ions and glycoprotein. Pathogens will exist in the droplets with the forms of single pathogen cells or spores, fungal spores or more virus and many cells, spores or virus polymer.

The droplet-borne pathogen can grow, reproduce and decay during the whole biological process. Pathogens can reproduce in each 1/3-1/2h if the condition is appropriate. The survival rate of pathogen will reduce with time going. The decay can be used describe quantitatively the instability of microbial activity. The relation microbial decay with time is an exponential function. The survival ability of pathogens is depend on droplet component. The small pathogens and viruses can live long in the air. The fungal spores is stronger due to itself relatively intact cell structure.

6. EXISTING RESEARCH GAPS AND OUTLOOK

These results achieved from only each certain study topic are the lack of general meaning. Although some general conclusions about human respiratory droplets characteristics are summarized, there are still some research gaps and conflicting results which need further study and supplement.

As we know different size droplets are inhaled and deposited on different sites in the respiratory tract. There is slightly different for respiratory droplet size between health people and patients, and the concentration of coughing droplets is largest, speaking second, breathing least. But how can we more accurately determine the quantity of droplets and size distribution in the indoor or outdoor space is also difficult problem. For health people and patients, even if the size and concentration of droplets are certain, the quantity and type of droplet-borne pathogens are different because of patients carrying more pathogens. All of these are basic data that we control and prevent respiratory disease transmission, it also need further research.

There are a lot of different indoor function zone in which the proportion and quantity of occupant types are also different. Therefore, it looks to be necessary to investigate relevant parameters, such as gender, age and health level, to get respiratory droplets characteristics for a certain space. It is important science support to formulate the respiratory disease prevention and control measures, but no studies have been given in this field. Therefore, how to quantify the number of droplet-borne pathogens in different spaces is further study key issue.

There are important areas, which still need to be focused on respiratory infection of risk assessment in different spaces, such as in hospital, kindergarten, nursing home, community and other the places with high density of people. If thresholds of respiratory disease breaking out for occupants can be obtained, we can use experiment or simulation methods to predict droplet-borne pathogen spread, and take effective measures to ensure public environment security. All these work will pave the way for epidemiological studies.

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