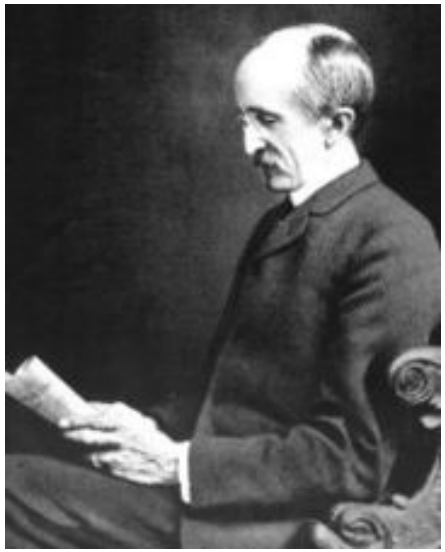
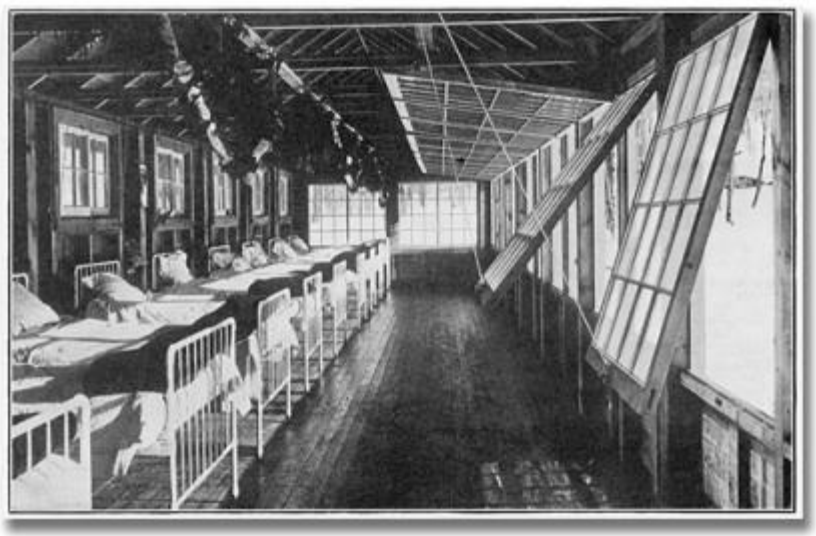
How room ventilation affect influenza infection control

Yuguo Li 李玉国
Built Environment and Energy Group 建筑环境与能源小组
Department of Mechanical Engineering机械工程系
The University of Hong Kong香港大学
Hong Kong SAR, China 中国香港特别行政区

The idea of Sanatorium露天疗养院(1863-

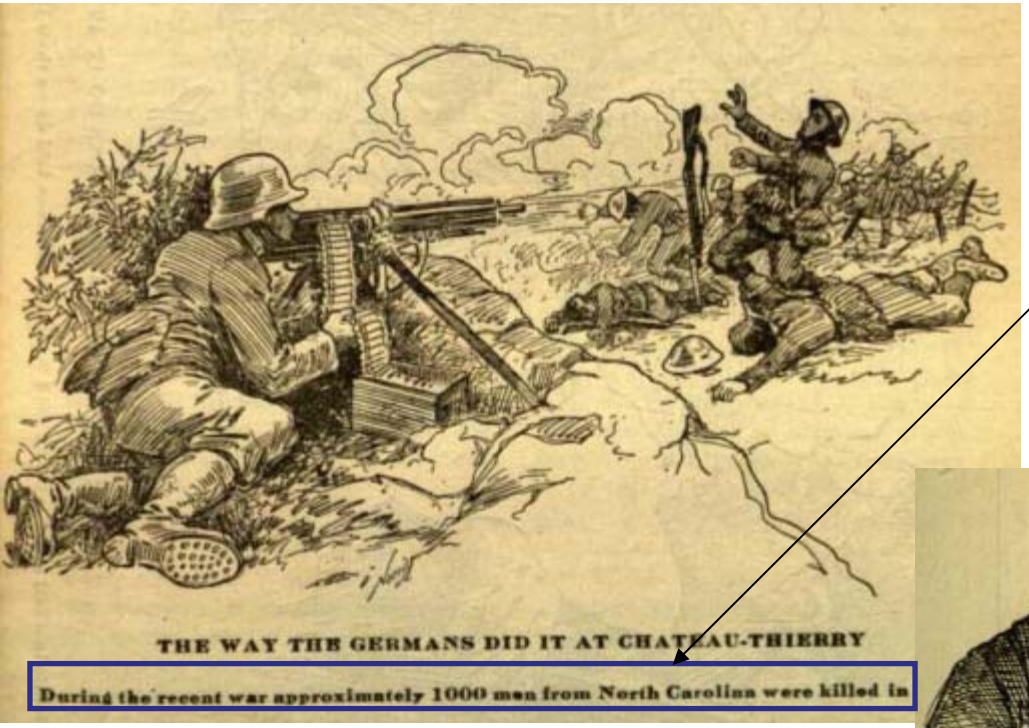


Dr Edward L Trudeau
(1848-1915)

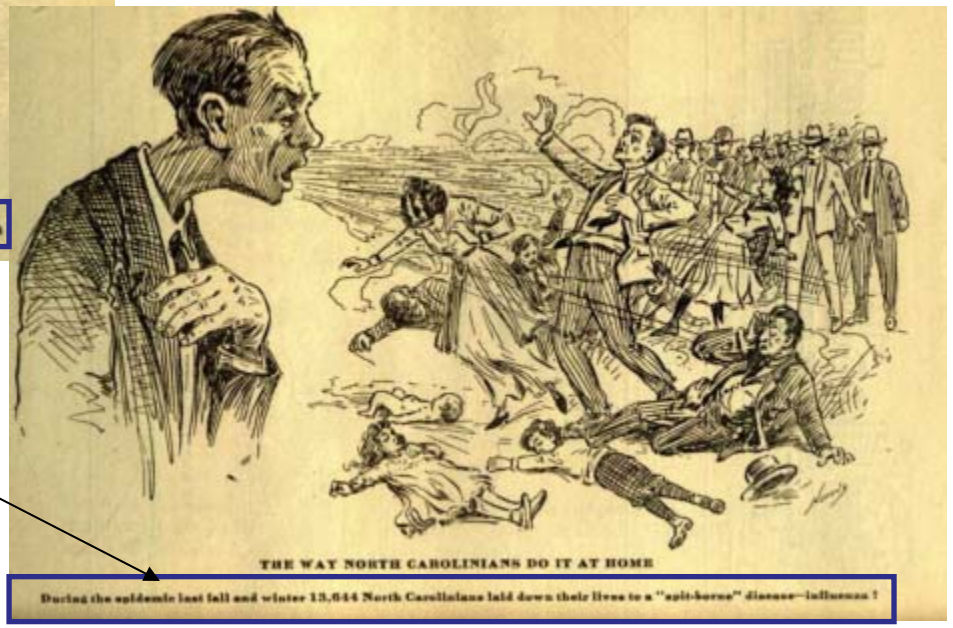


Dr Trudeau built the first Sanatorium near Saranac Lake, NY in 1882.
Trudeau博士在1882年在纽约Saranac湖附近建立美国第一个疗养院

The Health Bulletin, North Carolina State Board of Health, October 1919
南卡罗来纳州卫生局健康公告，**1919年10月**



During the recent **war** approximately **1000 men** from North Carolina were killed in battle.
在最近的战争（一战）中，南卡罗来纳州大约1,000军人阵亡



During the epidemic last fall and winter**13,664** North Carolinians laid down to their lives to a “spit-borne” disease – **influenza**!
去年秋冬两季，南卡罗来纳州13,664人死于飞沫传播的流感

Our understanding of the transmission of influenza is woefully inadequate.

可悲的是，我们对于流感传播过程的知识还差得远了！

US National Academy of Sciences Report on Preparing for Influenza Pandemic, 2007

美国国家科学院2007关于预防流感大爆发报告

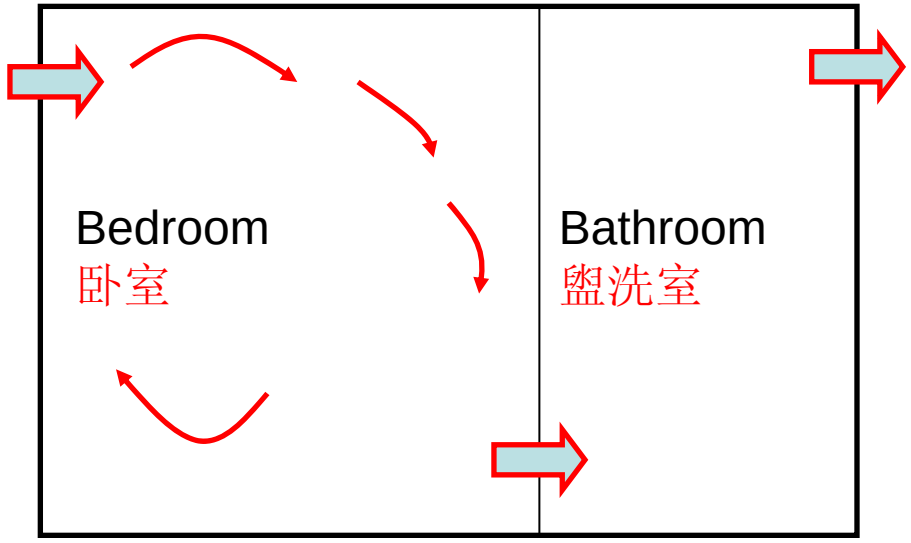
The myths in 2009 H1N1 pandemic 2009年H1N1大流行的一些误区

- Influenza infection mostly occurs in close proximity to the index patient. Hence it is unlikely to be airborne. Brankston et al. Lancet (2007) 流感感染通常与源病例有密切接触时发生，因此流感不会是空气传播的。 Brankston et al. Lancet (2007)

- There are some evidences for airborne transmission of influenza infection. Hence airborne precaution such as N95 masks need to be used. Tellier, EID, 2006 and NAS (2009) 我们有一些流感病毒空气传播的证据，因此需采取防止病毒通过空气传播的措施，例如有必要佩戴N95口罩。Tellier, EID, 2006 and NAS (2009)

Ventilation refers to supply of outdoor or "properly filtered" air in a building and distribute within it.

通风是指将室外空气或经过适当过滤的室内空气送入并分布在建筑内。

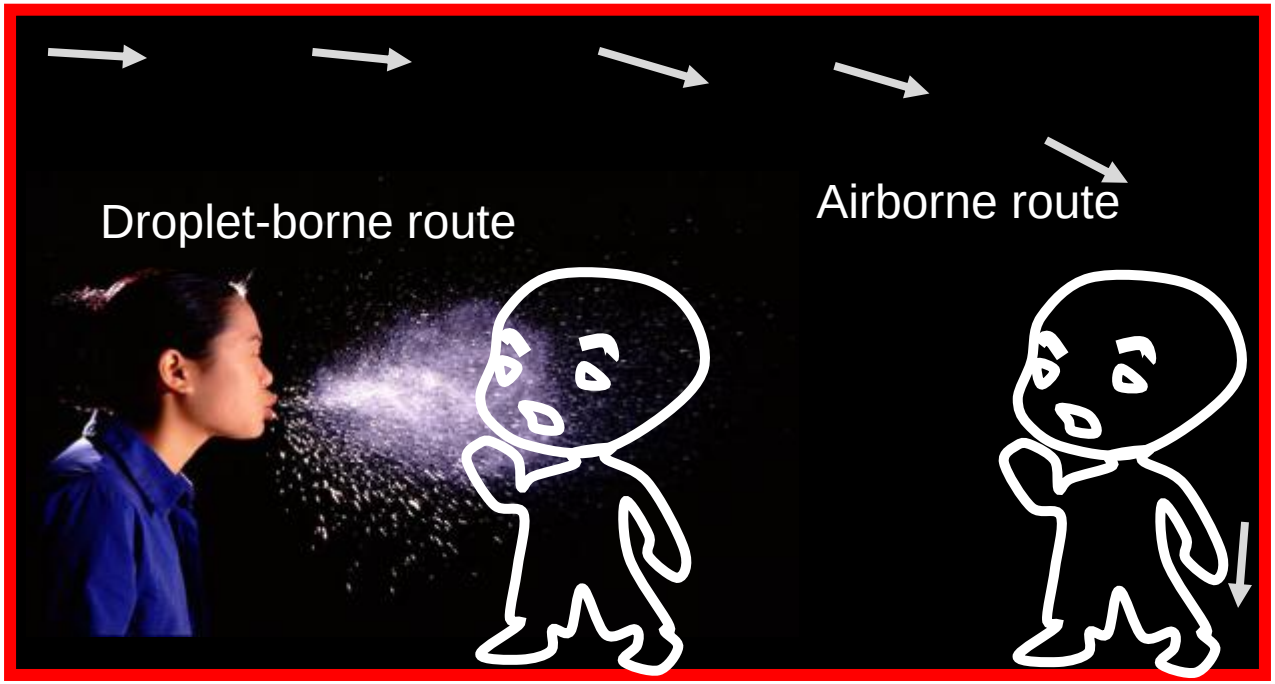


- Ventilation flow rates通风量
- Airflow direction流动方向
- Air distribution空气分布

Airborne infection空气传播传染 - the passage of micro-organisms from a source to a person through aerosols, resulting in infection with consequent disease.微生物从源头经过空气传播到人，导致人感染相应疾病

Droplet infection飞沫传染 occurs via large droplets (≥5 μm diameter), which propelled a distance of less than 1 m and are deposited on the nasal or oral mucosa of the new host or in their immediate environment. These large droplets do not remain suspended in the air; therefore, special ventilation is not required.病毒通过掺杂在传播距离不到一米的大液滴（直径不小于5微米）中，降落到新宿主的鼻腔或口腔粘膜上。这种大液滴不能悬浮于空气中，因此，不需要特别的通风措施。

Modified from Brankston et al., Lancet Infect Dis 2007:7:257-65



The sneezing photo, courtesy of Dr Julian Tang 人打喷嚏时的情形， 由Dr Julian Tang提供

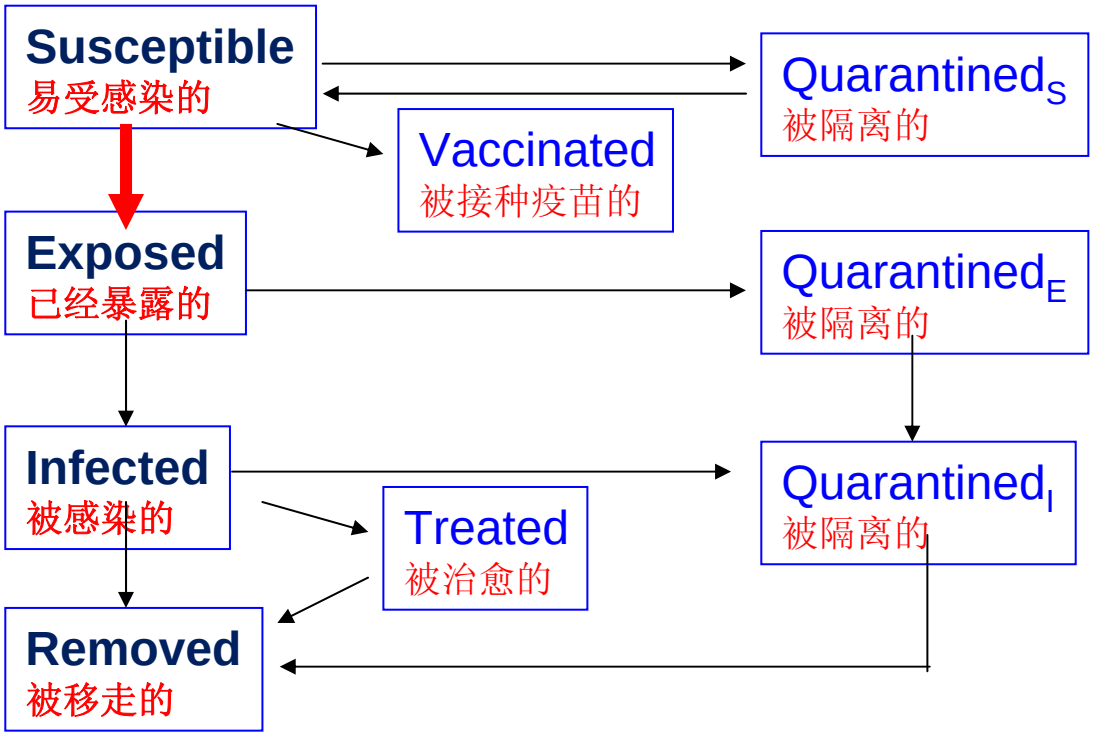
An **epidemic** occurs when new cases of a certain disease, in a given human population, and during a given period, substantially exceed what is "expected," based on recent experience, e.g. 2003 SARS epidemic.

根据以往经验，当一定人群在一定时间段内，某种疾病出现新的病例并且其发展速度远超过预期，这时被称为局部流行。例如2003年非典

A **pandemic** is an epidemic of infectious disease that spreads through human populations across a continent, or even worldwide, e.g. **2009 H1N1 pandemic**.

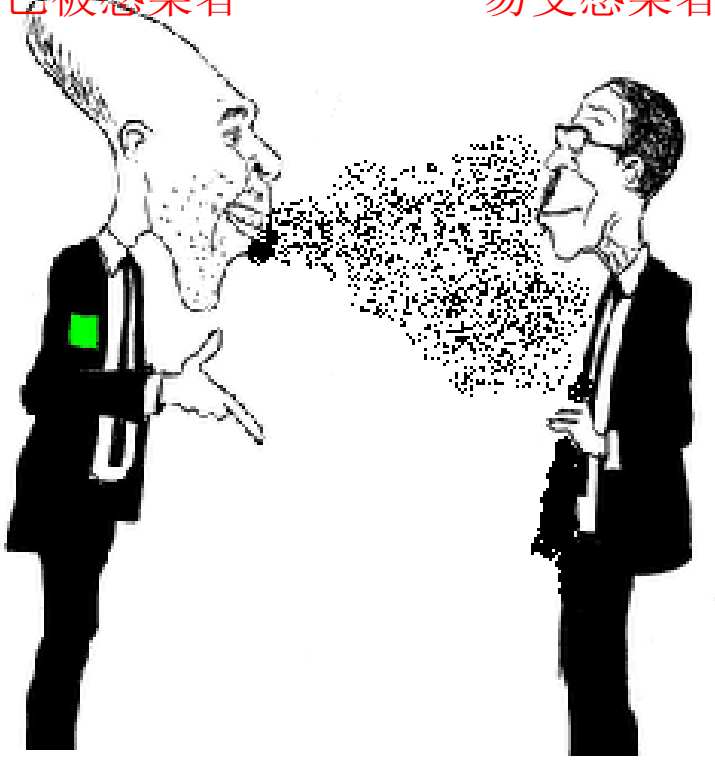
大爆发是指传染性疾病传播范围达到一个大洲，甚至是在世界范围均有人群被感染。例如2009年H1N1流感大爆发

Ventilation?
通风?



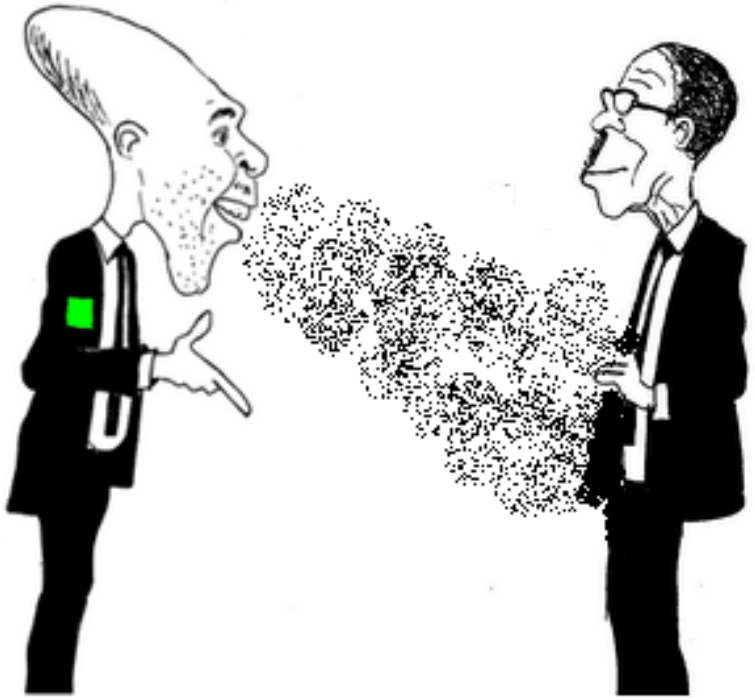
Infected
已被感染者

Susceptible
易受感染者



Infected
已被感染者

Susceptible
易受感染者



Direct (spray) droplet
直接（飞沫）液滴传播

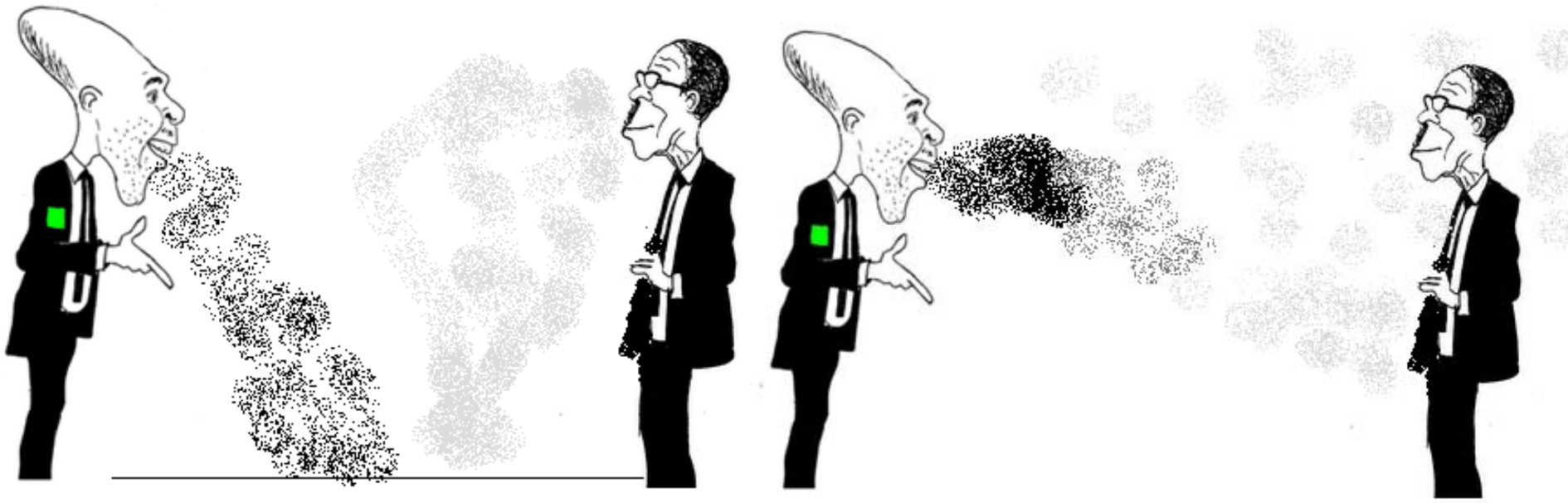
Indirect contact
非直接接触

Infected
已被感染者

Susceptible
易受感染者

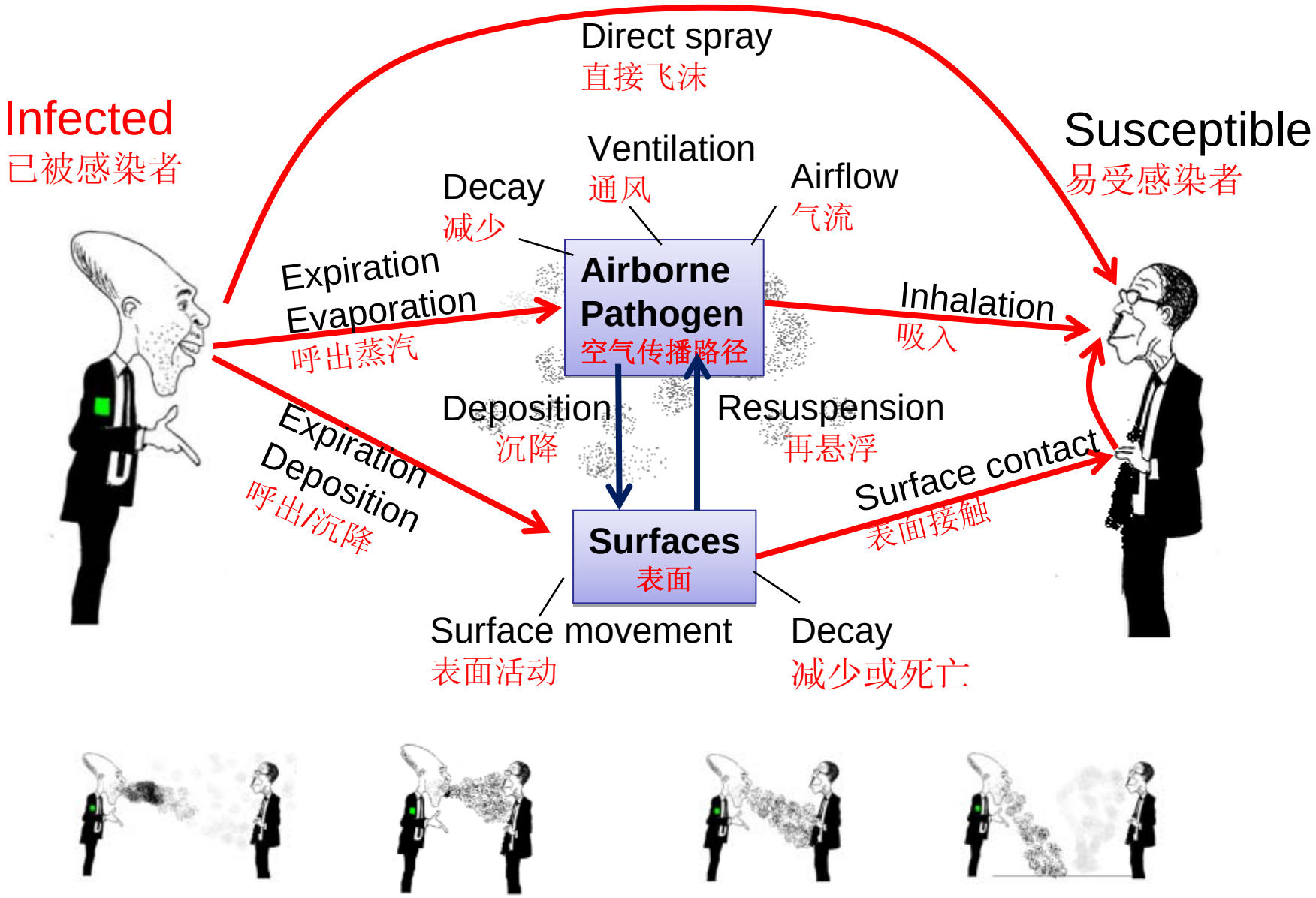
Infected
已被感染者

Susceptible
易受感染者



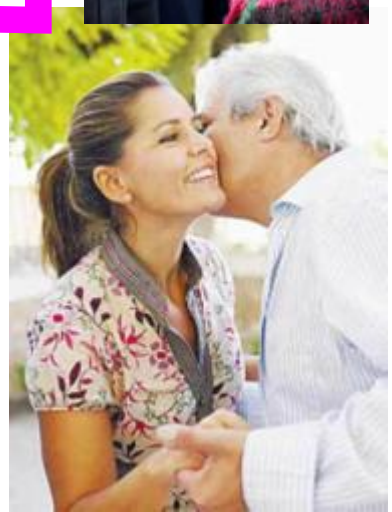
Dust-borne
尘埃传播

Airborne
空气传播



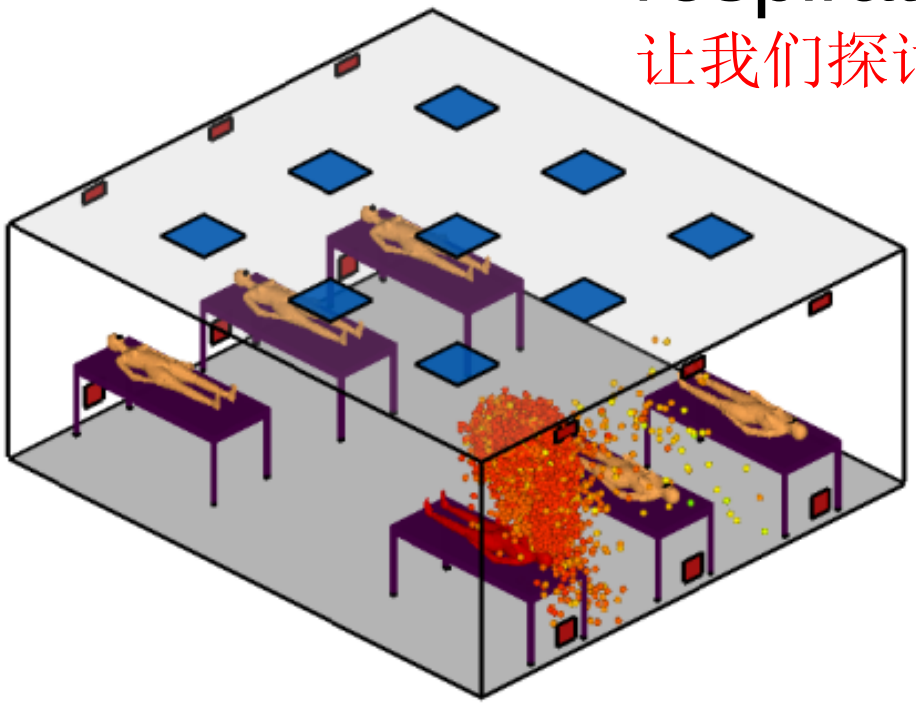
Modified from Atkinson and Wein, Bulletin of Mathematical Biology, 2008, 70:820-867

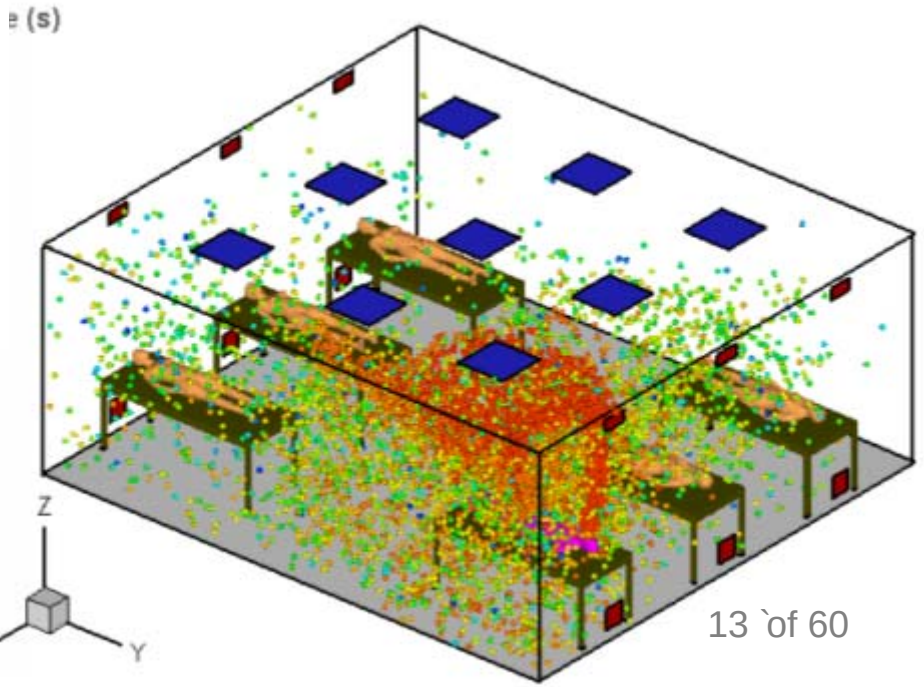

cnsphoto



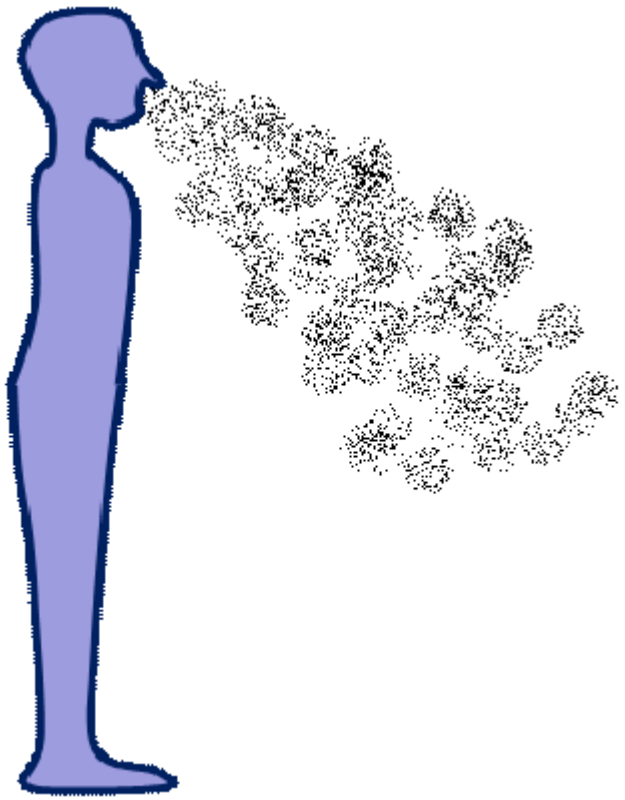
Let’s explore what happens to respiratory droplets in detail??

让我们探讨液滴呼出后的详细情况？？





1

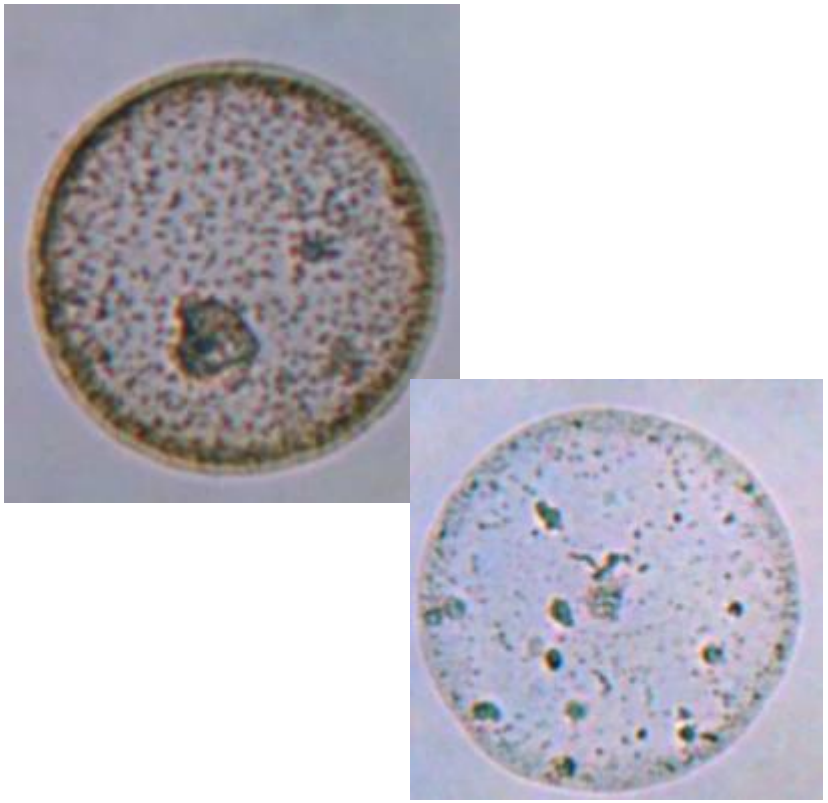


Exhalation puffs/jets – breathing, coughing, sneezing or even singing

呼气射流或者阵流－呼吸，咳嗽，喷嚏或者甚至唱歌

Droplets – the beauty and the Beast

小液滴－美与丑共存

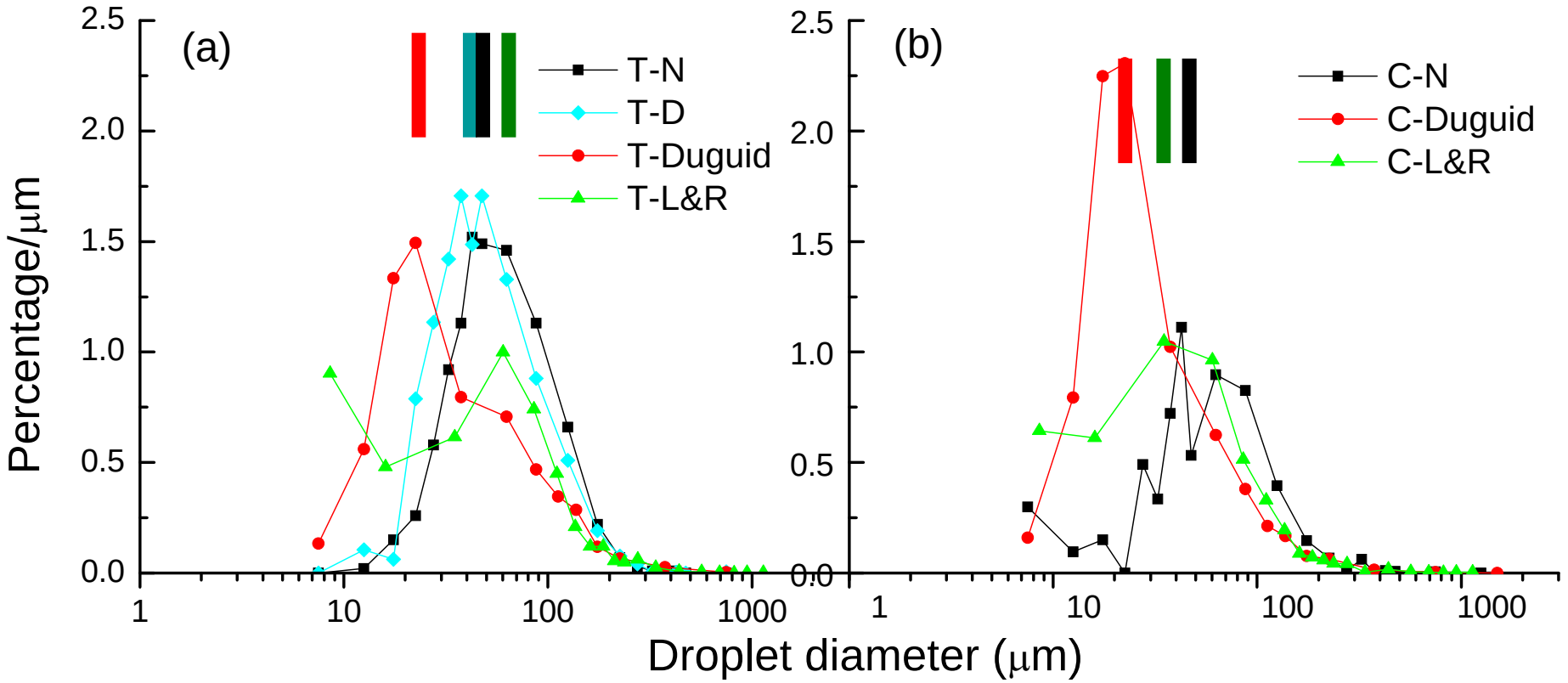


Droplet stain-mark on Teflon surfaces

特氟隆表面的液滴污点

The peak size of exhalation droplets are 50-70 μm!

呼出液滴的最大尺寸是50－70微米



a) Talking

说话

b) Coughing

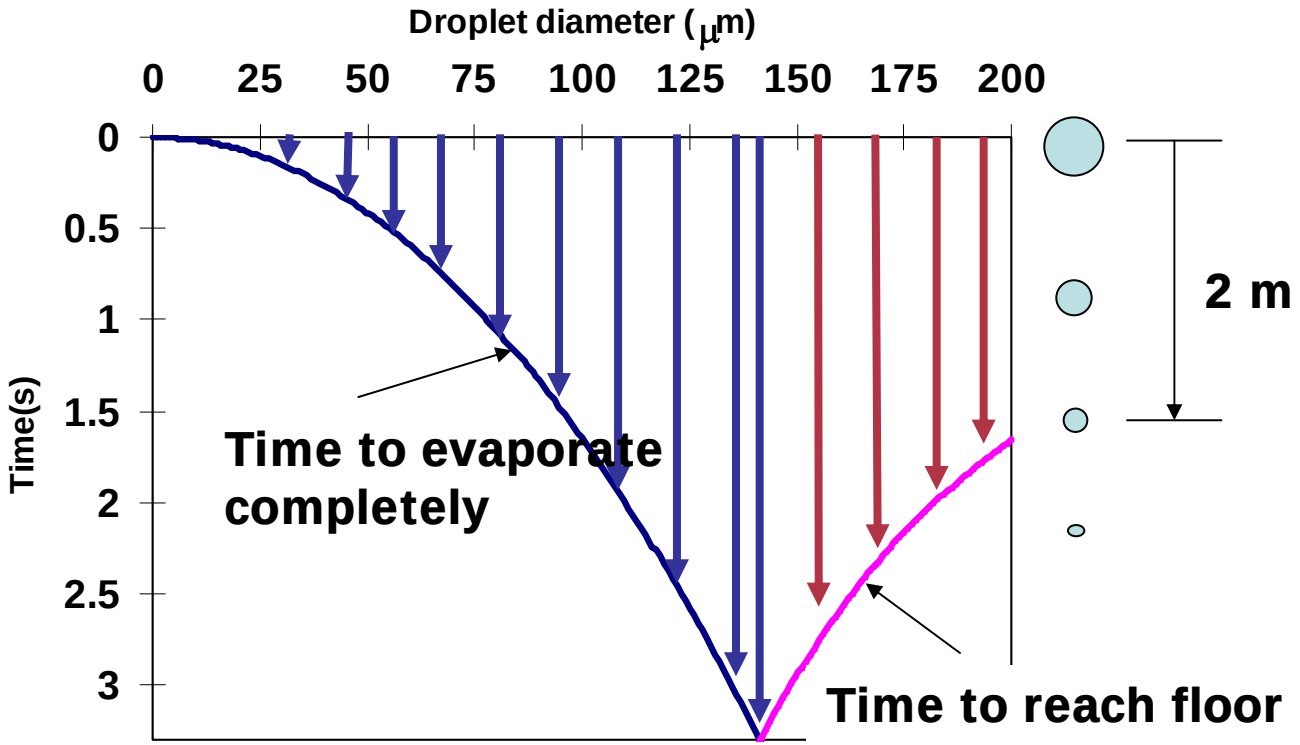
咳嗽

Xie et al, Journal of the Royal Society Interface, to appear

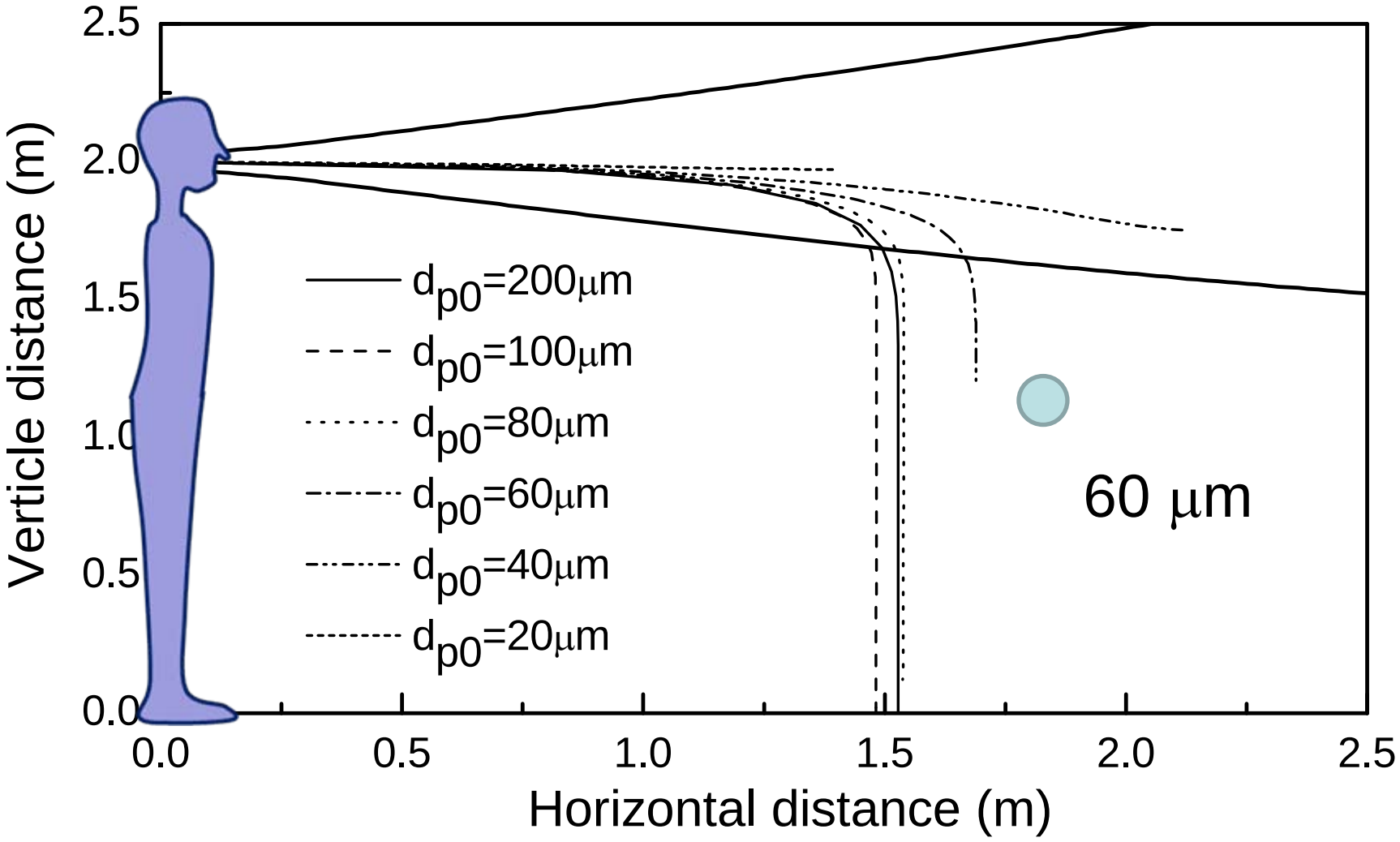
Morawska et al., 2009, Chao et al., 2009, Xie et al (not published)

Large droplet and droplet nuclei

大“小液滴”和小液滴核



Adapted摘自from Wells, Am J Hyg 1934;20:611-618
Xie et al, Indoor Air 2007;17:211-225



Trajectories of coughing droplets咳嗽产生小液滴的传播轨迹

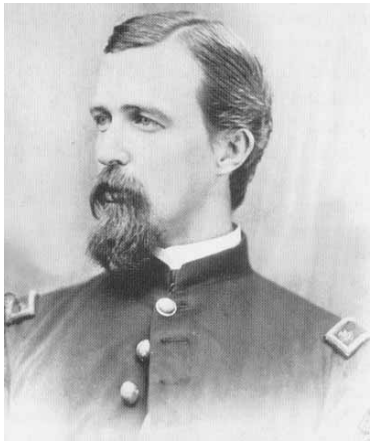
(Tp = 33°C, T∞ = 20 ° C, RH = 50%, U_0 = 10 m/s, d_0 = 0.04 m, Re =24,640).

Xie et al, Indoor Air 2007;17:211-225

Important studies/events related to airborne infection and ventilation.
关于空气传播传染病和通风的重要研究和事件

Year	Description
1840	Jacob Henle (1840) suggested "Miasmatic diseases…develop epidemically…where a large number of people are crowded together with a diminished circulation of air.".
1854	**John Snow** showed London cholera outbreak was caused by something in sewage-contaminated water, not by miasma as shown by William Farr.
1861	Pasteur showed there are microorganisms in air as S-shaped flask kept microbes out but let air.
1884	**JS Billings (1884)** recommended 60 cfm ventilation rate per person to minimize the disease spread, and 30 cfm for comfort.
1897	C Flugge (1897) showed that droplets from the nose and mouth contained bacteria, but did not travel more than 2 m.
1910	**Charles V Chapin (1910)** argued that "most diseases are not likely to be dust-borne, and they are spray-borne only for two or three feet, a phenomenon which, after all, resembles contact infection more than it does aerial infection as ordinarily understood". "In reviewing the subject of air infection it becomes evident that our knowledge is still far too scanty, and that the available evidence is far from conclusive…It is impossible, as I know from experience, to teach people to avoid contact infection while they are firmly convinced that the air is the chief vehicle of infection…"

Dr. John Snow
(1813-1858)



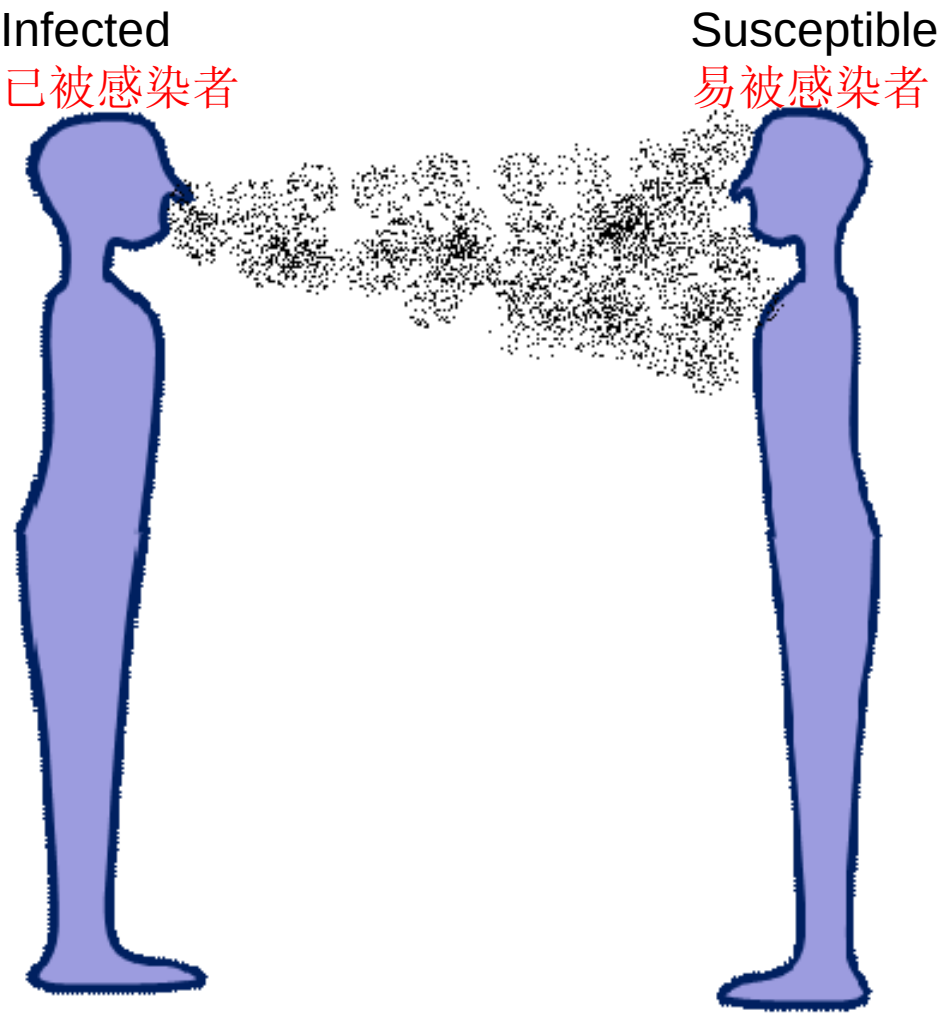
Lieutenant Colonel
John Shaw Billings
(1838-1913)

1934	William F Wells (1934) introduced the concept of droplet nuclei. First peak of studies on airborne infection in 1940s and 1950s.
1942	**William F Wells** et al (1942) showed UVGI prevented measles spread in schools.
1955	William F Wells (1955) introduced the quanta concept, and the Wells-Riley model, and the commonly-used form was first presented in Riley et al (1978).
1962	**Riley et al. (1962)** demonstrated that tuberculosis is airborne by infecting guinea pigs exposed to exhaust air from a human tuberculosis ward.
1976	Legionnaires' disease first identified among people attending a convention of the American Legion in Philadelphia in 1976, but from person to person.
1986	**Renewed interest in airborne TB** due to the first increase of TB cases in 1986 since 1953 (annual decrease of 5% until 1985) (CDC, 1989).
2004	Yu et al (2004) demonstrated the SARS outbreak in a high-rise estate was airborne.
2009	**Munster et al (2009)** showed that transmission via aerosol or respiratory droplets was equally efficient for the swine-origin 2009 A (H1N1) influenza.

Carl Flügge
(1847-1923)

Charles Value Chapin
(1856 -1941)

2



Exposure to exhalation puffs/jets by either direct spray or short range airborne

呼气射流暴露 -直接飞沫传播或是近距离空气传播？

Evidences for droplet infection飞沫传播的证据？

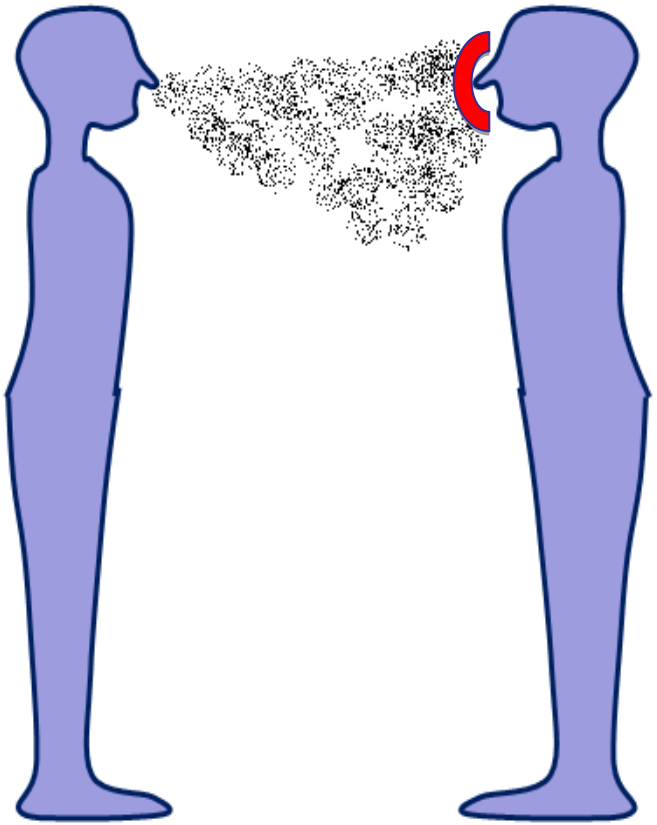
- Infection occurs in close proximity to the index patient in outbreaks.传染病爆发时，感染发生在离源病例近距离接触过的人群中
  - –e.g. Place animals such as ferrets into the same cage – how the short range airborne infection is ruled out比如将雪貂等动物放在同一个笼子里－怎样将空气传染排除？
- A logical problem with this “evidence” 这个“证据”的一个逻辑问题
  - **Correct** – Droplet spray infection occurs in close proximity to the index patient.
    正确－飞沫感染一定是发生在近距离接触过源病例时。
  - **Wrong -** Infection occurring in close proximity is always via droplet spray infection.
    错误－感染发生在近距离接触过源病例的人群中一定是通过飞沫传播
- There have been no any direct evidence of large-droplet infection. Droplet infection is a much lower probability event than airborne infection 没有直接的证据证明病毒通过飞沫传播。飞沫传播的可能性比空气传播的可能性小很多。(Atkinson and Wein, 2008）

Droplet precaution – the roles of surgical masks

液滴传播的预防措施－ 口罩的作用

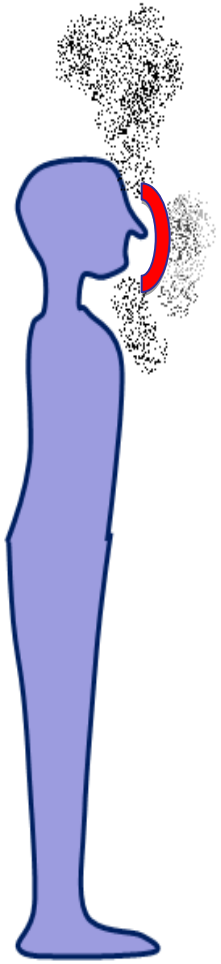
Infected
已被感染者

Susceptible
易被感染者



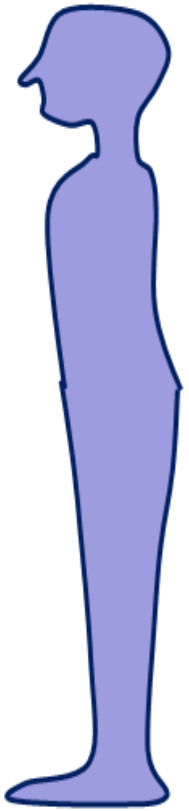
Respirator
呼吸器

Infected
已被感染者



Mask
口罩

Susceptible
易被感染者

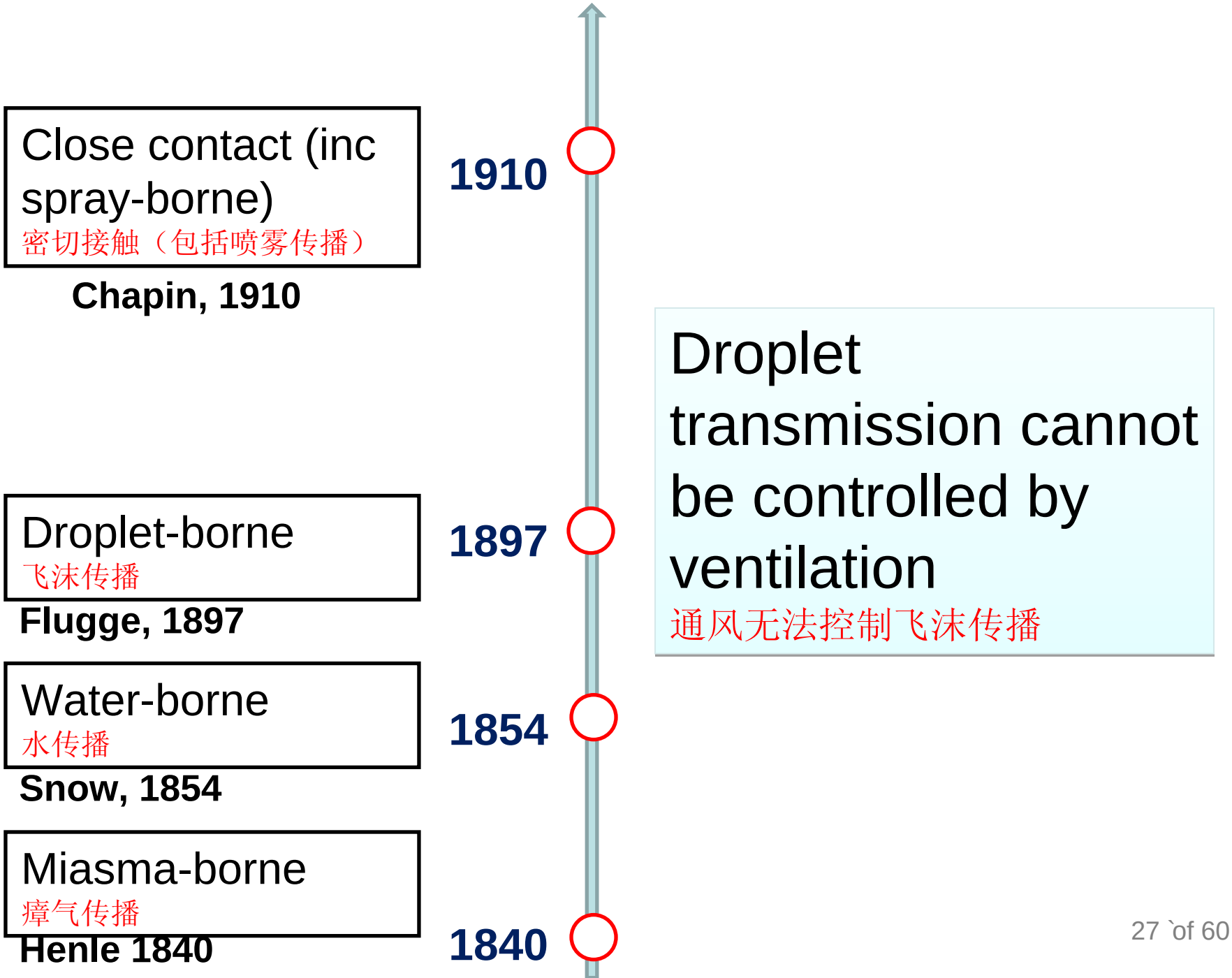


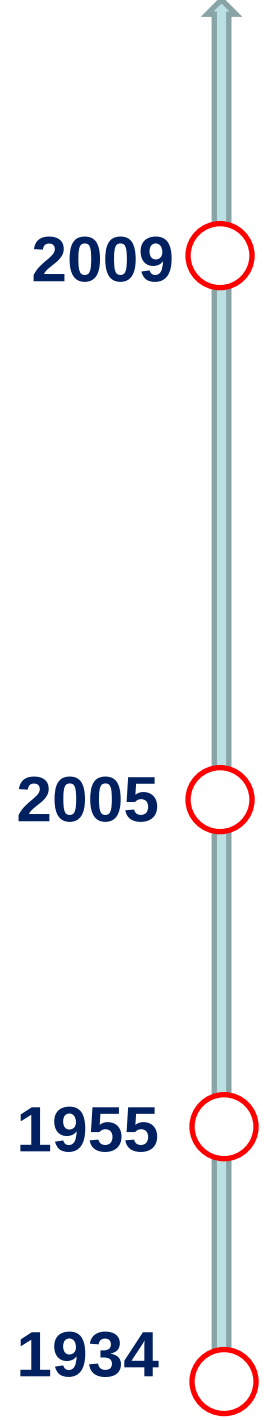
Settles G and Tang J. Journal of the Royal Society Interface, Oct, 2009

Settles G and Tang J. Journal of the Royal Society Interface, Oct, 2009

Droplet or short range airborne Infection
飞沫传播或近距离空气传播？

- Short range airborne infection has been incorrectly lumped into droplet infection since Wells (1934)从 Wells（1934）开始，近距离空气传播被错误的与飞沫传播混为一谈
- The two mechanisms are different.这是两个不同的物理过程
- Control methods of droplet and short range airborne infection routes are different. 飞沫传播和近距离空气传播的控制方法是不同的
- Droplet precaution does not work for preventing airborne infection.飞沫传播预防措施用在避免空气传播传染时是无效的


Close contact (inc spray-borne)
密切接触（包括喷雾传播）
Chapin, 1910
1910
Droplet transmission cannot be controlled by ventilation
通风无法控制飞沫传播
Droplet-borne
飞沫传播
Flugge, 1897
1897
Water-borne
水传播
Snow, 1854
1854
Miasma-borne
瘴气传播
Henle 1840
1840



•Direct contact直接接触

•Indirect contact非直接接触
•Droplet spray-borne飞沫传播
•Airborne 空气传播
short短距离< 1.5 m
long长距离 >1.5 m

2009

General ventilation for long range airborne
一般通风适用于长距离空气传播

Personalized ventilation for both short and long range airborne???
个性化通风适用于短距离和长距离空气传播？？

Contact接触

Direct contact直接接触
Indirect contact非直接接

Large droplet飞沫
Airborne空气传播

Mangili and Gendreau, Lancet, 365:2005, 989-996

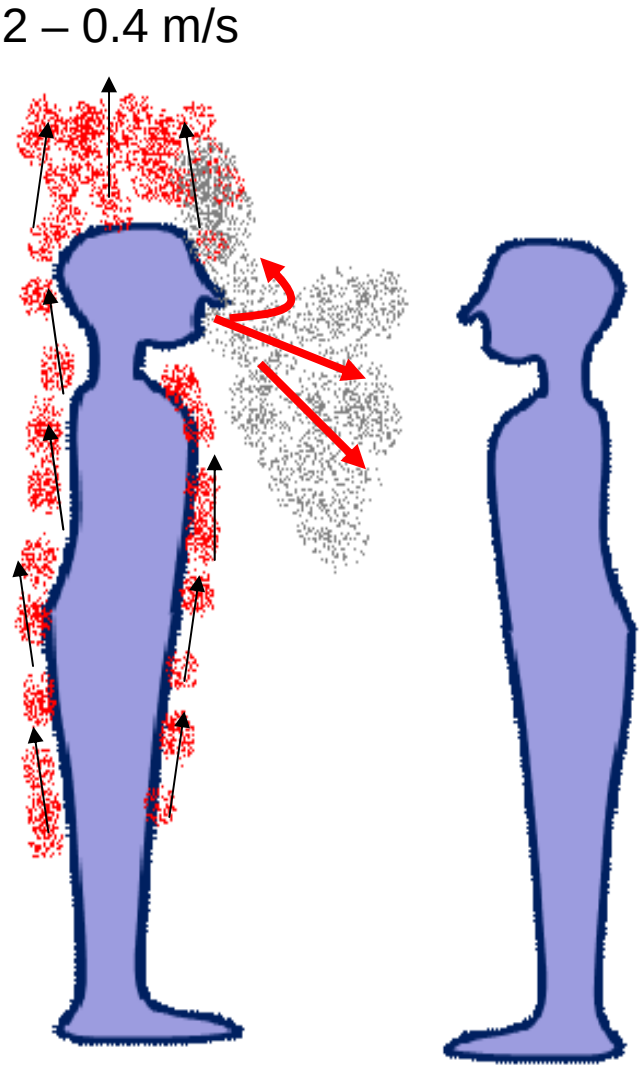
2005

Airborne epidemics are absent from an ecological population provided with adequate air hygiene. Wells, 1955
为人群提供充足的卫生的空气，空气传播传染病就会消失

1955

1934

3



Body convective flows and exhalation puffs/jets create a body microenvironment

身体周围的对流和呼气射流构成了身体周围的微环境

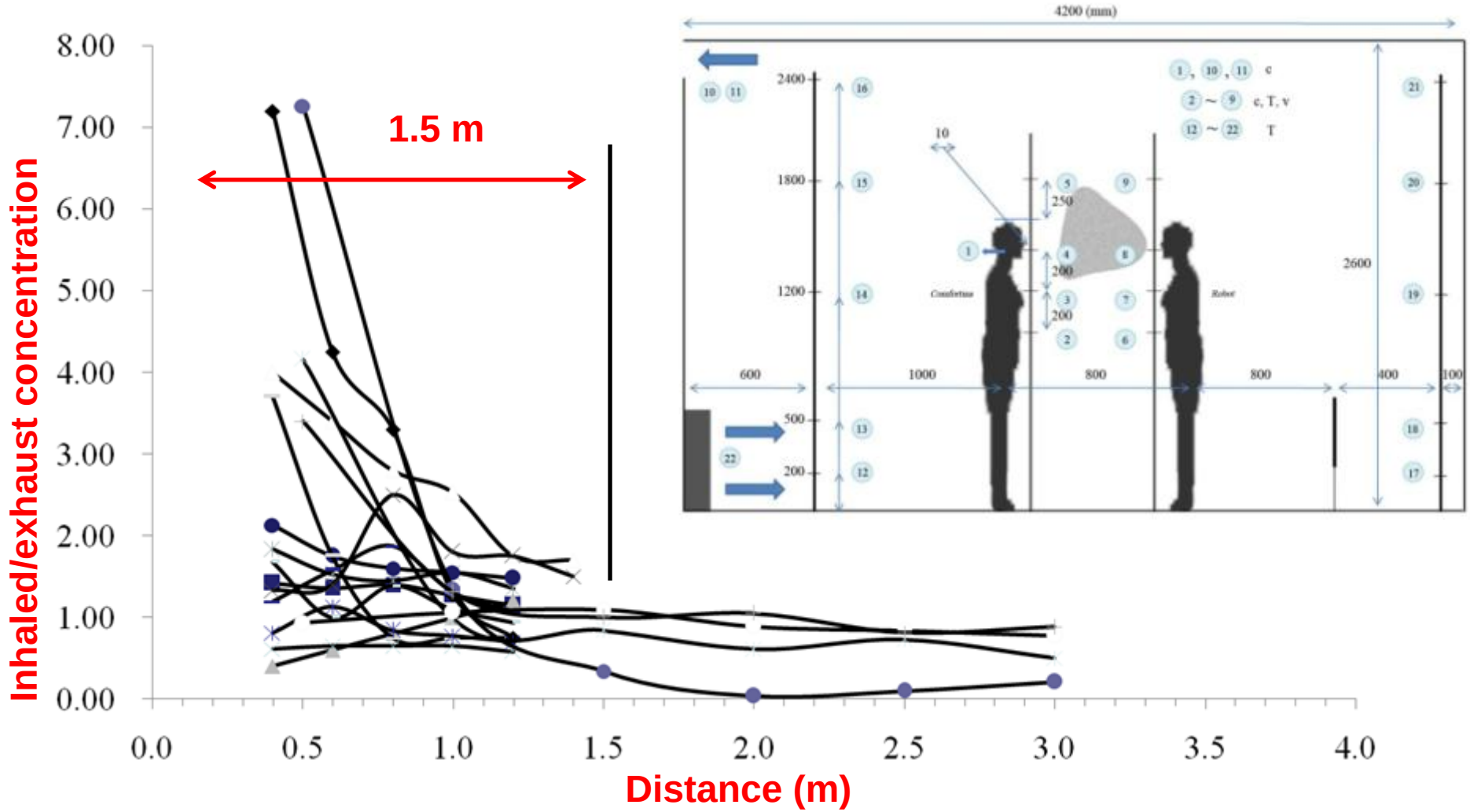
The so-called cloud baby and cloud adult may be relevant?
所谓的“雾婴”和“雾人”也许与之相关？

Eichenwald et al. Am J Dis Child. 1960;100:161-73 showed that some babies caused explosive S. aureus outbreaks in nurseries. They are literally surrounded by clouds of bacteria, so they were called cloud babies .

Eichenwald et al. Am J Dis Child. 1960;100:161-73表明有一些幼儿引起托儿所内金黄色葡萄球菌的爆发。他们被细菌雾状包围，所以称为“雾婴”

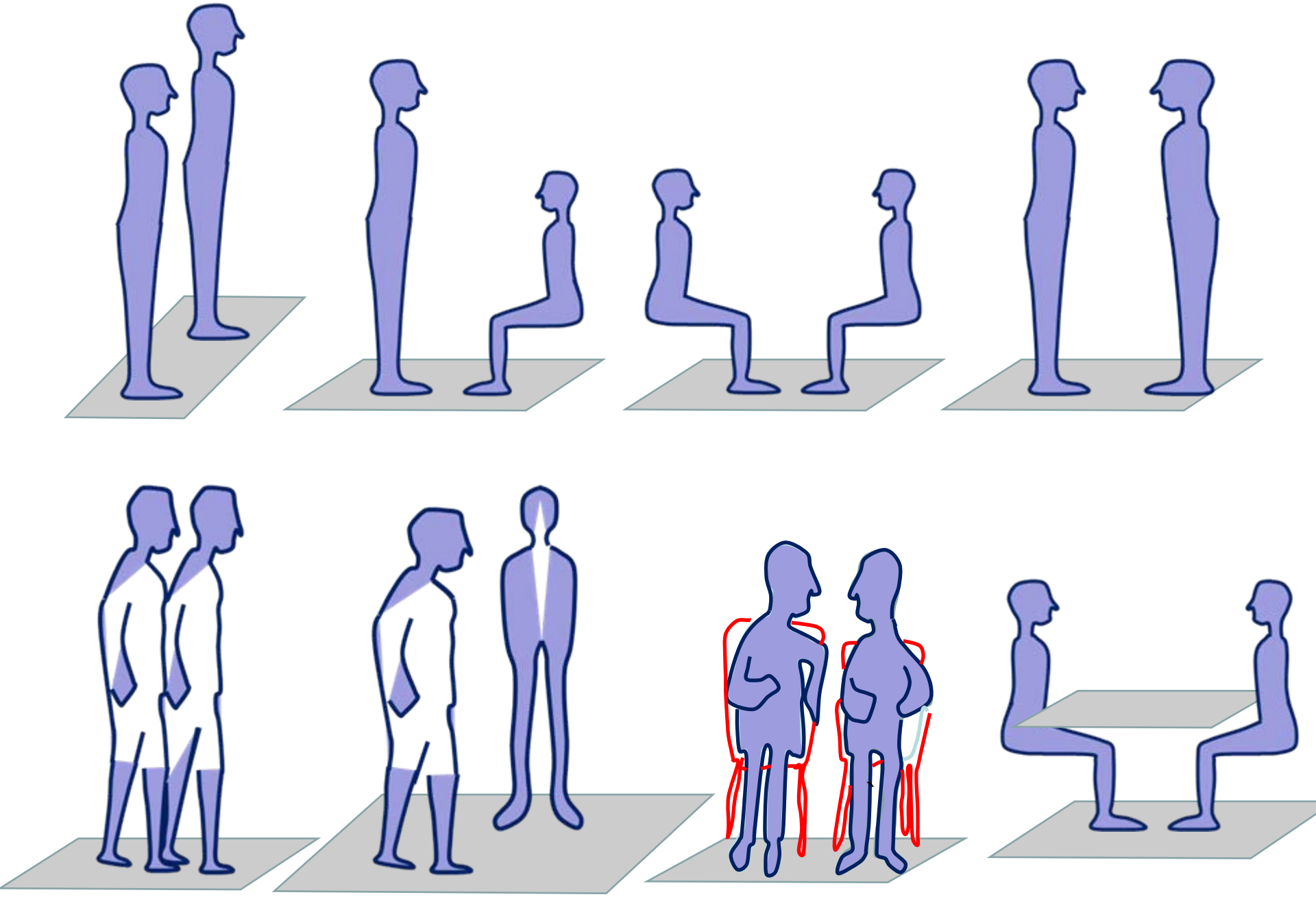
Sherertz et al Ann Intern Med. 1996; 124:539-47) showed cloud adults occur in certain nasal carriers of S. aureus - cloud adults.

Sherertz et al Ann Intern Med. 1996; 124:539-47)表明“雾人”也会携带金黄色葡萄球菌



Inhaled tracer gas concentration of the receiving manikin as a function of distance from the exhaled manikin受体人体模型吸入的示踪气体含量与两人体模型距离间的关系

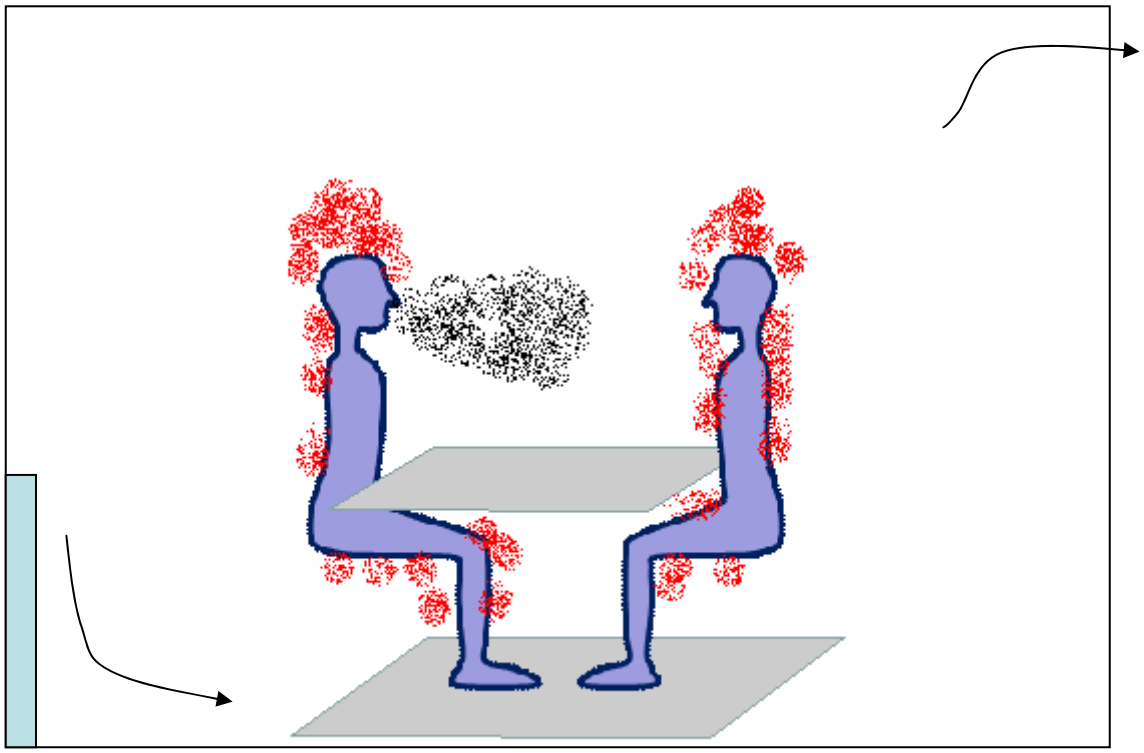
Compiled with data from Nielsen et al., ASHRAE Trans., vol. 114 (2), 2008
Liu et al, not published
根据Nielsen et al., ASHRAE Trans., vol. 114 (2), 2008中数据编辑
Liu et al, 未发表



Airborne transmission does not mean that everywhere in the room is infectiously risky.

空气传播并不意味着房间中任何一个地方都有被感染的风险

4



The body microenvironment and expiratory jet/puff interacts with the room air distribution system

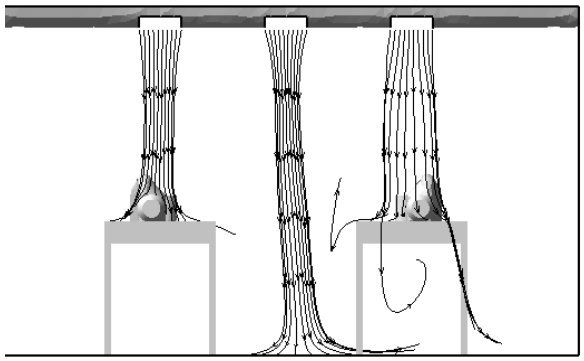
身体微环境和呼气射流在室内空气分配系统的影响下相互作用

Airflow pattern in the isolation room is not unidirectional, but mixed!

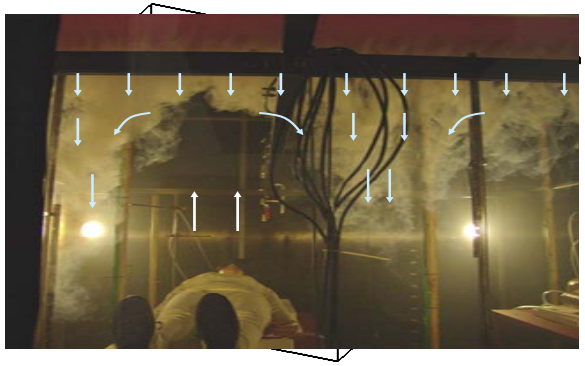
在隔离房中，气流组合并不是单向的，而是混合的。

(a)

(b)



(c)



(d)

(e)

(f)

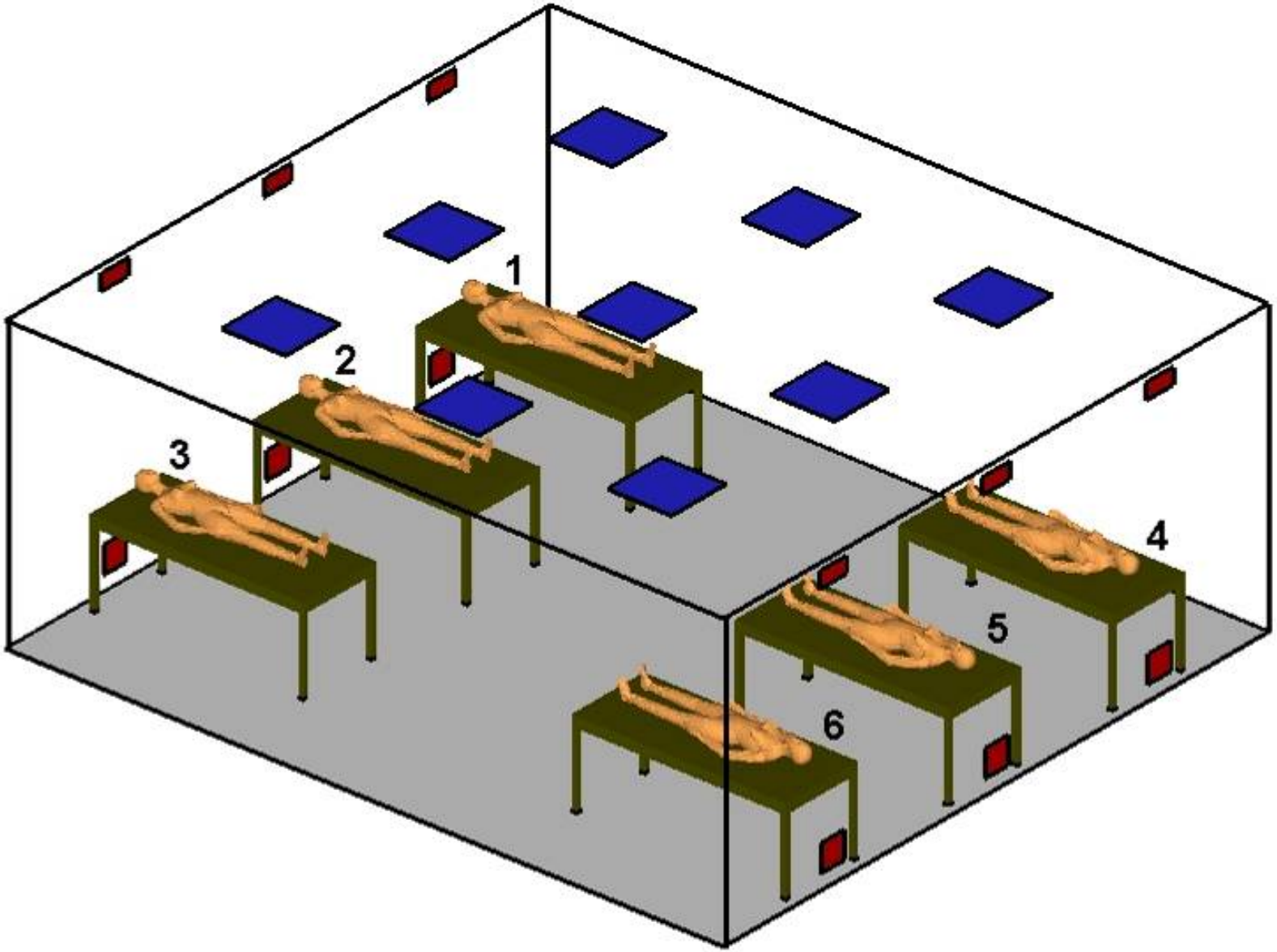
Qian et al., Building and Environment 2008;43:344-354

Ventilation control通风控制

- Control intake控制入口: Personalized ventilation for controlling body microenvironment 个人通风用来控制身体的微环境
- Control airflows控制气流: Overall air flow direction总气流方向
- Use “sufficient” ventilation rates to remove efficiently fine droplet nuclei, not large droplets用足够的通风量有效地带走小液滴核，而不是大飞沫！

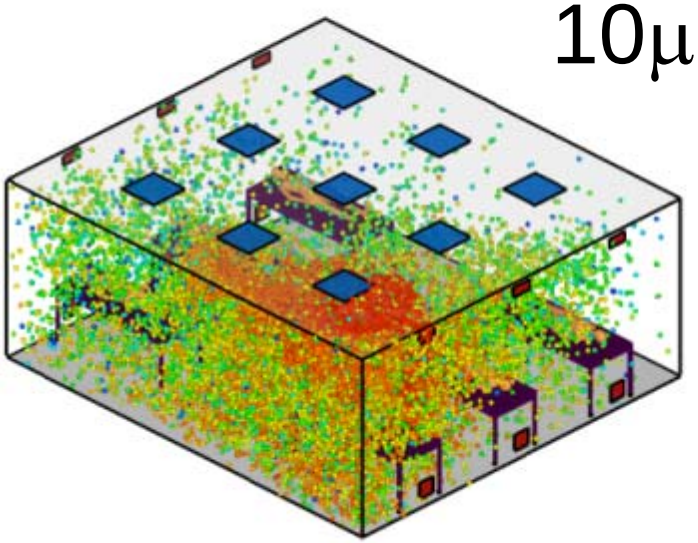
A typical CDC recommended design in a multi-bed ward – A full-scale test room at HKU

一个典型的美国国家疾病预防和控制中心推荐的多床位监护房－香港大学全尺寸测试舱



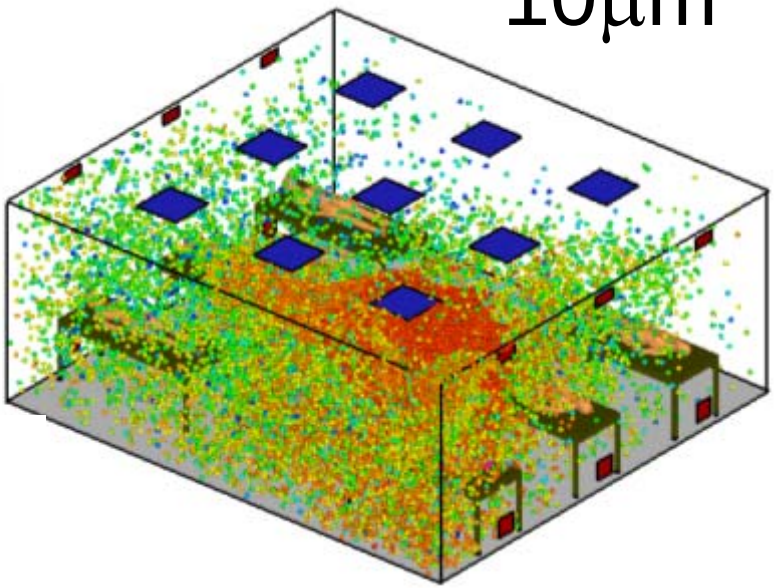
Particles
颗粒物

10μm

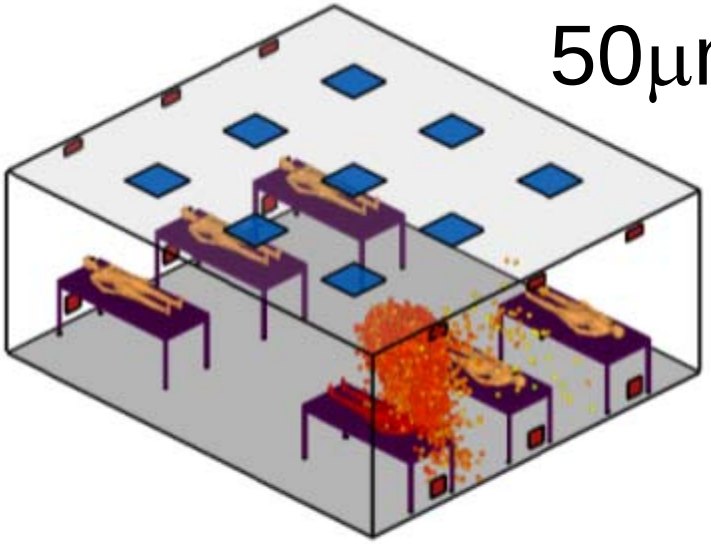


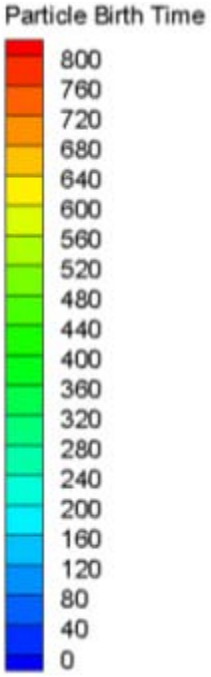
Droplets
飞沫

10μm

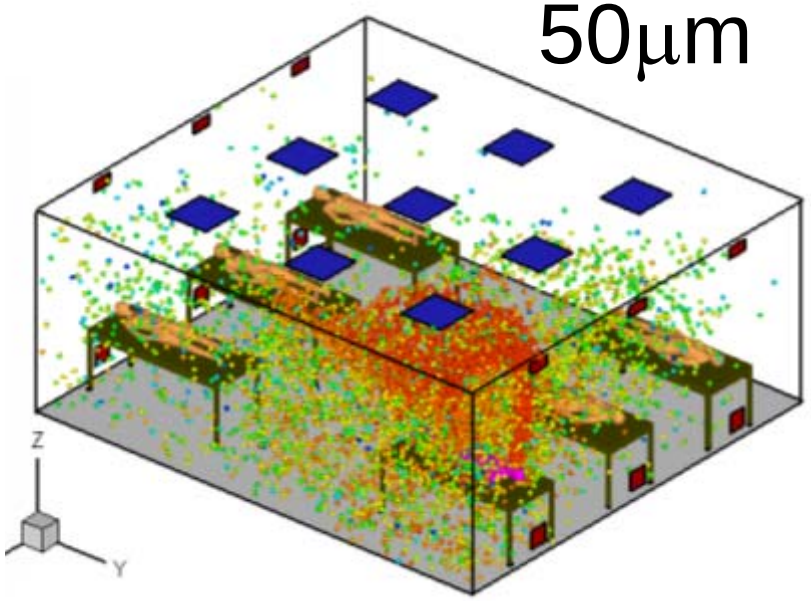


50μm



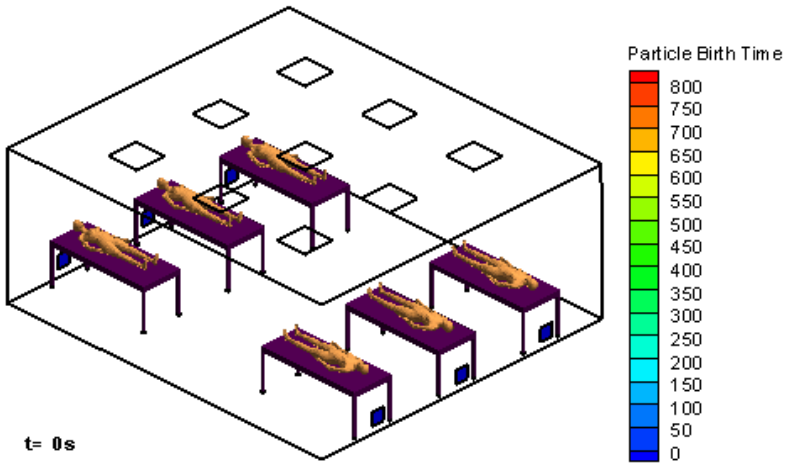


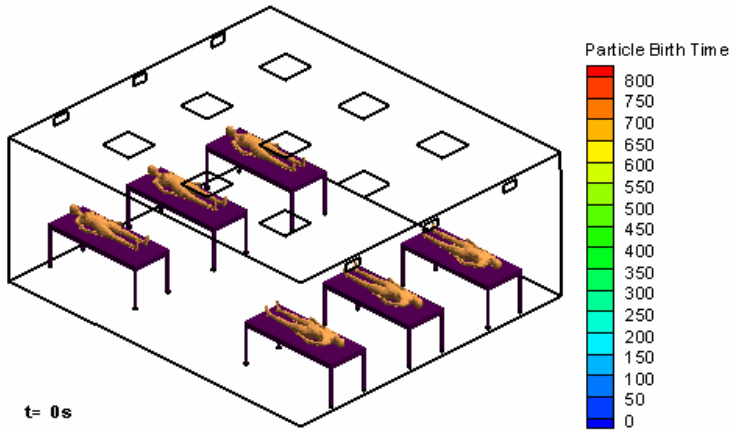
50μm



Qian Hua, PhD Thesis, 2007

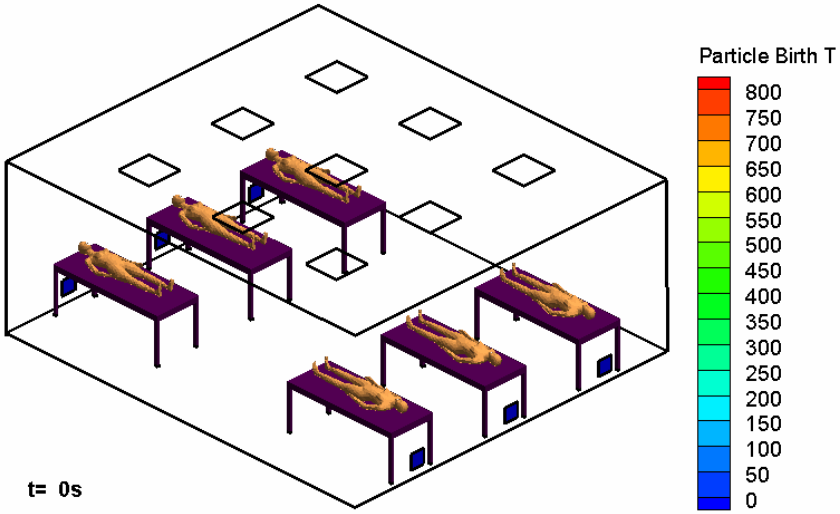
Xie Xiaojian, PhD Thesis, 2008

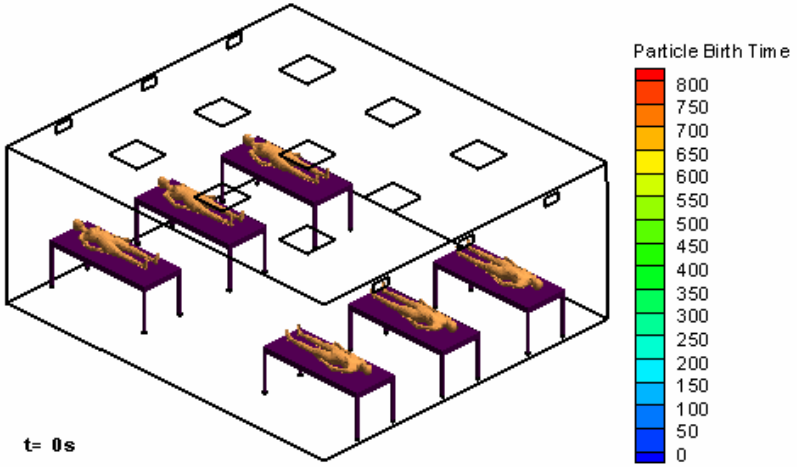




1 micron particles

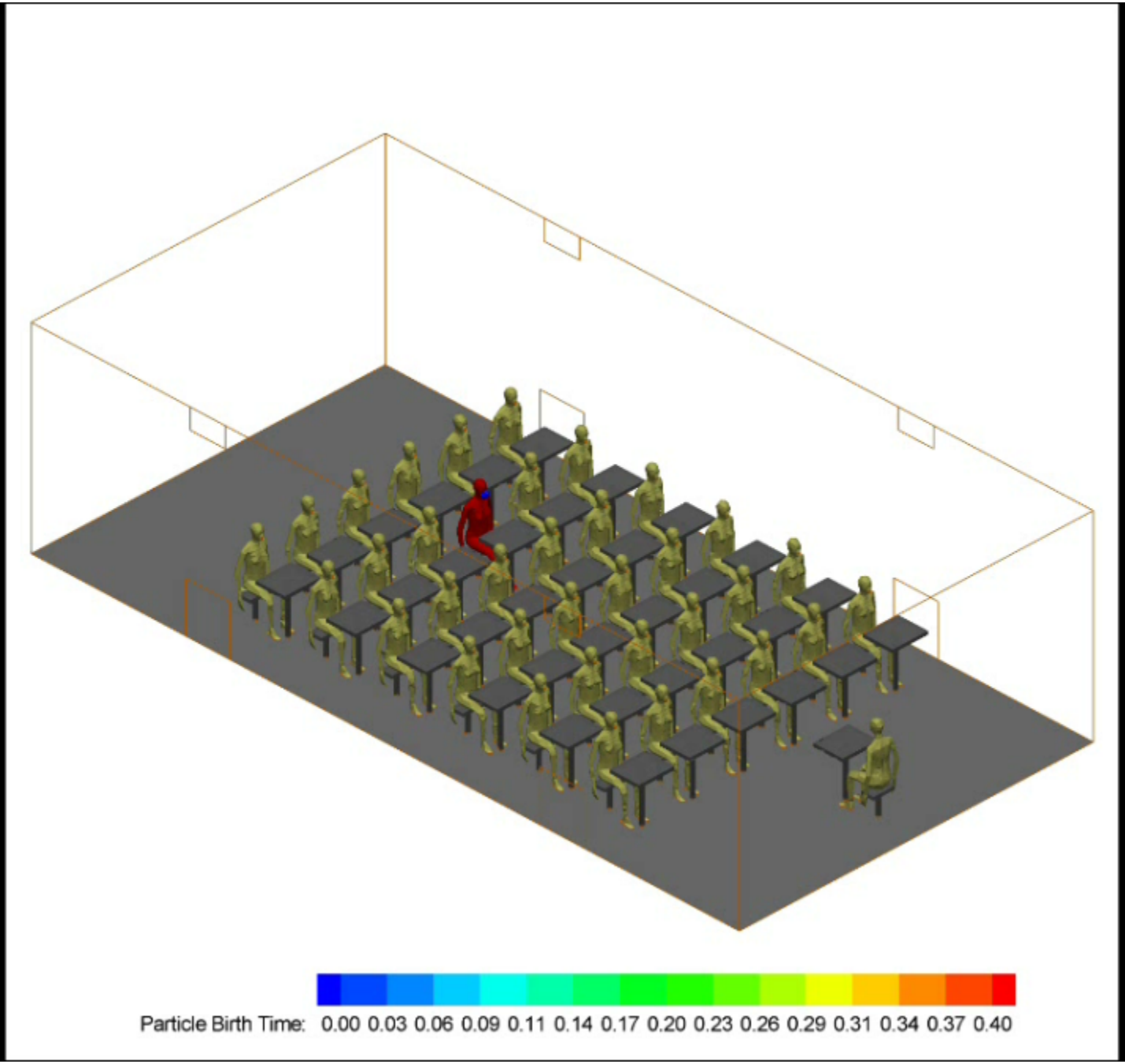
Video produced by Prof Qian Hua





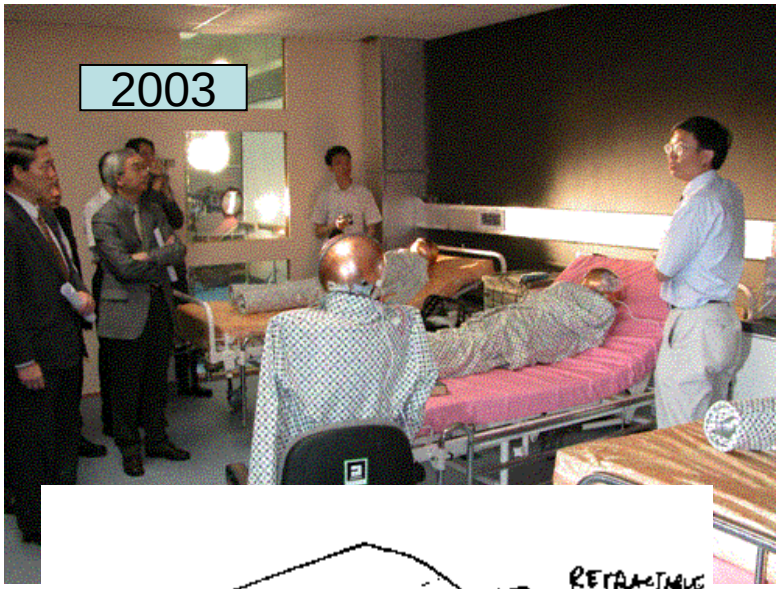
50 micron particles

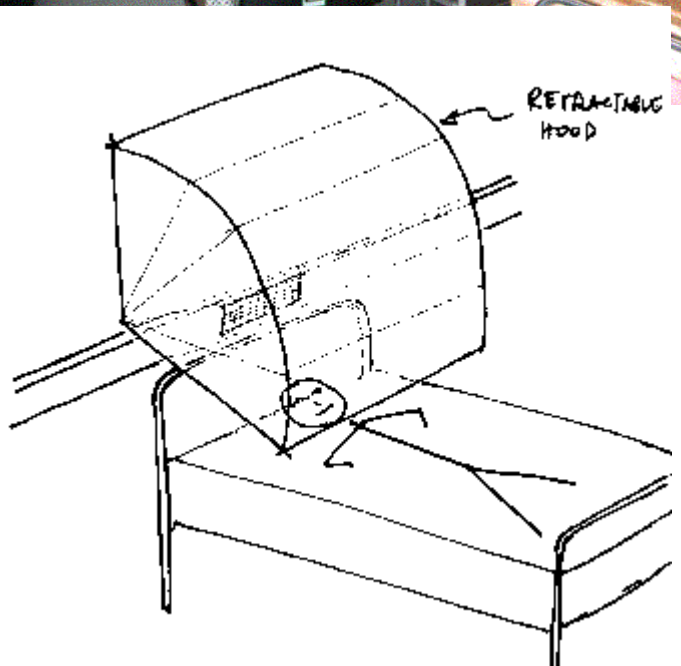
Video produced by Prof Qian Hua


Particle Birth Time: 0.00 0.03 0.06 0.09 0.11 0.14 0.17 0.20 0.23 0.26 0.29 0.31 0.34 0.37 0.40

Need to work with doctors and nurses

与医生和护士合作





Prototype in the test room

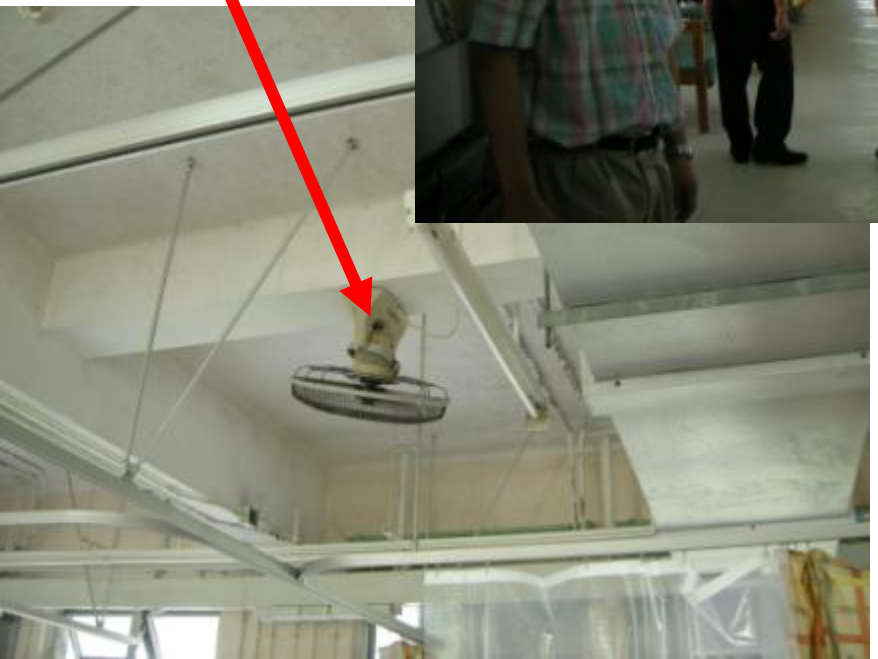
测试房间中的原型

Grantham Hospital -A TB hospital that has been naturally ventilated since 1950s

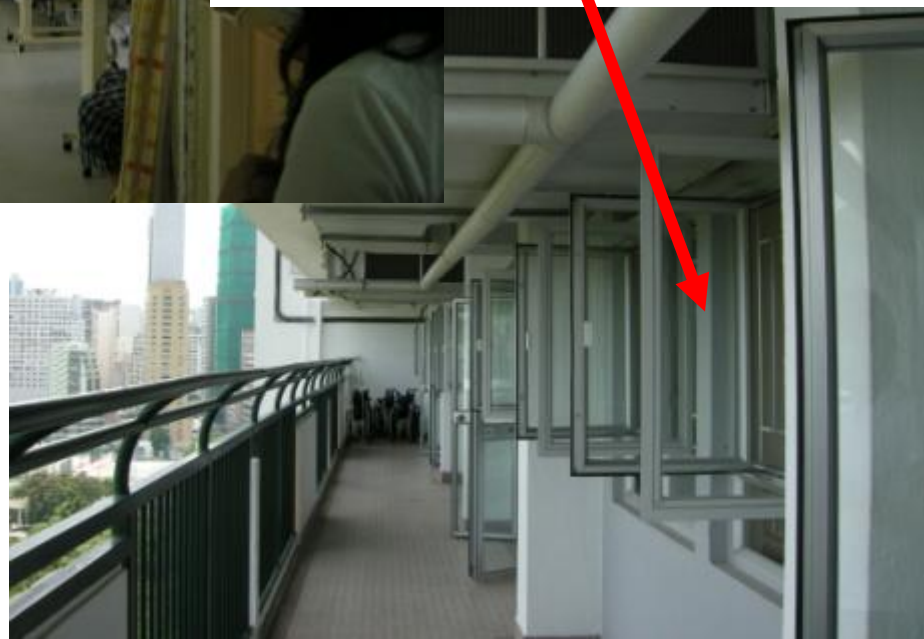
Grantham医院－20世纪50年代开始采用自然通风的一家治疗肺结核的医院

Spot cooling
局部冷却

Ceiling fans
吊顶电扇



Open windows for 24 hrs a day and 365 days a year
全年开窗



WHO publication/guidelines

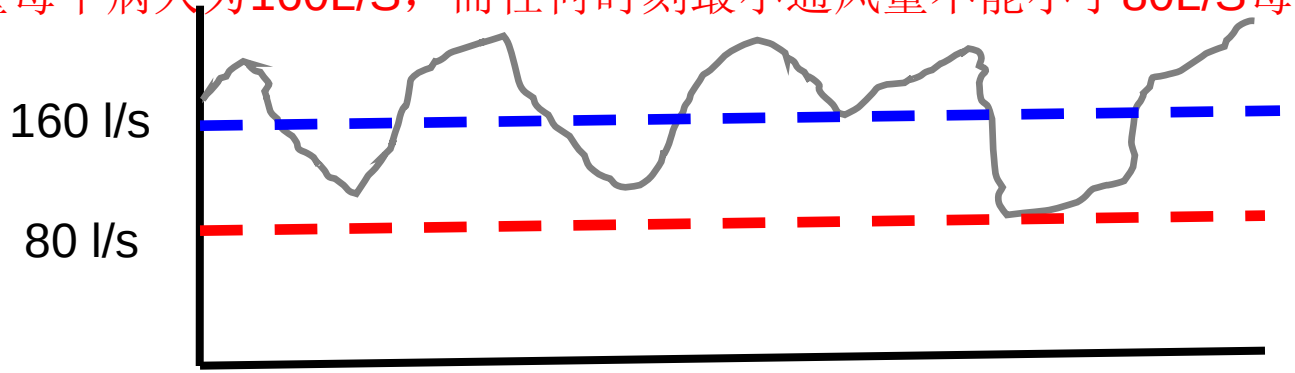
Natural ventilation for infection control in health care settings

Geneva Final 30/06/09

WHO 2009 NatVent Guideline – key ideas

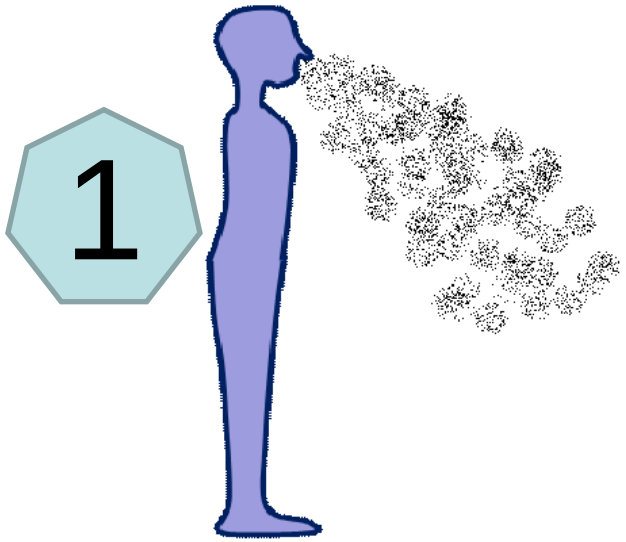
世界卫生组织2009年自然通风指引－关键思想

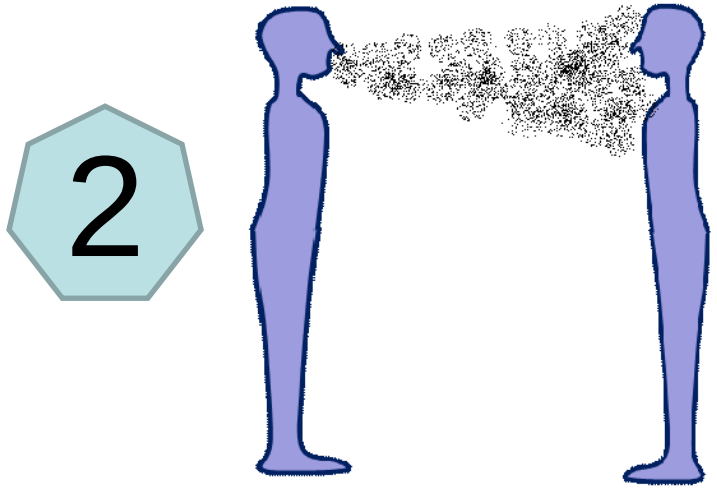
- **For natural ventilation, a minimum hourly averaged ventilation rate of 160 L/s/patient for airborne precaution rooms (with a minimum of 80 L/s/patient).**对于自然通风，为了预防空气传播传染病，平均每小时最小通风量每个病人为160L/S，而任何时刻最小通风量不能小于80L/S每个病人。

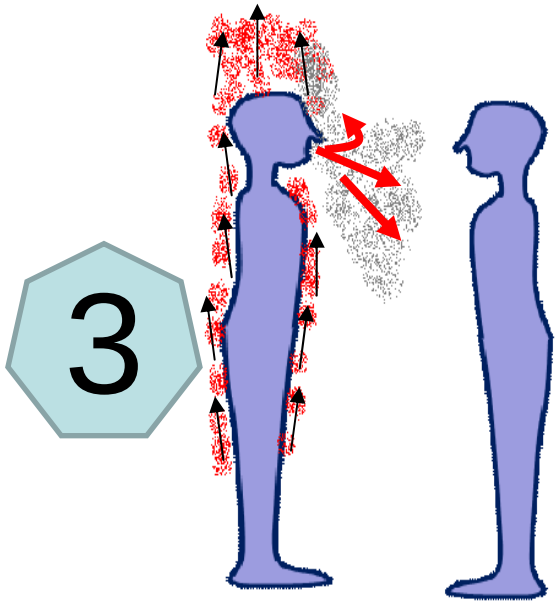


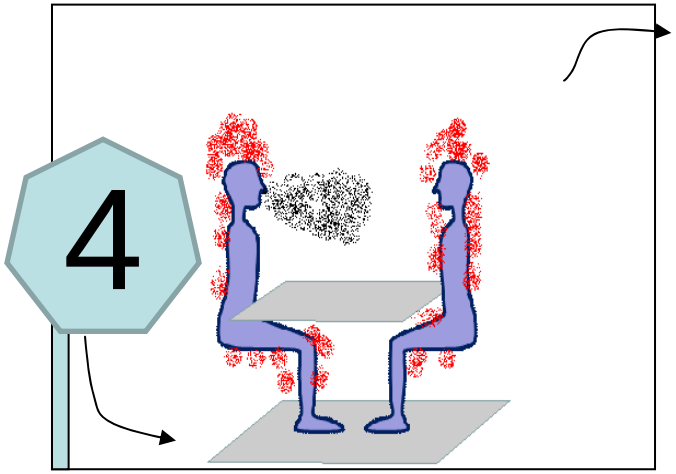
- When natural ventilation alone cannot satisfy the requirements, mechanically assisted natural ventilation system should be used.当自然通风无法满足要求时，需要额外使用机械通风来辅助自然通风
- **Overall airflow should bring the air from the agent sources to areas where there is sufficient dilution, and preferably to the outdoors.**

  气流应该可以将空气从感染源带到可以将其充分稀释的地方，最好是室外


1


2


3


4

Are there any evidences on associating between ventilation and airborne infection有没有证据揭示通风和空气传播传染病之间的关系?

?

Two systematic studies两个系统文献综述研究

IndiVent - Li et al. Indoor Air 2007 of 43 relevant studies

WHOVent - Li et al. WHO 2008 of 53 studies

Who is he? 他是谁？

5 minutes later
5分钟之后…

We cannot even get consensus in photo taking

Even more difficult in the WHO meeting, but enjoying 在**WHO**会议上甚至更加困难，但是享受这过程

Ventilation rate and infection

通风量和感染

- 8 good quality studies on ventilation rate.

  8项关于通风量的很好的研究

- The diseases were TB (2 studies), pneumococcal disease (1) , SARS (1), influenza (1), influenza for mice or ferrets (2); and febrile acute respiratory disease (1).

  肺结核病（2），肺炎球菌疾病（1），SARS（1），流感（1），鼠和鼬的流感（2），急性发热性呼吸系疾病（1）

- Lack of ventilation or low ventilation rates are shown to be associated with an increase of infection rates or disease outbreak for airborne transmission.

  研究表明缺少通风和通风量小与空气传播传染病的爆发有关系

- High ventilation rates could lead to decrease of infection rates.

  大的通风量会降低感染的风险

- But the minimum ventilation flow rate is unknown.

  但是控制疾病传播需要的最小通风量仍然未知

Airflow direction and infection

气流方向和感染

- 12 studies provide good quality of evidence on the association for an association of airflow direction with spread of certain infectious diseases.

  12项研究为揭示气流方向和特定疾病的传播之间的关系，提供了很好的证据

- The diseases are TB (3 studies), TB for guinea pigs (2), measles (1) , smallpox (1), chickenpox (2), SARS (2) , and coxsackievirus (1), **influenza** for guinea pigs (1) and ferrets (1))

  这些疾病是，肺结核（3），豚鼠肺结核（2）， 麻疹（1）， 天花（1），水痘（1），SARS（2），柯萨基病毒（1）以及豚鼠和鼬的流感（2）

- The airflow can “transport” infection.

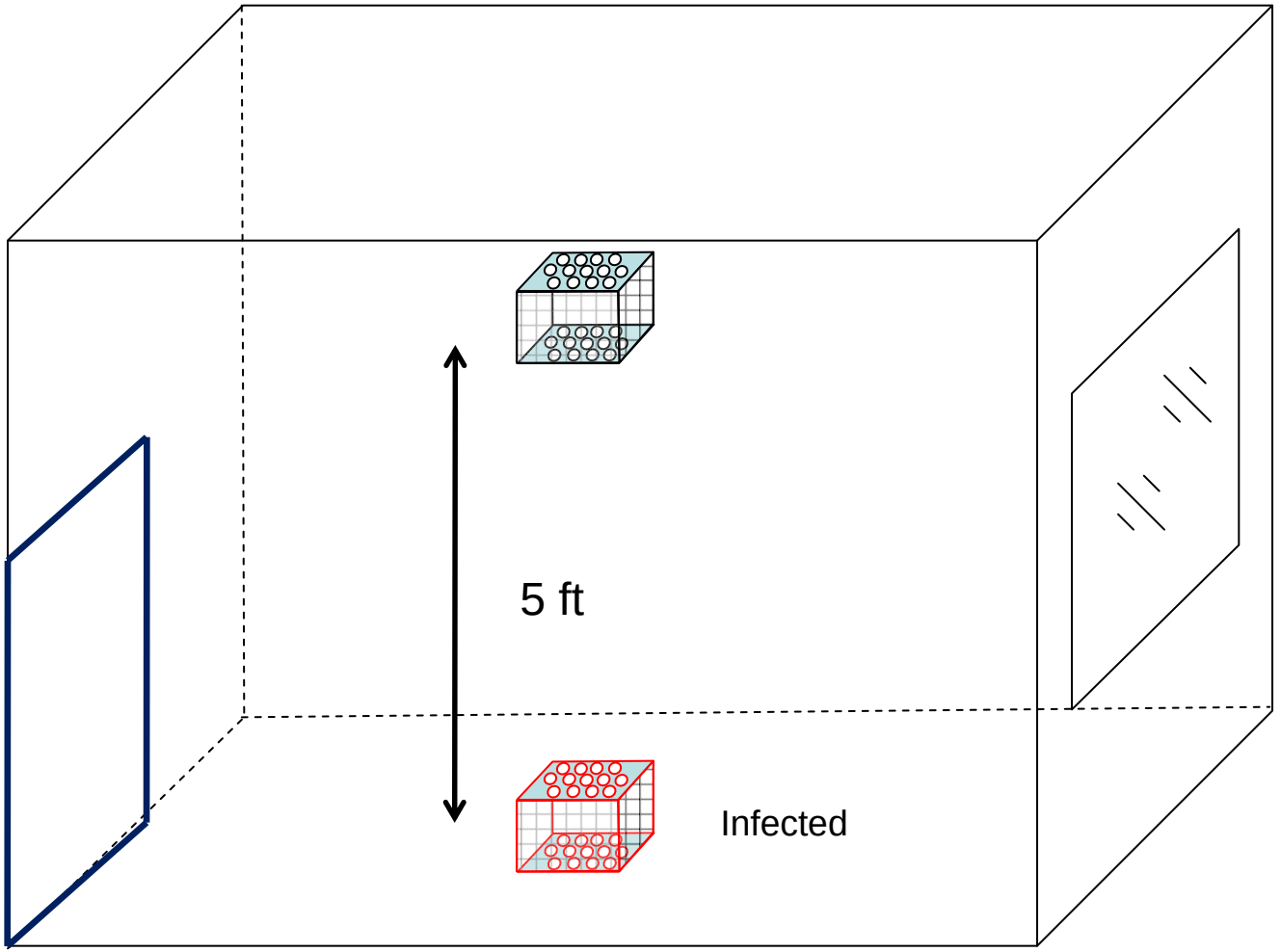
  气流可以“运输”感染风险

- The rate of infection (attack) was often found to reduce as the distance from the source increases.

  与感染源的距离越大，感染率越低

Example 1 - An old study一个很久以前的实验

11 experiments – 2 infected and 2 susceptible ferrets each, **13 transmission**
11组实验，每组分别有**2**只已感染的**2**只易受感染的鼬，共有**13**只被感染

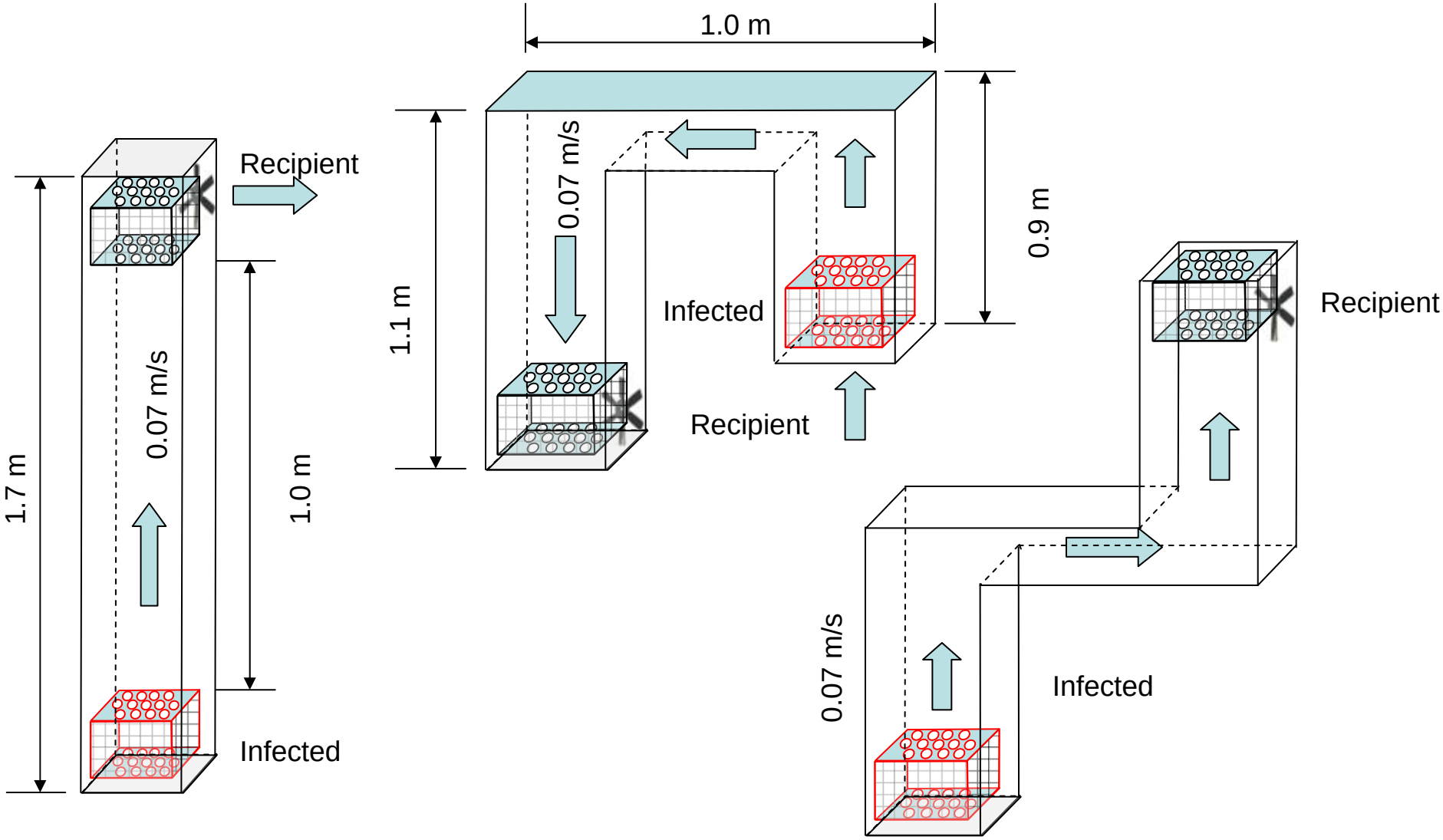


Ventilation rate of the room not provided, affected by wind室内通风量没有给出，受风的影响

Drawn based on Andrews and Glover, Bri J Exp Pathology,1941

3 experiments – 2 infected and 2 susceptible each, **4 transmission**

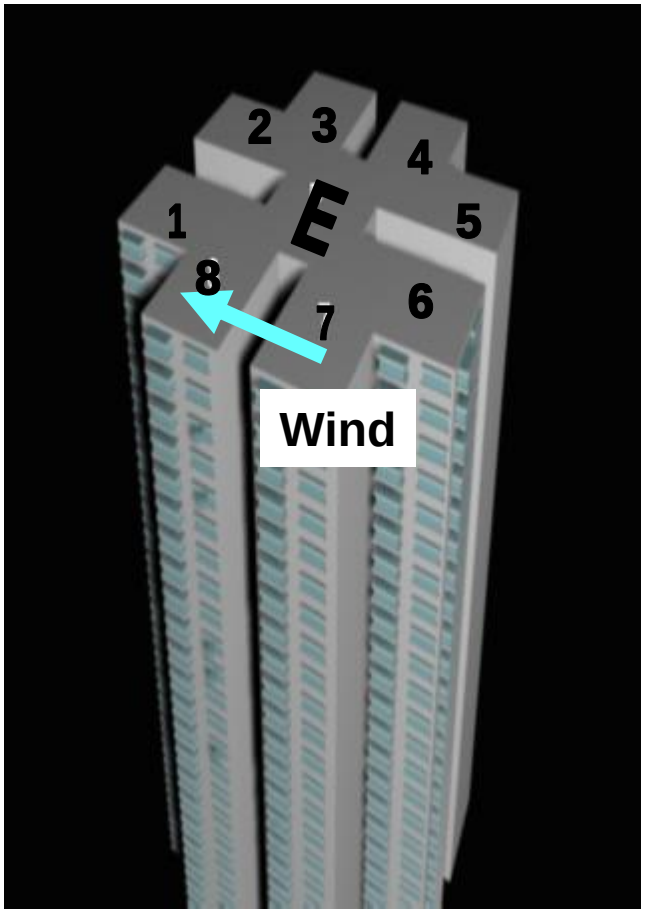
3组实验，11组实验，每组分别有2只已感染的2只易受感染的鼬，共有4只被感染

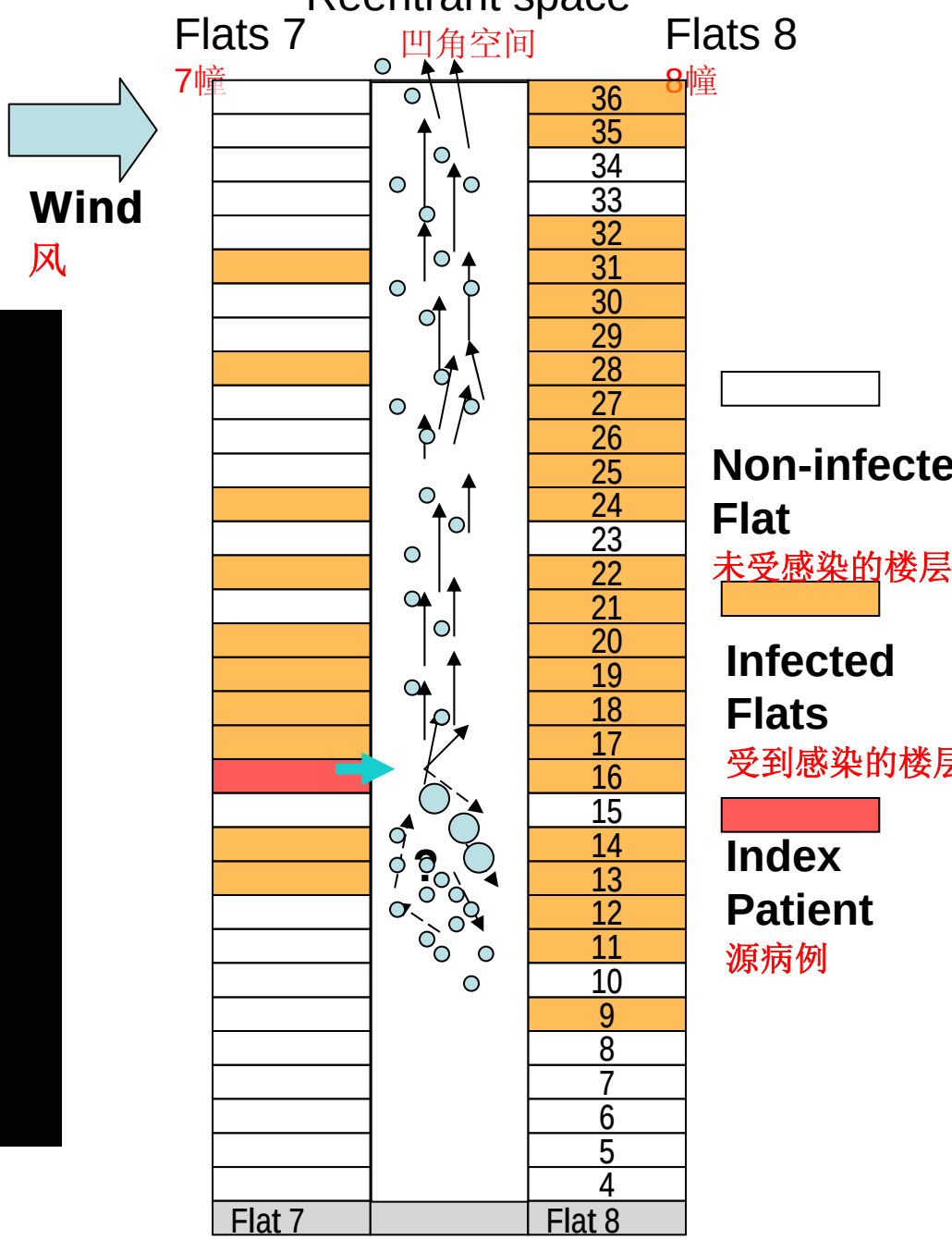


Modified from Andrews and Glover, Bri J Exp Pathology,1941

Example 2: The Amoy Gardens SARS outbreak

例二：淘大花园SARS爆发

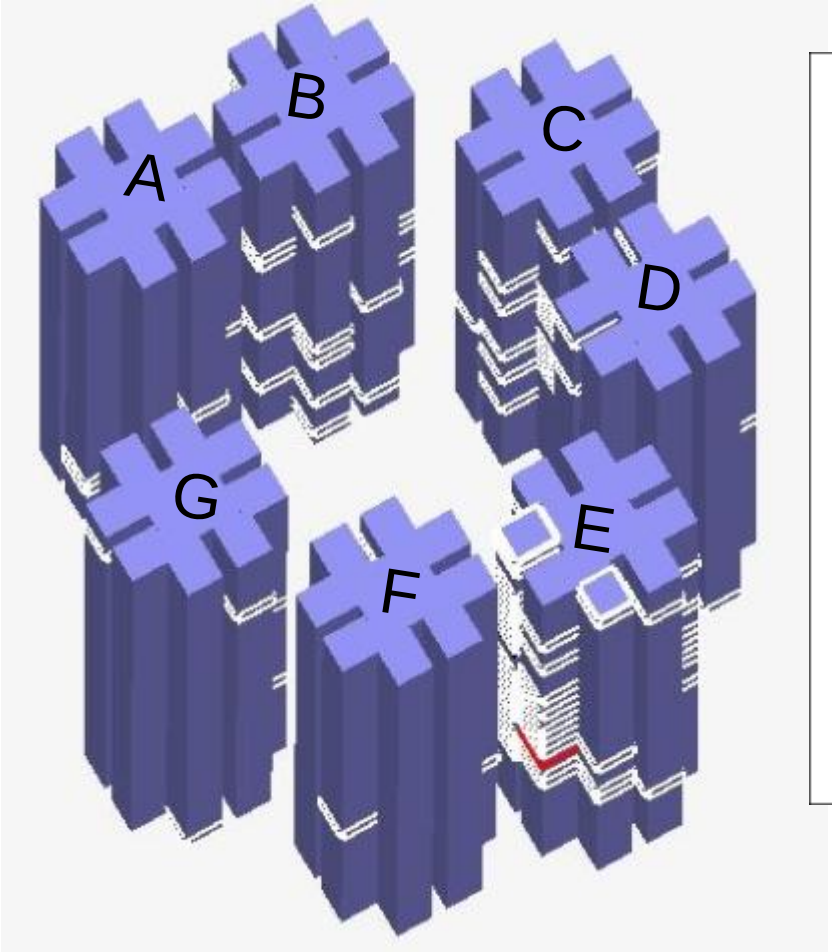


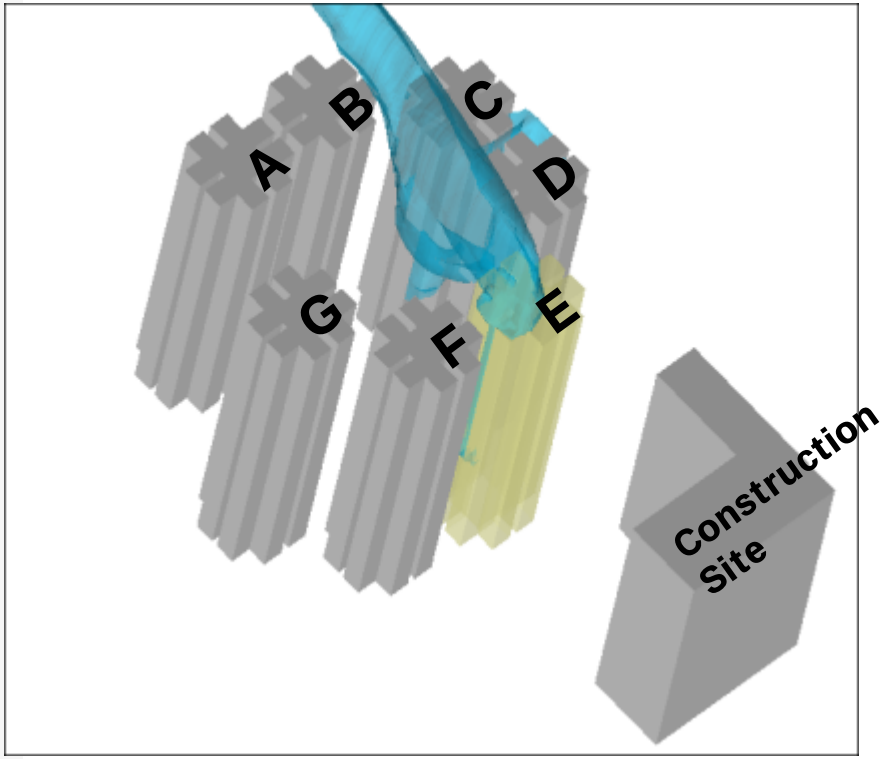


Li et al, Indoor Air 2005;15:96-111

Spread from Block E to other blocks in the Amoy Gardens Outbreak

淘大花园SARS爆发过程，从E楼传播到其他大楼





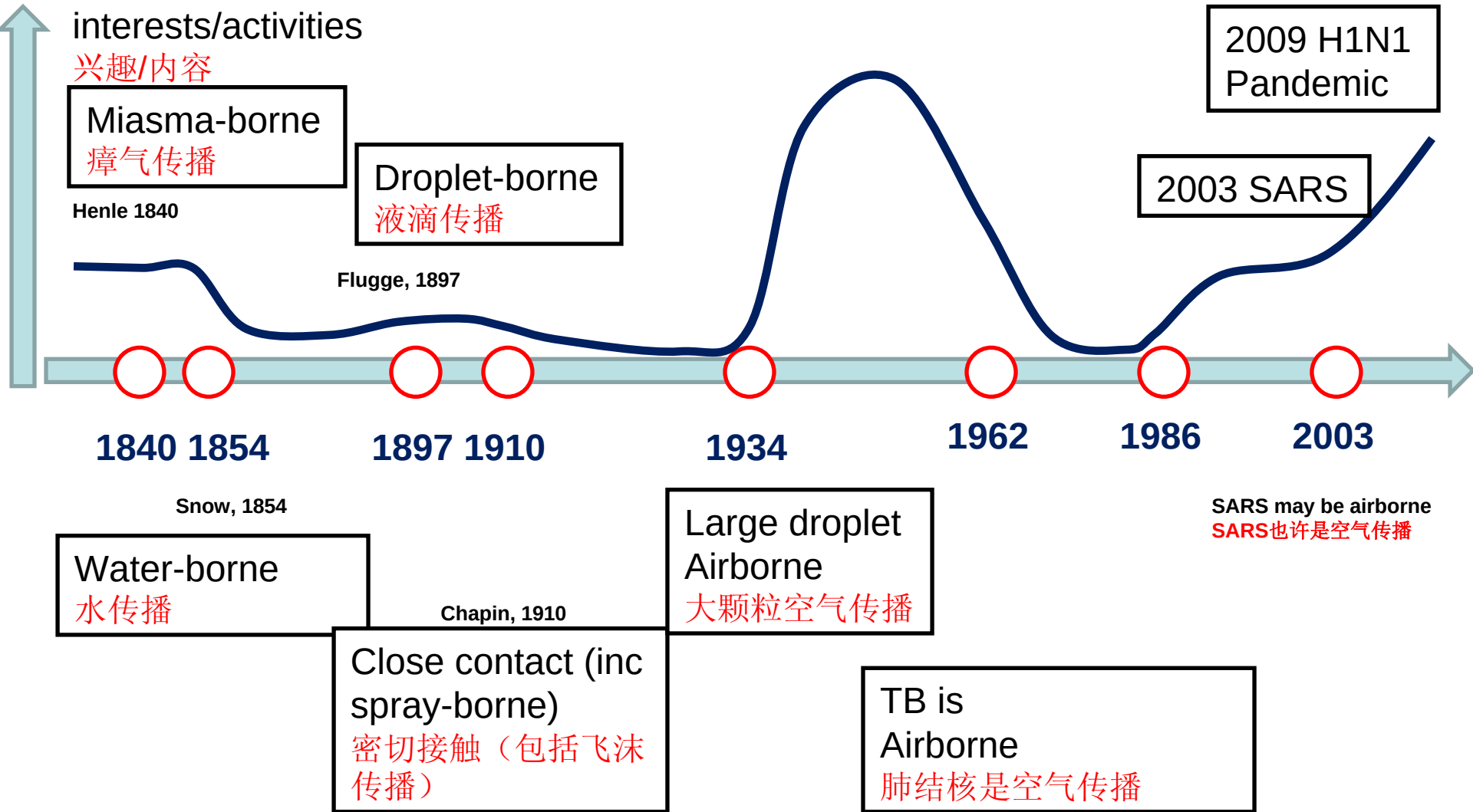
Li et al. Pop Dyn and Infect Dis in Asia 2006:305-327 (left)
Yu et al. NEJM 2004;350:1731-39 (right)

Ventilation and airborne infection通风和空气传播传染病

- We know我们知道:
  - Ventilation matters for “long range” airborne infection for some diseases通风与某些传染病的长距离空气传播有关系。
  - Ventilation may become an effective public health intervention method通风也许会成为有效的维护公共健康的方法.
  - There is a need for multi-disciplinary approach需要多学科之间的探讨
- We do not know我们不知道:
  - The minimum ventilation flow rate for infection control控制传染的最小通风量.
  - Relative importance of transmission routes不同传播途经的相对重要性
  - Effective control methods for short-range airborne route对短距离空气传播的有效控制手段
  - Multi-disciplinary effort is difficult多学科合作是困难的

Change of research interests/activities since 1840

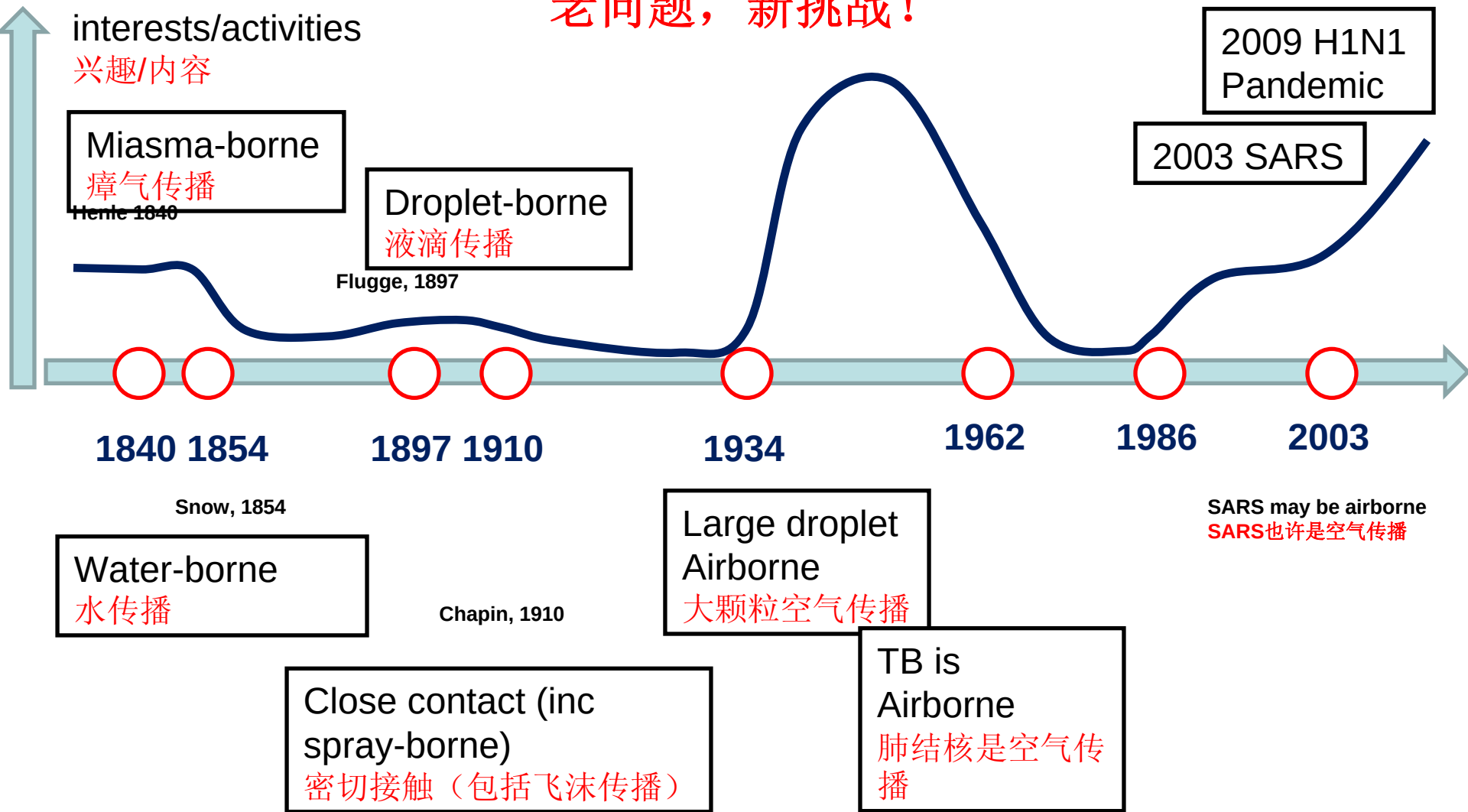
自1840年以来研究兴趣/内容的改变



Change of research interests/activities since 1840自1840年以来研究兴趣/内容的改变

Old problem, new challenge!

老问题，新挑战！



Thanks to my collaborators and students, and to Technical University of Denmark for my two months visit this summer where this talk was prepared. 感谢我的合作者以及我的学生们，同时也要感谢丹麦技术大学，我利用2009夏天访问丹麦技术大学的两个月时间，准备了这个演讲。