The impact of psychrometrics on the aerosol transmission of the SARS-CoV-2 virus in buildings

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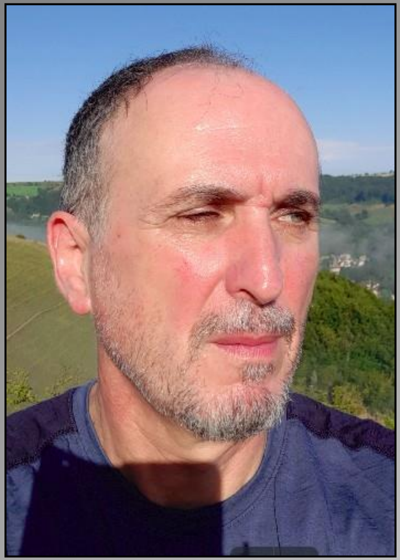
Collaboration



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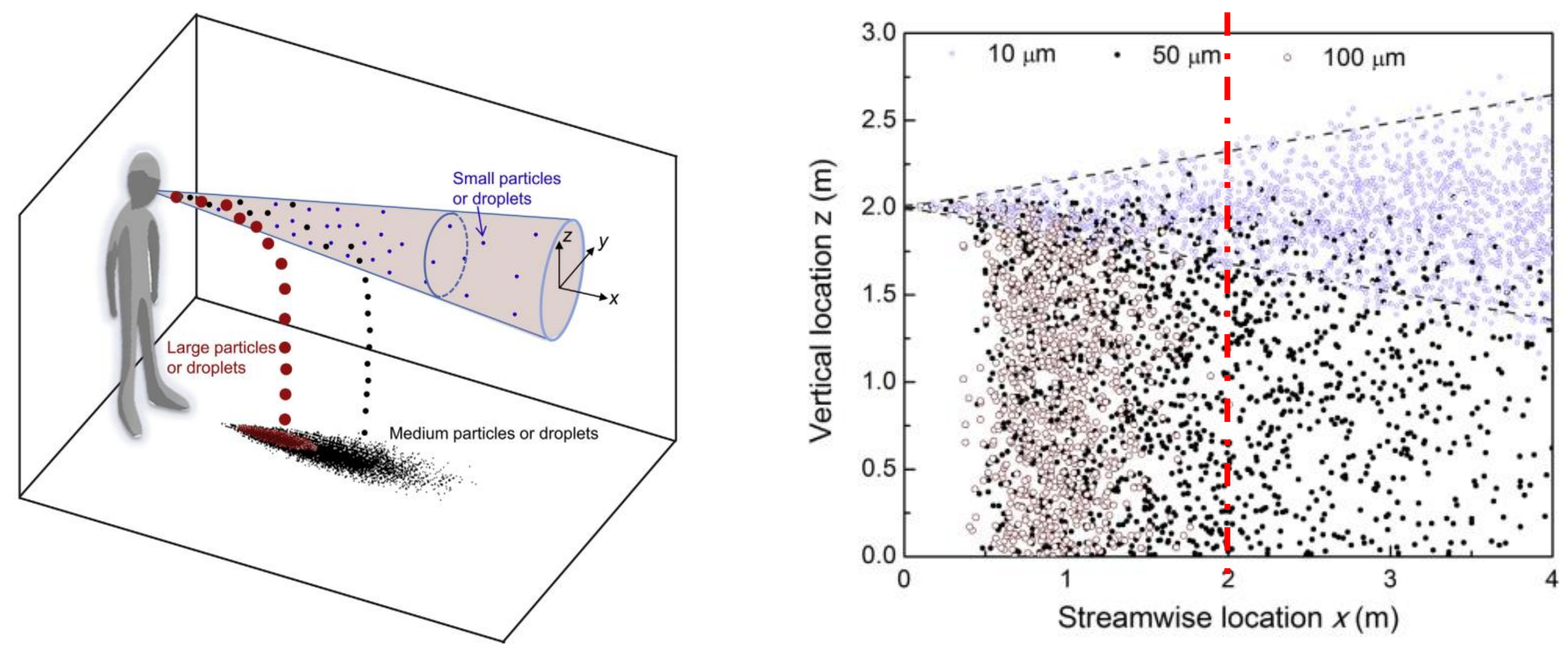
Respiratory Droplets & Aerosols

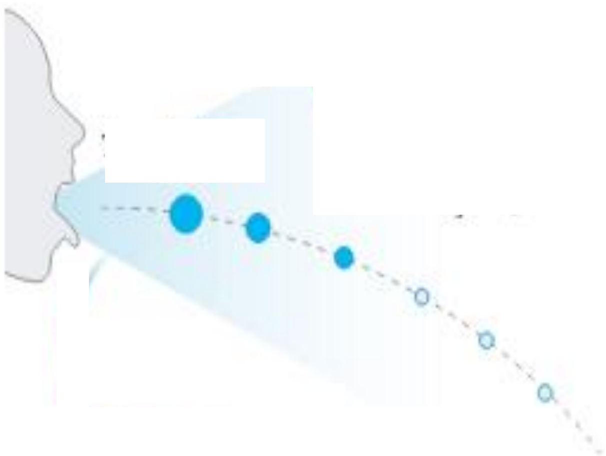


Respiratory droplet distribution

- Large respiratory droplets (>100 µm) behave ballistically and fall to the ground within <2 m [1].
- Respiratory droplets <100 µm diameter rapidly evaporate to become aerosols which can travel much further.
- During speaking and coughing =>85% of the droplets produced are <100 µm [2].

1. Wei J, et al. Building and Environment 93 (2015) 86-96; 2. Beggs CB. Is there an airborne component to the transmission of COVID-19?: a quantitative analysis study. medRxiv. 2020.

Evolution of Droplets <100 μm

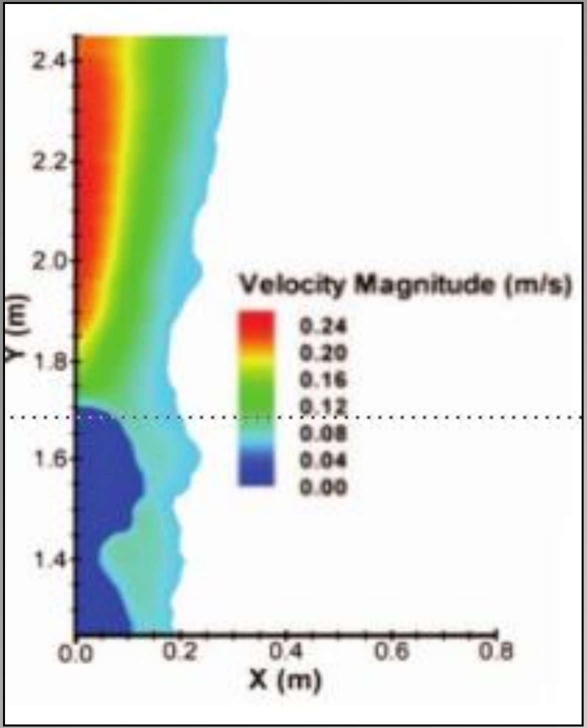


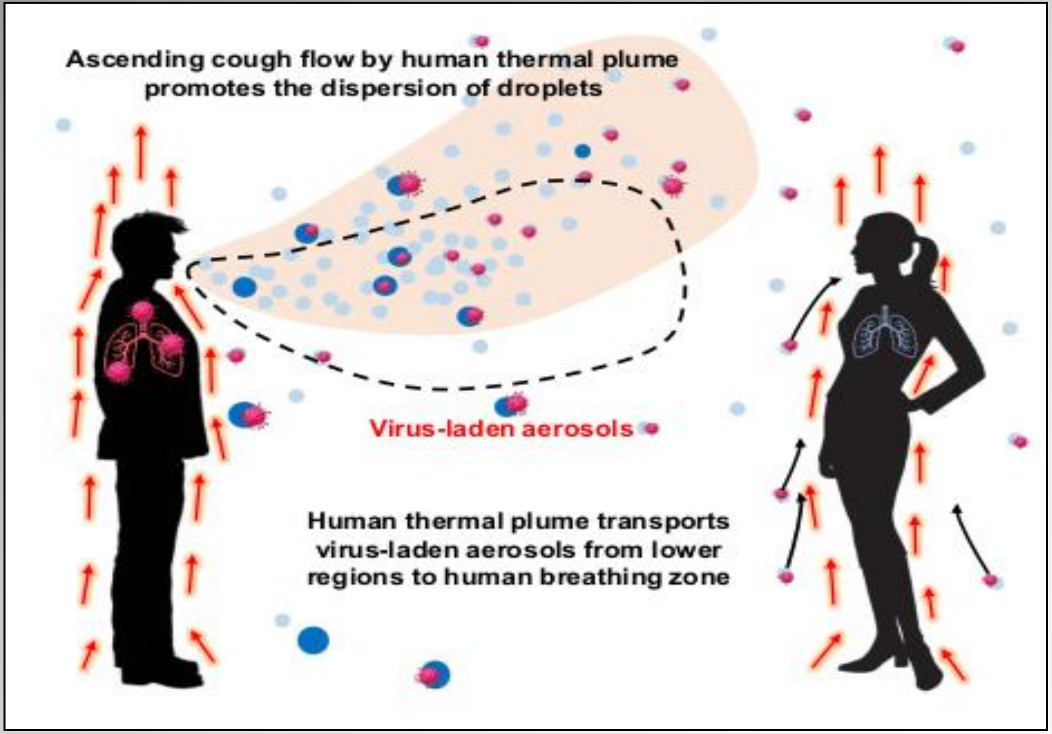
Source: https://doi.org/10.1101/2020.07.23.20160648

1. Nicas M, et al. Toward understanding the risk of secondary airborne infection: emission of respirable pathogens. *J Occup Environ Hyg*. 2005;2(3):143-54.
2. Marr LC, et al. Mechanistic insights into the effect of humidity on airborne influenza virus survival, transmission and incidence. *Journal of the Royal Society Interface.* 2019. 16.

- Respiratory droplets <100 μm in diameter rapidly evaporate to form smaller aerosol particles [1].
- Their final droplet size, depends on the concentration of proteins in the droplet and the room air conditions.
- Nicas et al. estimated the final droplet diameter to be about 50% of the exhaled droplet diameter [1].
- Marr et al. estimated final droplet diameter to be between 20-40% of the initial value [2].
- With COVID-19 the eventual size is likely to be <50 μm in diameter.
- Aerosol particles 50 μm in diameter have a settling velocity of 0.08 m/s.

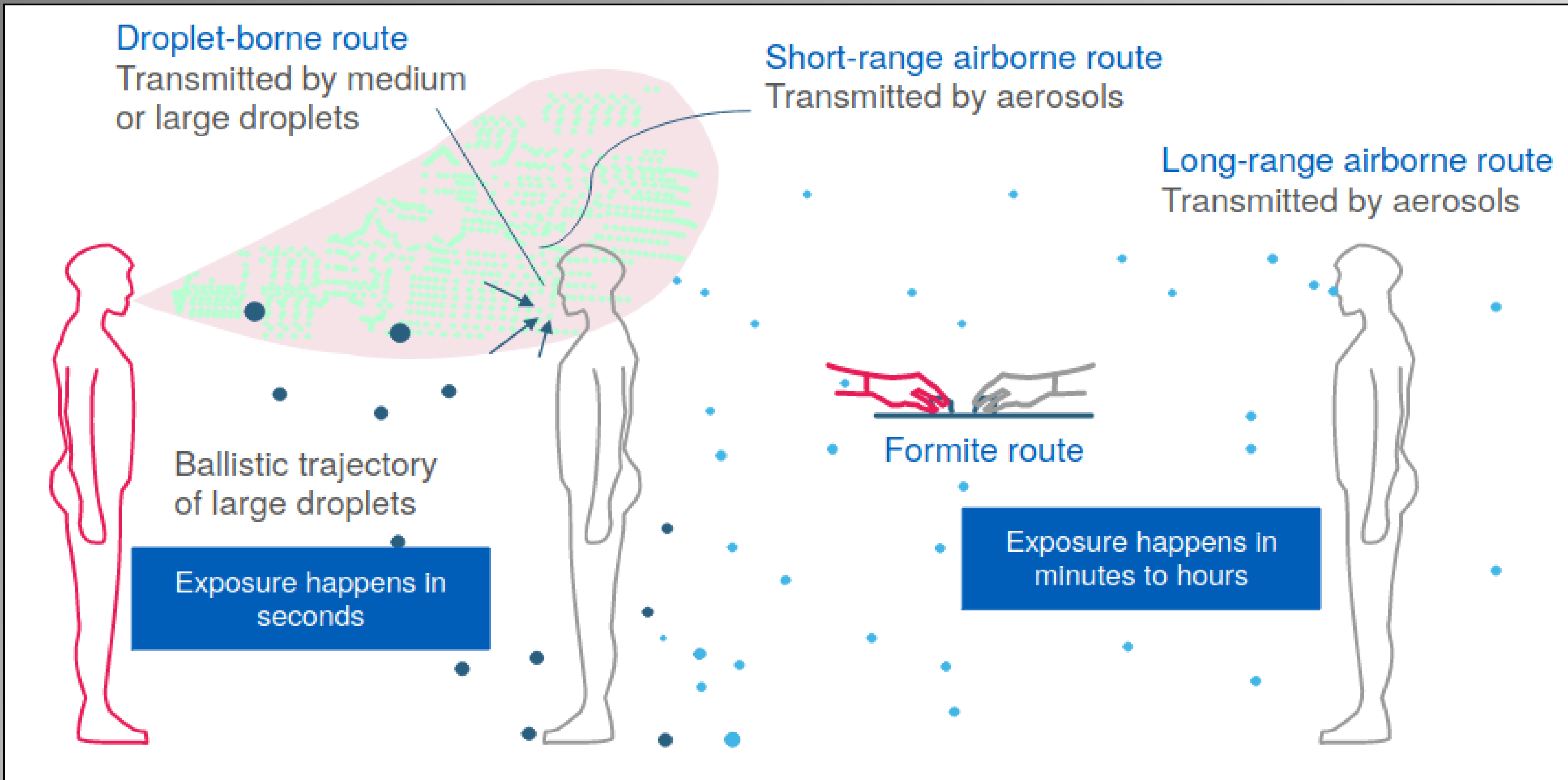
Respiratory Aerosols & Thermal Plumes





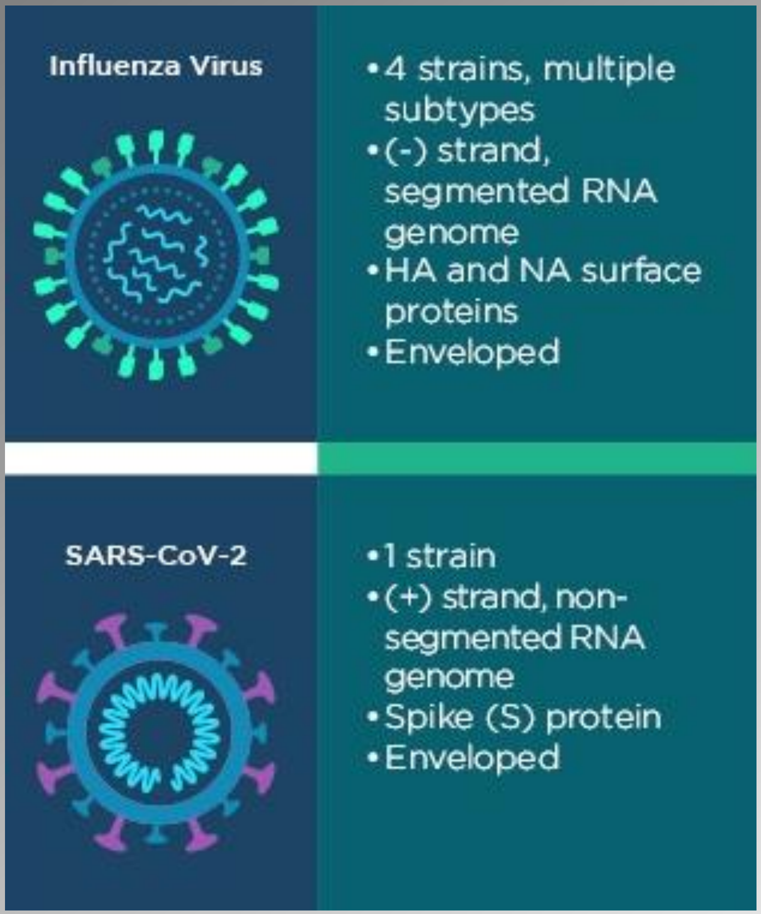
- Aerosol particles <50 µm in diameter have settling velocities <0.08 m/s and thus can easily be transported upwards by the thermal plumes of room occupants.
- Respiratory aerosol particles <50 µm (<100 µm at source) are readily transported by the thermal plumes and can be widely distributed around room spaces.
- Aerosol particles <50 µm diameter can take several (0.5-11) minutes to settle of the air, with many particles <10 µm becoming truly airborne.

Droplet & Aerosol Transmission of SARS-CoV-2 Virus



- Short-range transmission involves large ballistic droplets (travel <2 m) and ‘clouds’ of aerosols - occurs within seconds
- Long-range transmission involves ‘airborne’ aerosols (<100 µm at source) – occurs over minutes and hours

Influenza A & SARS-CoV-2 Viruses



Source: American Society for Microbiology

Influenza A virus

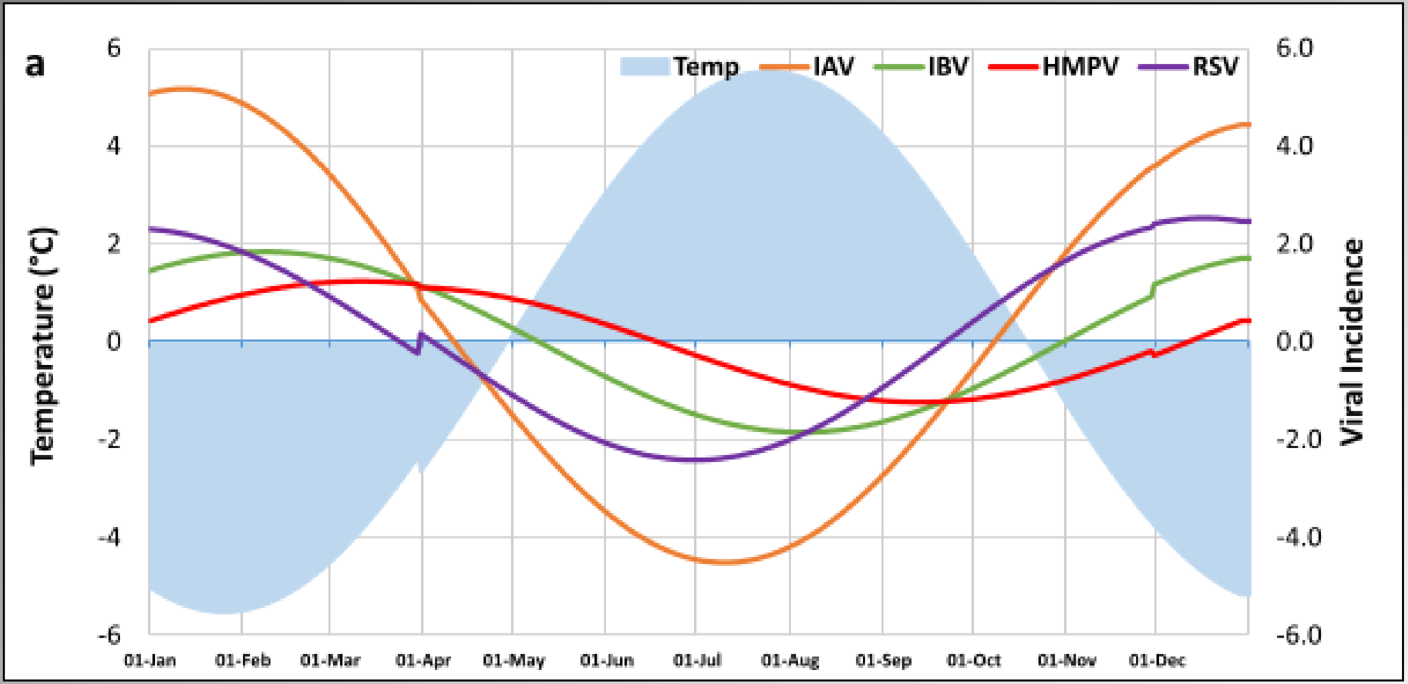
- Enveloped RNA virus
- Genome about 13.6 kilo-bases long
- Haemagglutinin (HA) & neuraminidase (NA) surface proteins
- Host cell receptor is sialic acid

SARS-CoV-2 virus

- Enveloped RNA virus
- Genome about 29.9 kilo-bases long
- Spike (S) surface proteins
- Host cell receptor is ACE2

NB. Both viruses share similarities in transmission behaviour. Both are transmitted via droplets and aerosols.

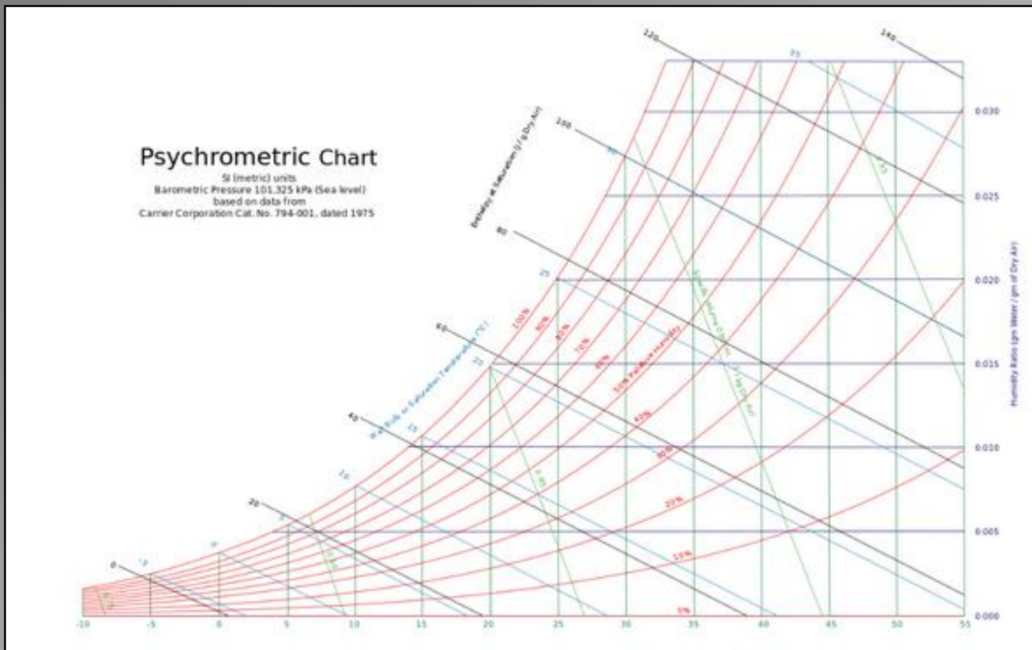
Seasonality: Enveloped Viruses



- Study undertaken in Edinburgh, Scotland [1].
- Enveloped viruses peaked in the winter: respiratory syncytial virus (RSV) – 17th December; influenza A (IAV) – 12th January; influenza B (IBV) – 8th February; human metapneumovirus (HMPV) – 11th March.
- RSV, IAV, IBV and HMPV are all enveloped negative-sense single-stranded RNA viruses.
- The SARS-CoV-2 virus also appears to exhibit seasonality.

1. Price, R.H.M., et al. Association between viral seasonality and meteorological factors. *Sci Rep* **9,** 929 (2019).

Psychrometrics



Relative humidity

$$RH = \frac{p_v}{p_s}$$

Moisture content

$$g = \frac{0.622 p_v}{p_b - p_s}$$

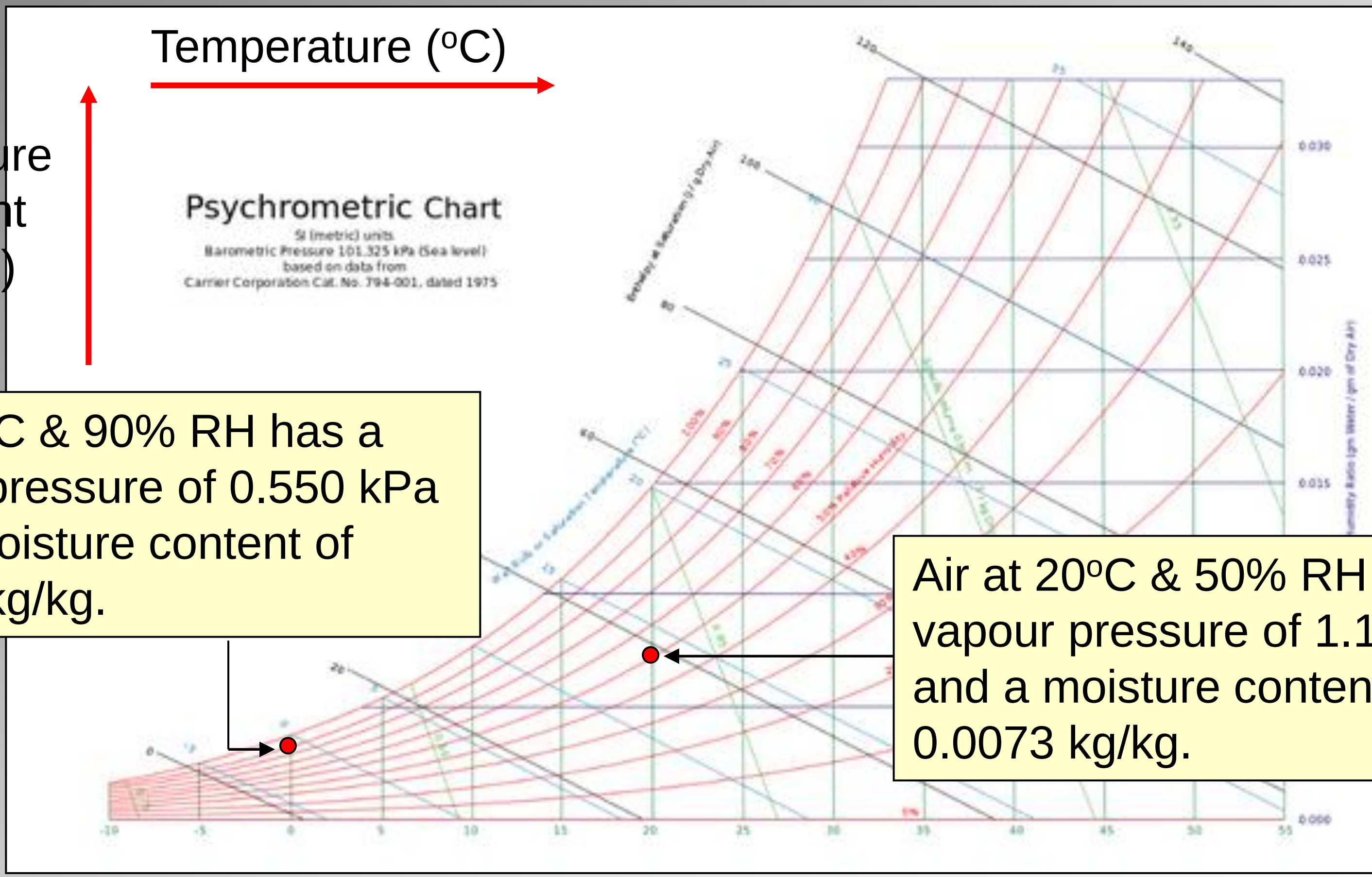
- RH is not an absolute value but rather a ratio of vapour pressures and therefore a function of air temperature.
- Therefore, it is incorrect to perform statistical analysis using RH as an independent variable.

- p_v is vapour pressure (kPa)
- p_s is saturated vapour pressure (kPa)
- p_b is barometric pressure (101.325 kPa)
- g is moisture content (kg/kg)

RH cannot be considered in isolation

Temperature (^oC)

Moisture content (kg/kg)

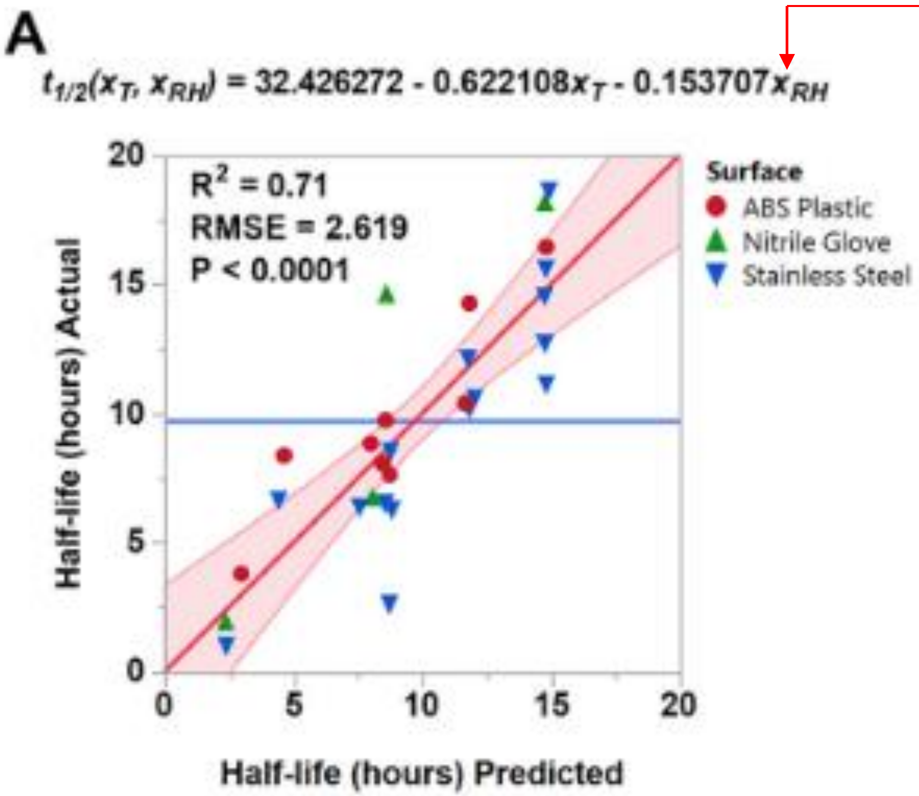


Air at 0^oC & 90% RH has a vapour pressure of 0.550 kPa and a moisture content of 0.0034 kg/kg.

Air at 20^oC & 50% RH has a vapour pressure of 1.169 kPa and a moisture content of 0.0073 kg/kg.

Relative humidity is misunderstood

Here RH is used in a regression model.



- Many researchers fail to realise that RH is not an absolute value but rather a ratio of vapour pressures and therefore a function of air temperature.
- This can lead to wrong conclusions.

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Increasing Temperature and Relative Humidity Accelerates Inactivation of SARS-CoV-2 on Surfaces

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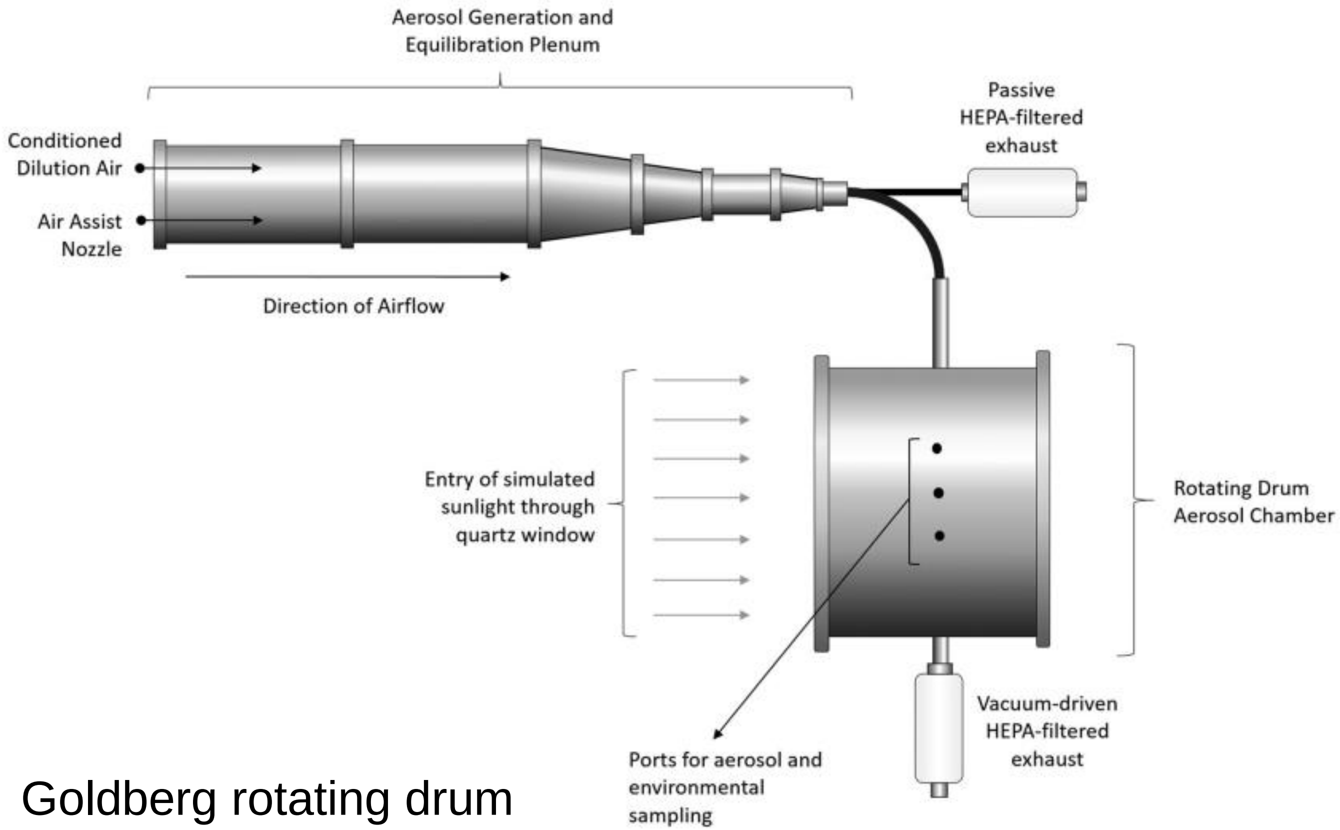
NB. This is very misleading. For example, air at 0°C & 90% RH is much drier and contains less energy than air at 25°C & 30% RH .

Experimental Studies (n =21)

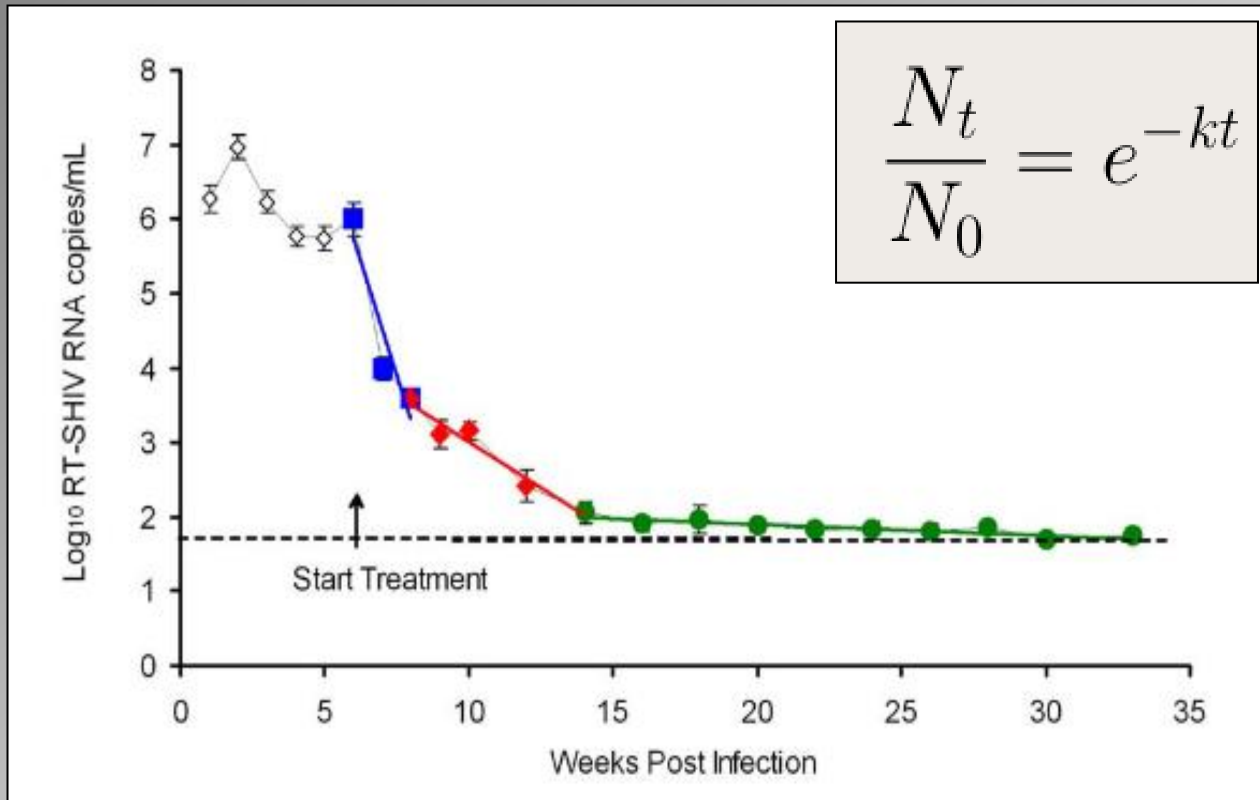


Goldberg rotating drum

- 5 teams performed aerosol experiments on SARS-CoV-2.
- All teams used a Goldberg drum to evaluate impact of temperature & humidity on virus survival.

- **Smither et al.** Experimental Aerosol Survival of SARS-CoV-2 in Artificial Saliva and Tissue Culture Media at Medium and High Humidity. *Emerging Microbes & Infections*. 2020; 9(1), 1415-1417
- **Dabisch et al.** The Influence of Temperature, Humidity, and Simulated Sunlight on the Infectivity of SARS-CoV-2 in Aerosols. *Aerosol Science and Technology*. 2020; 55(2), 142-153
- **Schuit et al.** Airborne SARS-CoV-2 is Rapidly Inactivated by Simulated Sunlight. *The Journal of infectious diseases*. 2020; 222(4), 564–571
- **Fears et al.** Comparative dynamic aerosol efficiencies of three emergent coronaviruses and the unusual persistence of SARS-CoV-2 in aerosol suspensions. *medRxiv*. 2020
- **van Dormalen et al.** Aerosol and surface stability of SARS-CoV-2 as compared with SARS-CoV-1. *New England Journal of Medicine*. 2020; 382, 1564-1567

Exponential Viral Decay

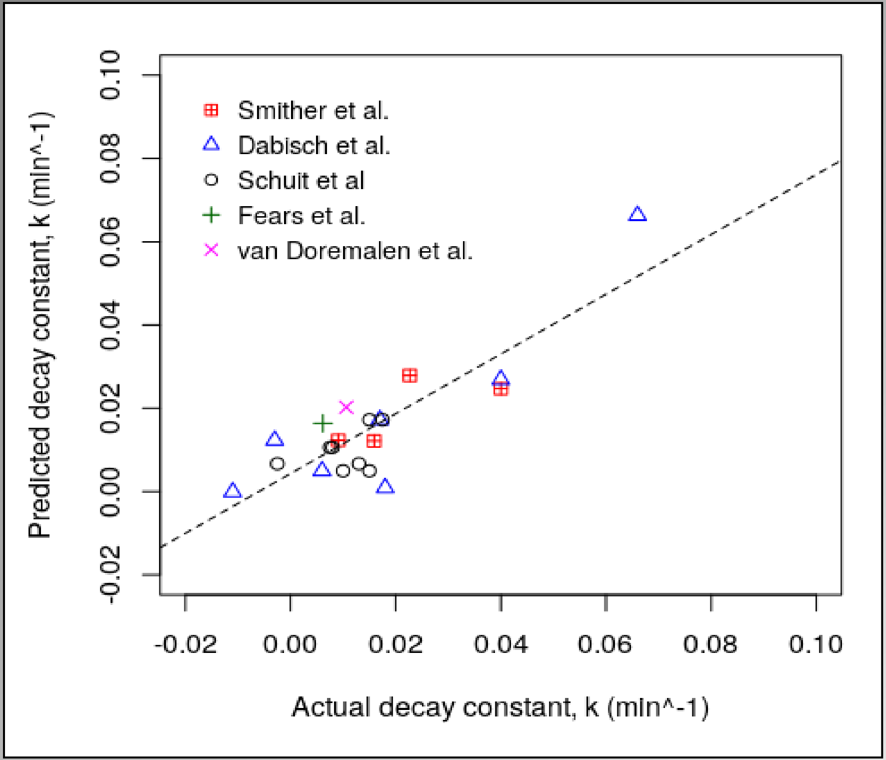


$$\frac{N_t}{N_0} = e^{-kt}$$

Viral decay on surfaces and in aerosols typically conforms to an exponential decay model.

Where:
k = Decay constant of the virus (min^{-1})
t = Time (minutes)
N_0 = Virus RNA copies at $t = 0$
N_t = Virus RNA copies at t minutes

Psychrometric model for SARS-CoV-2 survival in aerosols



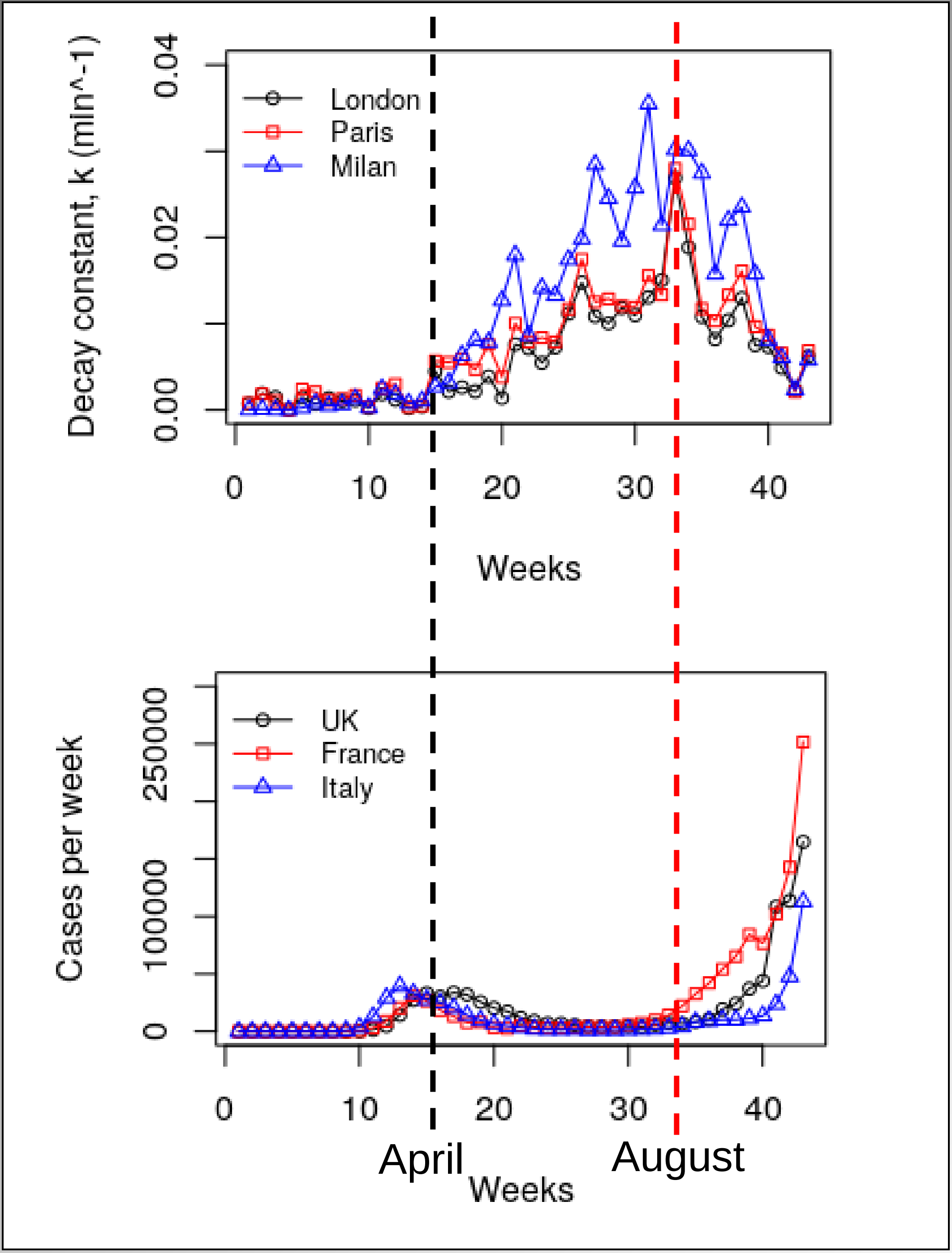
- Decay constant, *k*, can be predicted with reasonable accuracy ($R^2 = 0.718$, $p<0.001$), using enthalpy, vapour pressure, and specific volume of the air.
- Virus half-life can then be computed using:

$$l_{0.5} = \frac{ln(2)}{k}$$

Beggs CB, Avital EJ. A psychrometric model to assess the biological decay of the SARS-CoV-2 virus in aerosols. PeerJ. 2021 (in revision)

$k = 16.980 + (0.062 \times h) - (0.796 \times p_v) - (21.950 \times s)$

Where:
- k = Decay constant of the virus (min^{-1})
- h = Specific enthalpy of air (kJ/kg)
- p_v = Vapour pressure (kPa)
- s = Specific volume of air (m^3/kg)



k-values & COVID-19 cases for 2020

- March mean half-life value (minutes): London – 888; Paris – 495; Milan - 517
- August mean half-life value (minutes): London – 41; Paris – 38; Milan – 26
- Virus half-life dramatically reduced from April to August, which is the period when infections dramatically dropped in Europe.
- In September infections rose dramatically in Europe when the k-value decreased.

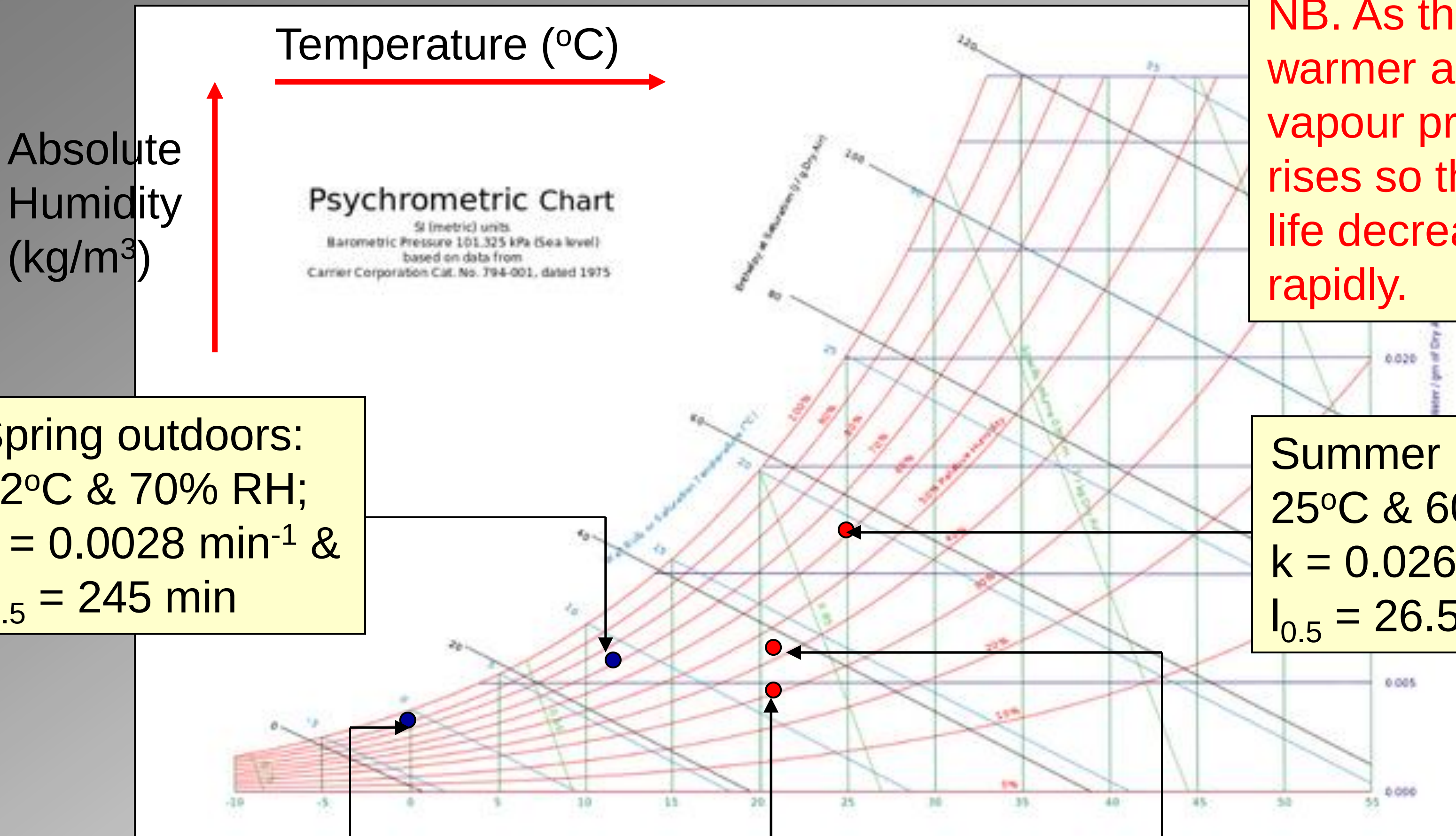
Outside air: mean half-life of SARS-CoV-2 virus

City	Parameter	January Mean (SD)	February Mean (SD)	March Mean (SD)	April Mean (SD)	May Mean (SD)	June Mean (SD)	July Mean (SD)	August Mean (SD)	September Mean (SD)	October* Mean (SD)
London	k.pred (min^{-1})	0.00113	0.00108	0.00078	0.00262	0.00484	0.00963	0.01150	0.01697	0.00980	0.00488
		(0.00192)	(0.00183)	(0.00158)	(0.00265)	(0.00388)	(0.00528)	(0.00486)	(0.00828)	(0.00607)	(0.00355)
London	Mean half-life (min)	613.4	641.8	888.6	264.5	143.2	72.0	60.3	40.8	70.7	142.0
Paris	k.pred (min^{-1})	0.00110	0.00171	0.00140	0.00500	0.00704	0.01143	0.01287	0.018.23	0.01224	0.00545
		(0.00192)	(0.00254)	(0.00229)	(0.00359)	(0.00548)	(0.00562)	(0.00530)	(0.00830)	(0.00639)	(0.00380)
Paris	Mean half-life (min)	630.1	405.3	495.1	138.6	98.5	60.6	53.9	38.0	56.6	127.2
Milan	k.pred (min^{-1})	0.00008	0.00077	0.00134	0.00442	0.01142	0.01756	0.02626	0.02686	0.01762	0.00565
		(0.00035)	(0.00149)	(0.00208)	(0.00386)	(0.00521)	(0.00722)	(0.00870)	(0.00824)	(0.00800)	(0.00417)
Milan	Mean half-life (min)	8663.8	900.1	517.2	156.8	60.7	39.5	26.4	25.8	39.3	122.7

* Data for 1 to 25th October 2020 only.

Beggs CB, Avital EJ. A psychrometric model to assess the biological decay of the SARS-CoV-2 virus in aerosols. PeerJ. 2021 (in revision)

Model Predictions



NB. As the air get warmer and the vapour pressure rises so the half-life decreases rapidly.

Spring outdoors: 12°C & 70% RH; $k = 0.0028\ min^{-1}$ & $I_{0.5} = 245\ min$

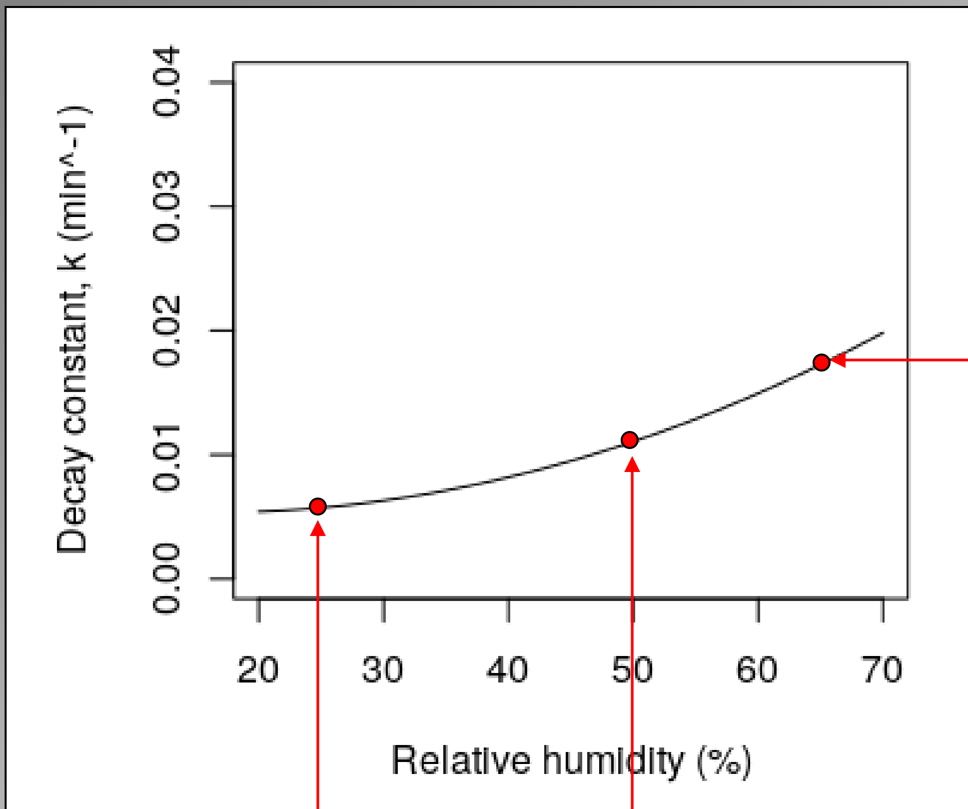
Summer indoors: 25°C & 60% RH; $k = 0.0262\ min^{-1}$ & $I_{0.5} = 26.5\ min$

Winter outdoors: 0°C & 90% RH; $k = 0\ min^{-1}$ (i.e. no decay)

Winter indoors: 21°C & 30% RH; $k = 0.0063\ min^{-1}$ & $I_{0.5} = 110\ min$

Spring indoors: 21°C & 42% RH; $k = 0.0087\ min^{-1}$ & $I_{0.5} = 80\ min$

Half-life in room space at 21°C



Summer (very humid):
21°C & 65% RH;
$k = 0.0173$ min^{-1} &
$I_{0.5} = 40$ min

Winter (very dry):
21°C & 25% RH;
$k = 0.0057$ min^{-1} &
$I_{0.5} = 121$ min

Summer (air cond):
21°C & 50% RH;
$k = 0.011$ min^{-1} &
$I_{0.5} = 62.5$ min

- Indoors in winter the air much drier than in summer.
- As the air becomes more humid so the k-value greatly increases and the virus half-life decreases.
- Air conditioning dries out the air increasing the half-life.

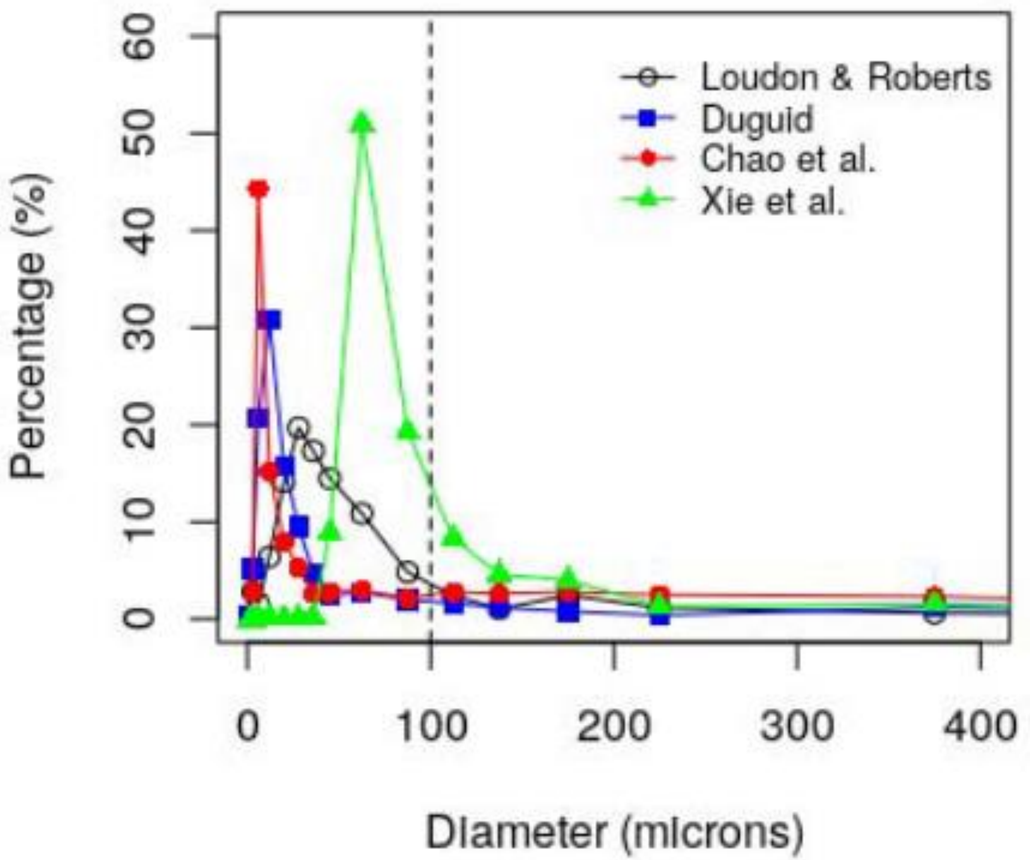
Indoor virus half-life range

- In the UK internal air conditions might range from, say,18^{o}C and 25% RH, equating to k = 0.0038 minute^{-1} (half-life = 181.5 minutes) in winter, to, say, 25^{o}C and 60% RH, equating to k = 0.0262 minute^{-1} (half-life = 26.5 minutes) in summer.

- In the UK the half-life of the SARS-CoV-2 virus within buildings could be as much as seven times longer during the winter months compared with the summer.

- However, we cannot be certain that this increase in virus half-life contributes to the spread of COVID-19 in buildings, or if it does, the mechanism by which it contributes.

Distribution of droplets when speaking



Implications

- When speaking on average 88.2% of the aerosol droplets produced are <100 μm [1].
- However, in winter when the air is drier, the aerosol droplets will tend to be smaller due to greater evaporation.
- The smaller aerosol particles will take longer to fall out of the air and thus are more likely to be inhaled.

- The psychrometric quality of the air will alter the viral load in aerosol droplets.
- During winter when the air is cooler and drier, and the half-life of the virus is longer, the viral load in any aerosol particles that are inhaled is likely to be greater [2].

1. Beggs CB. Is there an airborne component to the transmission of COVID-19?: a quantitative analysis study. medRxiv. 2020; 2. Beggs CB, Avital EJ. A psychrometric model to assess the biological decay of the SARS-CoV-2 virus in aerosols. PeerJ. 2021 (in revision)

Differences between summer and winter

Attribute	Winter	Summer
Virus half-life	Half-life is long. So, viral load in inhaled aerosol droplets is high.	Half-life is short. So, viral load in inhaled aerosol droplets is lower.
Aerosol droplet size	Air is dry. So droplets evaporate quickly. Greater number of small aerosols <10 microns produced which stay in the air for longer.	Air is less dry. So droplets evaporate slowly. Aerosols are therefore larger and fall out of the air more quickly.
Ventilation	Buildings less well ventilated, because high proportion of air is recirculated.	Buildings well ventilated.
Habits	People spend more time indoors.	People spend less time indoors.
Immunity	Lower vitamin D levels and nasal cavity more dry.	Higher vitamin D levels and nasal cavity more moist.

COVID-19 Transmission: Key Issues

Proximity	Risk increases with shorter distance and face-to-face
Enclosure	Risk higher indoors, increases with poor ventilation
Crowding	More people means a higher chance of an infector
Duration	Risk increases the longer you are close to an infectious person
Activity type	Singing, loud speaking, aerobic activity etc. increase viral emission & breathing rate
Environmental	The virus survives in cool, dry and dark
Symptoms	Asymptomatic transmission means it is hard to detect infectious people

(Courtesy of: Prof. Cath Noakes)

Conclusions

- Clear evidence that COVID-19 is transmitted via respiratory aerosols that become airborne.
- It is possible to predict the expected half-life of the virus using a linear regression model and the psychrometric qualities of the air.
- The SARS-CoV-2 virus survives for much longer when the air is cooler and drier.
- Many more small respiratory aerosols are produced when the air is cool and dry in winter, and these will tend to remain suspended in room air for longer.
- However, we cannot say conclusively that increased virus half-life contributes to increased transmission of the SARS-CoV-2 virus – even if we suspect it does.