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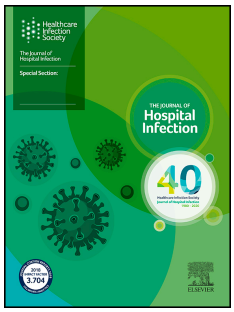

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Dismantling myths on the airborne transmission of severe acute respiratory syndrome coronavirus (SARS-CoV-2)

Narrative review

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Summary

The Covid-19 pandemic has caused untold disruption and enhanced mortality rates around the world. Understanding the mechanisms for transmission of SARS-CoV-2 is key to preventing further spread but there is confusion over the meaning of “airborne” whenever transmission is discussed. Scientific ambivalence originates from evidence published many years ago, which has generated mythological beliefs that obscure current thinking. This article gathers together and explores some of the most commonly held dogmas on airborne transmission in order to stimulate revision of the science in the light of current evidence. Six ‘myths’ are presented, explained, and ultimately refuted on the basis of recently published papers and expert opinion from previous work related to similar viruses. There is little doubt that SARS-CoV-2 is transmitted via a range of airborne particle sizes subject to all the usual ventilation parameters and human behaviour. Experts from specialties encompassing aerosol studies, ventilation, engineering, physics, virology and clinical medicine have joined together to present this review, in order to consolidate the evidence for airborne transmission mechanisms and offer justification for modern strategies for prevention and control of Covid-19 in healthcare and community.

Introduction

As the severe acute respiratory syndrome coronavirus-2 (SARS-CoV-2) pandemic rages on, so does the debate over what fraction of transmission occurs by aerosol exposure – as opposed to direct or indirect transmission by droplets and fomites.[1-9]

This is an old debate that has been reignited by the appearance of yet another respiratory viral pandemic.[10-14] There is significant confusion over the definition and application of relevant terms, such as droplets, droplet nuclei, aerosols and particles (**Table 1**). Clearly, if there are differences amongst professionals in defining these terms, then there will be problems in understanding the science. Ultimately, consensus will prove difficult, perhaps impossible, to achieve.[15,16]

The way that evidence is being interpreted and applied differs among interested parties across the world. Baseline definitions of what constitutes sufficient evidence to support transmission by aerosols are many and varied. Without agreement, the debate will continue to drag on, confusing the issue, and placing more and more people at risk because the practical preventive interventions needed to control the virus are not adequately supported.

There is little, if any, direct evidence for transmission of SARS-CoV-2 via any specific pathway. This statement applies to fomites and direct contact just as much as for large droplets and smaller airborne particles. It is notable that transmission through large droplets has never been directly demonstrated for any respiratory virus infection.[7,17] The proof required to elicit these routes of transmission should include genomic sequencing and matching of the target pathogen at source (e.g. on fomites or hands) with that causing subsequent disease in the recipient, along with sufficient evidence to exclude any other source of the pathogen strain before or during the study. However, genomic studies tracking a single virus are very difficult and expensive to perform, and they may fail.[18]

To encourage both comprehension and consensus on airborne spread, we present a series of common ‘myths’ related to the science of viruses within aerosols. Our use of the term ‘myth’ implies a generally accepted statement about viral transmission that deserves fresh and unbiased consideration, especially in the light of the current pandemic. Each myth emanates

from historical studies that merit evidence-based scrutiny to re-evaluate present day opinion. By reviewing the science underpinning these myths, we hope to facilitate understanding of why the common statements are outdated and why current evidence points in a different direction.

Myth 1: "Aerosols are droplets with a diameter of 5 µm or less"

This myth originated from a historically incorrect definition, more recently reported by the World Health Organization (WHO) as, "… droplets <5 µm in diameter are referred to as droplet nuclei or aerosols".[2]

Respiratory droplets, formed from respiratory secretions and saliva, are emitted through talking, coughing, sneezing, and even breathing. Their diameters span a spectrum from <1 µm to >100 µm. The smaller ones rapidly desiccate to 20-40% of their original diameter, leaving residues called "droplet nuclei," which most clinicians believe to be synonymous with "aerosols".[19]

Respiratory droplets over a wide range of diameters can remain suspended in the air and be considered airborne. The sizes of exhaled particles cover a continuum (**Figure 1**). One cannot definitively specify a cut-off for the diameter of airborne particles because the ability of a particle to remain suspended depends on many factors other than size, including the momentum with which they are expelled, and characteristics of the surrounding airflow (speed, turbulence, direction, temperature, and relative humidity).

Depending upon airflow conditions, many particles that would have previously been classified as 'large' by this longstanding definition (diameter >5 µm), can travel much farther than the 'mythical' 1-2 m distance, within which such particles are claimed to fall to the ground. So taking this into account, even large particles can also behave like traditional 'aerosols'. Both 'aerosols' and 'droplets' should be thought of as extremes of a size range for which their airborne pattern will vary depending on the local environmental conditions.

For the purpose of describing transmission, a more rational size threshold to distinguish droplets from aerosols, in terms of their physical behaviour and route of exposure, is 100 µm.[20] To clarify the terminology used in this article, therefore, droplets are particles that fall to the

ground (or any surface including vertical surfaces) under the influence of gravity and/or the momentum of an infected person's exhaled air; and aerosols are particles that remain suspended due to size and/or environmental conditions. We will use the term "particles" to refer to droplets/aerosols in general.

Myth 2: "All particles larger than 5 µm fall within 1-2 m of the source"

This is an oft-repeated, but scientifically false, statement. Exhaled particles of diameter 5-10 µm slowly fall to the floor under the influence of gravity in still indoor air. This takes 8-30 minutes from a height of 1.5m. However, most rooms have typical ambient air currents of 0.1 – 0.2 m/s, which means that these particles are far too small to settle on the ground within 1-2 m of the source. A droplet must be larger than 50-100 µm to have a high probability of landing within 1-2 m of the emitting source indoors. Local turbulent airflows can extend this suspension time for even longer. It is already known that droplets larger than 50-100 µm can be carried beyond 1-2 m in a jet of exhaled air, especially during sneezing or coughing.[21,22]

Particles that are too small to settle rapidly under gravity can move upward in a person's thermal plume. This is the upwardly moving column of warm air produced by a person's body heat.[23-25] Such particles can be influenced by other airflows generated by ventilation, people-traffic, door movements and convective flows (e.g. air currents produced by warm electrical equipment and warm bodies),[26] before being finally inhaled. Transport by such flows is especially important for particles of <5-10 µm, which can be carried over long (>2 m) distances.

In still air, particles of different sizes have different settling times that can be accurately predicted by physical laws (i.e. Stokes' law). Based on this, calculations show that even particles with a diameter around 50 µm will take about 20 seconds to settle from a height of 1.5 m and should be considered as aerosols.[20] The effect of turbulent air movements in busy hospital wards and clinics may result in particles of this size remaining airborne for even longer and capable of travelling >2 m from the source.

The time period that is clinically relevant for particles suspended in air depends on the ventilation. Hospital ventilation systems supply clean air, which flush room air and any particles it contains, out of the room. If the room has an uncontaminated air-exchange rate of 6 air

changes per hour (ACH) from the combined effects of outdoor air, filtration and other air cleaners, then the duration of interest is 10-30 minutes. If the room has an air-exchange rate of 12 ACH, then the duration of interest is 5-15 minutes. Of course, some hospitals do not have mechanical ventilation systems and in the absence of open windows or doors, airborne particles could potentially take hours to settle to the ground.[27] The latter would constitute a risk for both staff and patients, especially if unprotected by distance from source or face masks.

Myth 3: "If it's short range, then it can't be airborne"

For the purpose of discussing this myth, we define the social-distance proximity of 1-2 m as the scale that differentiates between "short-range" and "long-range." It is commonly believed that long-range transmission is proof of airborne transmission, *but* the absence of detectable long-range transmission does not exclude airborne transmission. Specifically, airborne exposure and aerosol inhalation at short- or close-range (i.e. over conversational distance) may still be important, and even predominant, for SARS-CoV-2 transmission, even if long-range transmission has not been demonstrated.

Delivery of the infectious agent by means of inhalation can occur over any distance, but it is more likely to occur at close range because aerosols are more concentrated nearer the source. A visual example of this can be seen by watching how smoke dissipates from a smoker over distance from the cigarette. A similar phenomenon can be experienced from smell, e.g. if you are standing close enough to someone who has had garlic or alcohol for lunch, you may detect this when you inhale, but the odour fades as you move further away. However, if you do smell lunchtime odours in exhaled breath, then you may also be inhaling any viruses present in that exhaled breath. Such encounters typically occur at a conversational distance (~1 m or less). This has been confirmed by experiments and modelling studies of aerosol dynamics.[17,28-33]

We know from influenza studies, that exhaled breath and talking can carry viable viruses over conversational distances that can be inhaled by susceptible persons nearby.[34,35] These experiments demonstrate the presence of airborne viruses in different sized particles produced by infected persons over short conversational distances within 1 m.

Although we do not yet have genotypic evidence that inhaled virus causes COVID-19 in humans, many outbreaks are difficult to explain other than inhalation of aerosolised SARS-CoV-2.[36-41]

Aerosols are present at close range to an infectious emitter (<1 m) and, obviously, at much higher concentration than at longer range. At close range, one is exposed to the full spectrum of expired particles from ballistic "large droplets" to tiny aerosols. Whether transmission over longer ranges (beyond the social-distancing range of 1-2 m) does occur depends on several parameters. These include the quantity of airborne virions produced by the source; the distribution of virions carried by different particle sizes; airflow patterns in the local environment; the decay rate of virus infectivity; the infectious dose needed to cause an infection in an individual; dilution of the inoculum at a distance; and timely removal by fresh air, ventilation or air cleaning.

The risk of longer range (>2 m) transmission may be smaller when compared with the risk of infection at close range (<1 m) but it could still occur, and it could be significant. Unfortunately, longer range transmission events for a pathogen can be very difficult to prove when that pathogen is already widespread in the community, with multiple sources able to emit the virus over various distances. A famous historical example is smallpox, for which long range transmission could only be proven at the time of a single outbreak in Germany, in the complete absence of ongoing community transmission.[42]

Myth 4: "If the basic reproductive number, R_0, isn't as large as for measles, then it can't be airborne"

The basic reproductive number or R_0, is generally defined as the average number of secondary cases arising from presence of one single infected 'index' case in a population of uniformly distributed but otherwise totally susceptible individuals.

The key problem with this statement is that this number, R_0, is not directly related to whether or not a disease is transmitted through aerosol inhalation. R_0 signifies how many people become infected after contact with one infected person, but the mechanism of the transmission is irrelevant.

Various organisms can be disseminated by the airborne route but are not necessarily transmitted person-to-person. For example, hantaviruses, which cause hantavirus pulmonary syndrome, and *Bacillus anthracis*, causing anthrax, both have animal reservoirs and both are acquired by inhalation - but they are not transmitted person-to-person. They have an R_0=0 and yet they are considered to be airborne diseases.[43,44]

Furthermore, the value of R_0 is only as accurate as the ability to identify secondary cases. For viruses widely accepted to be airborne, such as measles and chickenpox, accurate identification of cases is relatively simple because these viruses cause distinctive skin pathology in >99% of infected cases. These can be diagnosed without laboratory testing, making identification and enumeration of secondary cases relatively easy. Estimates of R_0 are consequently much more accurate. Since so many COVID-19 cases are asymptomatic, R_0 is much more difficult to assess. A step further is the determination of R_e, which is the 'effective' reproductive number. This is used when only a fraction of the exposed population may be susceptible to infections for which there is an effective vaccine, e.g. measles and chickenpox.

When patients present with an 'influenza-like illness', mild symptoms, or none at all, the extent of any outbreak and consequently, the number of secondary cases, is much more difficult to ascertain. People will not necessarily know that they have been exposed, or be conscious of their ability to transmit the infection to others. They will not self-isolate and they won't be counted as potential secondary cases. This makes it impossible to contact trace and follow up everyone involved in one specific exposure event, unless comprehensive details are recorded. Additionally, we cannot exclude other contacts during their daily lives that could have led to the same infection from a different source. Even in cases for which a single outbreak event can be associated with an infectious source, that same source may have already propagated other secondary cases that cannot be easily traced and counted. A substantial amount of pre-symptomatic transmission can occur with COVID-19, and as for SARS-CoV-CoV-1, not all infected patients are equally contagious.[45]

There is now good evidence that other respiratory viruses such as influenza, SARS-CoV-1, MERS-CoV and RSV (respiratory syncytial virus) are transmitted through the air, so a similar

application of this 'myth-busting' rationale can also be applied to the transmission of these viruses.[46-50]

Myth 5a. "If it's airborne then surgical masks (or cloth face coverings) won't work"

This statement is false because it is essentially presented as an over simplified binary scenario, i.e. masks work (completely) or don't work (at all) against viruses in respiratory particles.

Several laboratory studies have already shown that surgical and home-made masks are somewhat (but incompletely) effective in both limiting exhaled particles, and in protecting wearers from inhaling particles from others. Surgical masks can contain, and therefore reduce, the dissemination of viruses shed by an infected wearer by up to 3-4-fold (i.e. ~67-75%), and even 100% in the case of seasonal coronaviruses.[34,51] When an infectious person wears a mask or face covering, the size of the exhaled plume is also reduced and this also helps to reduce the risk of exposure to those nearby.

Surgical masks also protect the wearer, by reducing the exposure to incoming droplets and aerosols from infected individuals by an average of 6-fold (range 1.1 to 55-fold).[52,53] The filtration capacity of surgical masks in the micron size range is often considerable, although it varies between brands.[54] We know that the filtration capacity of N95/FFP2 respirators is better if they have been appropriately fit-tested, to avoid leakage of aerosols around the side of the respirator into the breathing zone.

Even home-made cloth masks (made from tea cloths or cotton t-shirts) can reduce the exposure from incoming particles by up to 2-4-fold (i.e. ~50-75%).[55,56] This mainly depends on how the mask is made, what materials it is made from, the number of layers, and the characteristics of respiratory secretions to which it is exposed. Based on the evidence supporting a role for airborne transmission of COVID-19, the use of N95/FFP2/FFP3 respirators by frontline healthcare workers should be recommended. For those that cannot tolerate wearing these masks for long periods, the less restrictive surgical masks still offer some protection, but it needs to be acknowledged that these won't be quite so effective.

Myth 5b: "The virus is only 100 nm (0.1 µm) in size so filters and masks won't work"

This myth is related to 5a. There are two levels of misunderstanding to be considered for this myth. Firstly, there is a lack of understanding of how high efficiency particle air (HEPA) and other filters actually work. They do not act as simple 'sieves', but physically remove particles from the airstream using a combination of impaction and interception (where faster moving particles hit and stick mask fibres via a direct collision or a glancing blow); diffusion (where slower moving particles touch and stick to mask fibres); and electrostatic forces (where oppositely charged particles and mask fibres adhere to each other). Together, these create a 'dynamic collision trap' as particles pass through the network of air channels between fibres at various speeds.[57]

The minimum filtration efficiency typically occurs for particles in the vicinity of 0.3 µm in diameter. Those smaller than this "most penetrating particle size" are captured with greater efficiency because their Brownian motion (allowing diffusion at an atomic level) causes them to collide with fibres in the filter at a high rate. Particles larger than this limiting diameter are efficiently removed through impaction and interception.

Secondly, viruses that are involved in transmission of infection are not generally 'naked'. They are expelled from the human body in droplets containing water, salt, protein, and other components of respiratory secretions. Salivary and mucous droplets are much larger than the virus,[58] and it is the overall size that determines how the droplets and aerosols move and are captured by mask and filter fibres.

High efficiency particle air (HEPA) (or 'arrestance') filters can trap 99.97 % or more of particles that are 0.3 µm (300 nm) in diameter. Exhaled salivary/mucous droplets start from about 0.5 µm size range and are entirely removed by HEPA filters. Indeed, HEPA filtration is not strictly needed in the ventilation systems of most commercial buildings other than healthcare, where specialist areas such as operating theatres, clean rooms, laboratories and isolation rooms benefit from single-pass capture of particles. Stand-alone 'portable' air cleaners that filter room air through built-in HEPA filters are an option for non-specialist areas such as offices and

classrooms, though their performance may be limited by imperfect mixing, noise and draught effects.[59]

Myth 6: "Unless it grows in tissue culture, it's not infectious"

Viral culture is surprisingly difficult, which is one reason why virus isolation in cell culture is much less sensitive than detection by molecular methods. This is partly because it takes more than one virus to successfully initiate infection in a cell culture. For example, using influenza virus, Fabian et al. found that one $TCID_{50}$ (i.e. the amount of virus required to infect 50% of an *in vitro* cell monolayer) represents approximately 300 genome copies; this is similar to previous estimates of 100-350 copies by Van Elden et al. but smaller than 650 copies reported by Wei et al.[60-62]

This sensitivity difference is further compounded by currently available air sampling techniques. Most studies use high-velocity 'impingers' which suck any airborne virus from the air into a bubbling liquid virus culture medium. However, these air-sampling devices generate high shear forces and vigorous mixing at the air-liquid interface, which may damage viral surface proteins and stop them growing in culture.[63,64] In contrast, natural human exhalation and inhalation flow velocities are much slower, which make them much less likely to cause shear stress damage to viruses.[65,66] Clearly, our air-sampling technologies do not accurately replicate the mechanisms leading to human respiratory infection through inhalation.

As a consequence, failure to detect viable viruses in air samples does not necessarily prove the absence of live virus in samples where viral RNA was detected by molecular methods. Finding viral RNA in air samples should be interpreted as more likely to indicate the presence of live virus than not, as per the precautionary principle, which should always reinforce effective infection control.[67]

For SARS-CoV-2, two different research groups have recently demonstrated the presence of infectious SARS-CoV-2 viruses in aerosol samples from patient rooms.[68,69] For the reasons stated above, these studies very likely underestimate the amount of viable airborne virus available for inhalation by others.[70]

Conclusions

We have attempted to clarify and dispel several common myths around the science underpinning airborne transmission of viruses. The myths presented are easily dismantled when consideration is given to the physical, epidemiological and virological principles of how respiratory aerosols are produced and disseminated; how secondary cases of infection can (or cannot) be readily identified; and how appropriate infection control measures actually can, and do, affect the risk of transmission. There is mounting evidence to support the presence and transmissibility of SARS-CoV-2 through inhalation of airborne viruses. Exposure to small airborne particles is just as - or even more - likely to lead to infection with SARS-CoV-2 as the more widely recognized transmission via larger respiratory droplets and/or direct contact with infected people or contaminated surfaces.[71,72] Some of the explanations and rationale for SARS-CoV-2 transmission can be applied to other respiratory viruses, but these need to consider the number and different types of studies available for those specific viruses.[73,74]

What does this mean for infection control practitioners in healthcare, as well as the general population? Aside from the obvious benefits of Personal Protective Equipment (PPE), the existing evidence is sufficiently strong to warrant engineering controls targeting airborne transmission as part of an overall strategy to limit the infection risk indoors.

These would include sufficient and effective ventilation, possibly enhanced by particle filtration and air disinfection; and the avoidance of systems that recirculate or mix air. Opening windows, subject to thermal comfort and security, provides more than a gesture towards reducing the risk of infection from lingering viral particles.[71,72,74]

Measures to control overcrowding in both healthcare and confined indoor environments in the community, including public transport, are also relevant. There exist a range of cost-effective measures aimed at diluting infectious airborne particles in homes and hospitals that are easily implemented, without major renovation or expenditure.[71,73] These will serve to protect all of us as we seek the evidence required to further reduce the risk from Covid-19 over the coming months and years. It is time to discard the myths and rewrite the science of viral transmission.

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Figure legend

Figure showing the range of respiratory particles and potential spread over distance. Blue particles: 'droplets' typically >100 um diameter that fall to the floor under gravity within 2 m of the source. Red particles: 'aerosols' typically <100 um that stay suspended for longer, but eventually fall to the ground if the air is motionless for long enough (at least 30 minutes).

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Table 1: Differences between clinicians, aerosol scientists and the general public in the understanding of airborne terminology

Term	Clinicians	Aerosol Scientists	General Public
Airborne	Long-distance transmission, such as measles; requires an N95/ FFP2/ FFP3 respirator (or equivalent) for infection control	Anything in the air	Anything in the air
Aerosol	Particle smaller than 5 µm that mediates airborne transmission; produced during aerosol generating procedures and also requires N95 respirator	Collection of solid or liquid particles of any size suspended in a gas	Hair spray and other personal/cleaning products
Droplet	Particle larger than 5 µm that rapidly falls to the ground within a distance of 1-2m from source; requires a surgical mask for infection control	Liquid particle	What comes out of an eyedropper
Droplet nuclei	Residue of a droplet that has evaporated to <5 µm; synonymous with "aerosol"	A related term, "cloud condensation nuclei," refers to small particles onto which water condenses to form cloud droplets	Never heard of it!
Particle	Virion	Tiny solid or liquid blob in the air	Like soot or ash

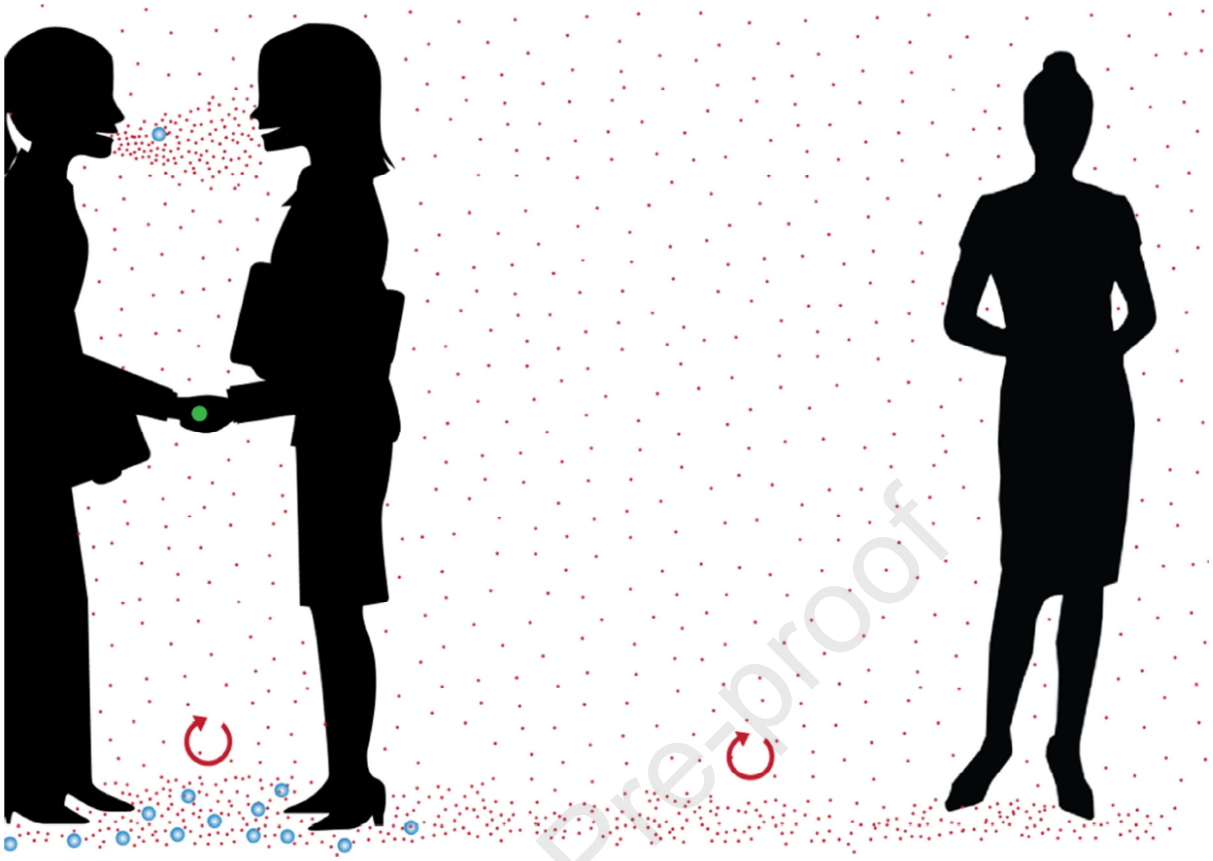

Figure 1. Showing the range of respiratory particles and potential spread over distance. Blue particles: 'droplets' typically >100 um diameter that fall to the floor under gravity within 2 m of the source. Red particles: 'aerosols' typically <100 um that stay suspended for longer, but eventually fall to the ground if the air is motionless for long enough (at least 30 minutes).