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LITERATURE REVIEW MAY 2020

Contents

1 Abstract

WHO guidelines on Indoor Air Quality (IAQ) specifically underline the elderly, as well as those who spend time within care homes, to be disproportionally at risk of indoor air pollution[1]. Poor IAQ is particularly important to consider because the majority of people spend 90% of their time indoors[2], whilst this figure is found to be even higher amongst elderly people living within a care home environment[3]. Furthermore, air pollution indoors can be up to 5 times worse indoor than the air found outside[4], this is also supported by evidence specifically undertaken in care homes[5]. As such, individuals in care homes are spending the vast majority of their time within environments in which the air quality is likely to be dangerously low.

Furthermore, elderly people are more likely to have weakened immunological defences, as well as existing underlying chronic diseases, making them more susceptible to the health risks associated with low IAQ. Such susceptibility amongst this group mean that even low concentrations of air pollutants can lead to detrimental effects upon an individual's health[6] . Contaminants likely to be particularly harmful to such a group include viruses[7] , fungi (particularly 'Aspergillus' species), bacteria[8] , volatile organic compounds (including NO2) and other particulate matter (PM), in the case of the later, fine-PM and below is partially threatening due to its potential to become lodged deep within an individual's respiratory tract[9]. Poor IAQ is known to produce or exacerbate numerous health problems including 'eye irritation, nausea, upper respiratory complications, cognitive impairment, asthma, respiratory infections, cardiovascular disease, chronic obstructive pulmonary disease, and cancer'[10].

[1] WHO, 2010
[2] British Lung Foundation, 2020
[3] Almeida-Silva et al. 2014
[4] EPA 2020
[5] Mendes et al. 2013
[6] Aguiar et al. 2014
[7] Comas-Herrera et al. 2020
[8] Aguiar et al. 2014
[9] Bentayeb et al. 2015
[10] Mendes et al. 2013

2 Risks of poor IAQ within the care home environment:

2.1 Overall respiratory health

Studies have found that levels of air pollutants commonly found within the indoor care home environment, such as NO2 and PM, have significant impacts on an individual's health, particularly in elderly people (measured as 65+). Such impacts were found to exist even when pollution concentrations existed far below health guidelines[11] , such findings support other research which concludes that even low concentrations on harmful air pollutants can cause detrimental effects in older people due to the underlying chronic diseases likely to be found in these individuals, increasing susceptibility. In a study of 600 individuals across 50 nursing homes in Europe, undertaken in 2015, conclusions indicated that not only did IAQ impact respiratory health within the elderly demographic, but that the frailty of these people's immune systems to such contaminants also increased with age[12].

The landmark 2015 study described above[13] , found elevated levels of PM10 and NO2 to be strongly correlated to breathlessness and cough (particularly for those aged over 80 years old), whilst high PM0.1 concentration exposure was 'associated' with 'wheeze' within the past 12 months. Such contaminant's detrimental effects on elderly people's health was similarly concluded by an earlier study, which found increased numbers of 'bronchitis-like' symptoms within elderly individuals in areas polluted disproportionally by SO2 and PM10[14] . The study also found a significant relationship between concentrations of PM0.1 and NO2 and criteria symptoms of airway obstruction. The most crucial part of the lungs, for optimum function, is the alveolar regions, as they have an extensive surface area, allowing for nanoparticles breathed in, to enter an individual's bloodstream. These are the regions within which tiny particulate matter can become lodged, creating respiratory symptoms to the human experiencing such pollution[15].

2.2 Spread of COVID-19

The ongoing COVID-19 pandemic, caused by the SARS-CoV-2 virus, has been particular problematic for care homes, who have experienced high levels of mortality within their vulnerable internal communities. NHS figures suggest that over a third (38%) of England's 15,514 care homes experienced an outbreak, resulting in 9,492 deaths as of 8 May 2020[16]. Due to the importance of 'airborne transmission' as a method in which the virus is known to spread, attempts can

[11] Barnett et al. 2006
[12] Bentayeb et al. 2015
[13] Bentayeb et al. 2015
[14] Bentayeb et al. 2010
[15] Almeida-Silva et al. 2014
[16] Public Health England A. 2020

be made to counter person to person transmission by removing viruses from the air within an indoor environment.

Airborne pathogens, often released when an individual exhales air by breathing, sneezing, and coughing can become suspended in the air for extended periods, given their often 'sub-micron' size. Such pathogens include viruses, bacteria, fungi, VOCs, as well as others. The transmission of severe acute respiratory syndrome (SARS) (a virus) for example, responsible for the 2002-2004 SARS outbreak, was believed to be spread by such means[17]. One study outlines that due to current epidemiological data, COVID-19 exhibits even higher 'transmissibility' (R0 basic reproduction ratio) than SARS, postulating the threat of nosocomial infection to be higher during the current time than it was in the aforementioned outbreak[18].

The transmission of airborne pathogens can occur via larger 'droplets' or via smaller 'aerosols'. The larger 'droplets' (generally be defined as those ¿ 5 m) exhibit a relatively shorter transmission range of around a meter from their source and can remain in the air for up to 17 minutes. These droplets typically deposit upon the mucous membranes and upper respiratory tract. 'Aerosols', on the other hand, are defined as droplet nuclei measuring <5 µm. These particles are able to remain in the air for 'an almost infinite amount of time', due to their low setting velocity, and can be discharged over larger distances of up to 6 feet from their source (in the case of SARS)[19] . Aerosols are able to be inhaled deeply into the respiratory tract including the lower airways, this can be particularly harmful to humans, especially older people. In a 2009 US study, 'real-time polymerase chain reaction' was used to confirm airborne influenza. The study found that 53% of the virus particulate detected fell within 'respirable' bounds- which the study defined as diameter, <4 mm[20]. It is consequently a significant public health threat to leave air contaminated with such 'aerosols' untreated[21], particular within an environment within which vulnerable people live.

Furthermore, care homes are often at high levels of utilisation. In the UK for example, care home capacity is already overstretched in the context of an ageing population[22]. Such high utilisation thus exacerbates the spread of any possible virus, creating a 'hotspot' environment for the spread of such a virus such as SARS-CoV-2. It follows that increasing numbers of people within an enclosed environment can lead to rapid transmission between individuals. Further, many care homes within the UK are located in geographical regions considered to have air that exceeds safe air pollution limits, thus, even attempts to mitigate air quality via the use of 'natural ventilation', simply allow dangerously high levels of particulate matter/airborne contaminants from outside to enter the building[23].

[17] Chowell et al. 2015
[18] GE et al. 2020
[19] Kutter et al. 2018
[20] Blachere et al. 2009
[21] Fiegel et al. 2006
[22] GOV A. 2020
[23] British Lung Foundation. 2018

2.3 Influenza Virus transmission

Not to be confused with the ongoing pandemic caused by the novel coronavirus (SARS-CoV-2), the group of viruses known as 'influenza' causes a different disease altogether, more commonly referred to as the common cold/flu[24]. This virus exists amongst the leading causes of respiratory infection and thus, exists as a common cause of mortality in elderly people, in the 2017/18 season a total of 22,237 deaths were associated with influenza amongst those older than 65 years in England alone[25]. Studies show that the environment plays a large role in determining an individual's susceptibility to this virus, and that the 'grouping' of elderly, frail people living with a care-home setting, present favourable conditions for the spread of such an infection[26] . These viruses have been shown to transmit person to person via 'airborne' 'droplets'/'aerosols' by carriers of the virus[27]. In a similar way to SARS-CoV-2, thus, attempts should be made to engineer solutions to this airborne risk (Possible Role of Aerosol Transmission in a Hospital Outbreak of Influenza).

2.4 Exacerbated memory loss

The contamination of the air with pollutants such as NO2 and PM10 have also been found to contribute to the exacerbation of the monatomic age-gradient in memory. As individuals grow older, their memory declines, so much so that those aged over 80, on average, remember three and a half fewer words when compared to a 21-year-old. Thus, it is important that every attempt is made by the elderly to avoid environments in which memory is likely to become further deteriorated. One study of over 34,000 British citizens across 318 different geographical regions saw that memory was worse in areas in which NO2 and PM10 levels were found to be greater. The study also yielded the conclusion that the difference in the quality of memory between England's 'cleanest' and 'most-polluted' areas, was the equivalent to lost memory associated with 10 additional years of total age[28].

An American study tracking cumulative exposures to PM2.5 and individual's health from 2004 through 2013, concluded that exposure to PM2.5 'degrades health', whilst increasing said individuals' risk of developing a dementia-type disease at a later stage of life. Quantifying this relationship, the study used a series of complex mathematical models to conclude that a moderate change in exposure to PM2.5 ('1 $\mu g/m^3$ increase in 10-year average residential concentrations') over the 10 year period, led to an increased probability of later receiving a dementia diagnosis by 1.68 percentage points(pp). To further contextualise this relationship, the increased risk associated with the moderate PM2.5 exposure is approximately half as large as the increased risk someone experiences

[24] Higginson, R. 2020
[25] Public Health England. 2019
[26] Carman et al. 2000
[27] Lindsley et al. 2014
[28] Powdthavee et al. 2020

who has previously been diagnosed with diabetes[29].

2.5 Reduced general cognitive function

Studies have also examined the relationship between exposure to air pollutants and cognitive function more generally. One US study of elderly US men found a statically significant relationship between exposure to fine particulate matter (in this study associated with emissions from their residency's proximity to traffic) and cognitive decline. Participants were required to undergo seven standardised mental assessment tests (including those relating to attention, memory, executive function, language, and visuomotor ability) to assess their cognitive deterioration after a certain extended exposure. It follows that such contaminants within the air may exert certain detrimental effects upon the central nervous system (CNS) function within an adult man[30].

Further research that considered the relationship between air pollution levels and cognitive ability, across a wider age distribution, used an Air Pollution Index as a proxy to gauge the air pollution over time (such an index considered levels of exposure to the following: SO2, NO2, and PM10 and ranged 0-500 with 500 as the worst air quality). This research concluded that the hazardous relationship, between the two variables, became increasingly pronounced as age increased, and that men tended to suffer from greater deterioration, after exposure, than women[31].

3 An empirical look at the IAQ within care homes

Numerous studies have found air pollution within the care home environment to at levels concerning to resident's well-being. An extensive 2015 study found concentrations of the following contaminants: NO2, PM10, and PM0.1, within the 'common room' of the CH, to measure 20.1 $\mu g \cdot m^3$, 29.8 $\mu g \cdot m^3$ and 12 907 $pt \cdot cm^3$ respectively. Whilst NO2 and PM10 did not, on average, exceed EU limits, significant relationships were drawn between these contaminants and the overall well-being of the 600 participants, even when adjusting for external factors. Furthermore, some care homes within the study did exceed European air quality standards reaching PM10 concentrations of 56 g·m3 in one instance (over double the average measurement). A further European study in 2015, found PM2.5 levels to exceed international reference levels across all 22-care home studied across both summer and winter seasons. These results are indicative of the variability in IAQ standards across regions and between various care home locations. Large amounts of evidence suggest that even when IAQ falls within air quality standards, the susceptibility of those within the care home environment leads such individuals to still be at significant risk[32].

[29] Bishop et al. 2018
[30] Power et al. 2011
[31] Zhang et al. 2018
[32] Aguiar et al. 2014

3.1 Why are care homes themselves likley to exhibit low IAQ?

The air within a care home environment has been found to achieve very low numbers of air changes per hour. These ‘air changes’ (ACs) have become a standard metric used to understand how stagnant, or flowing, the air within a building is. Low numbers of hourly air changes creates an increased potential for the air to remain contaminated with potentially harmful pollutants, increasing the likelihood of a poor IAQ score. One study, for example, found an AC rate of 0.2-2 ACs within a bedroom care-home environment, and 0.7-2 in living rooms, whilst current Public Health England guidelines response to COVID-19 indicates a requirement for 6 air changes per hour in an environment within which a suspected COVID-19 carrier exists[33].

The regular use of disinfectant cleaning equipment is common within the care home setting, this is because, although care homes might have single rooms to use for isolation purposes, unlike medical environments, they are generally unable to close beds for control[34]. Thus, it is important that cleaning and disinfection procedures are undertaken regularly. However, from an air quality perspective, the use of such disinfectants on surfaces has been widely associated with deteriorations in IAQ, leading to the triggering of conditions such as asthma, skin irritations, mucus membrane irritations, as well as possible neurological side effects[35] . A further paper also commented on risks associated with the use of disinfectant products and their detrimental effect on air quality metrics[36].

Additionally, care homes are environments in which people live typically in very close quarters, thus it can be difficult for residents to isolate / self-quarantine once they fall sick (Barnett et al, 2020). This factor reinforces the notion than preventing outbreaks of disease should be of particularly high concern to those responsible for the operations of a care home environment.

4 Air purification can eliminate these issues

4.1 Air purification units in the care home setting

According to the literature, the most widely accepted solution to the issue of low air quality is through the utilisation of air purification units. Such units have been proven to be extremely successful in purifying the air by removing dangerous pathogens suspended within it[37] , they have also been successfully proven to vastly diminish associated health risks[38] [39]. In one study, a HEPA-

[33]Public Health England B. 2020
[34]meakin et al. 2012
[35]Sattler. 2002
[36]Capolongo et al. 2017
[37]Griffiths et al. 2005
[38]Boswell et al 2006
[39]Rutala et al. 1995

filter based filtration unit was able to remove aerosolised sub-micron particles of Mycobacterium Tuberculosis within a non-ventilated room by 90% within a time between 5-31 minutes, as compared to >171 minutes under a control (no purification unit). Such a study concluded the use of such units could 'rapidly reduce levels of airborne particles similar in size to infectious droplet nuclei' and as such has the capability to significantly reduce bacterial exposure.

Another study considered the use of a high-efficiency particulate air (HEPA) filtration unit to counter cross-infection of methicillin-resistant Staphylococcus aureus (MRSA). Poisson regression was used to analyse the effectiveness of a purifier compared to a controlled environment. It was found that without air filtration, 80-100% of settle plate sites- tested positive for MRSA, whilst the frequency and concentrations fell dramatically when air purification was used (even at relatively low throughput speeds of 140-235 m^3)[40] . The use of a HEPA H13 purification unit to decontaminate suspended MRSA bacteria from the contaminated hospital air achieved MRSA bacteria count reduction of 75–93%[41] . Such impressive decontamination was achieved, despite the researchers reporting doors being left open during times of purification- an occurrence considered likely to compromise the ability of a purification unit to operate at maximum capability[42] .

Due to the diversity of pollutants capable of causing harm within low quality indoor air, particularly within the care home setting, it is, however, appropriate to integrate additional filters and technologies within an air purification unit alongside the H-13 HEPA filter. As discussed, a fundamental hazard is that of the transmission of virus particles, such as the human coronavirus (which is between 0.12-0.16 microns in diameter)[43] . Current HEPA filter capability dictates, by definition, a standardised efficiency of at least 99.97% for removing particulate >0.3 microns in diameter[44]. Therefore, although HEPA filters are able to filter below the 0.3-micron level via diffusion and interception[45], they become less effective at this level and utilisation of UV-C irradiation within the purification unit is therefore critical to remove such tiny viruses from there air. One study, for example, observed the ability of UV-C irradiation to inactivate the 'MS-2 phage' virus (predominantly through the action of the bulk phase free hydroxyl radical)[46], whilst another observed the successful re-activation of MS2, Qβ, and φX174 viruses through the application of UV-C irradiation[47].

The benefits of air purification are widely considered in the literature and are particularly pronounced within the healthcare environment where the risks associated with low air quality are magnified[48]. Such benefits include the reduction in transmission of infectious disease including viruses, bacteria, and

[40] Boswell et al. 2006
[41] Boswell et al. 2006
[42] James et al. 2015
[43] Ward et al. 2020
[44] Sehulster et al. 2004
[45] Perry et al. 2016
[46] Cho et al. 2005
[47] Kim et al. 2018
[48] Qian et al. 2010

fungi[49], as well as the reduction in health concerns associated with high levels of VOCs or a 'complex combination' of VOCs within the air[50].

4.2 The technologies involved:

4.2.1 Pre-filters

A pre-filter removes large impurities from the air and acts as an initial purification step prior to the engagement of the subsequent processes. This filter also plays an important role in extending the lifespan of other filters in a device.

4.2.2 Carbon filters

Carbon filters (or 'activated carbon') are an advanced type of filter that allows volatile organic compounds (VOCs) to be removed from the air as well as odours and other potentially present gas pollutants. These filters enable gases to become trapped on a highly porous bed of charcoal and are particularly effective in removing mould and dust from the air. The pores in the charcoal exhibit a large surface area, causing large amounts of gas to be held upon them. In the healthcare setting, contaminants such as mercury vapour and other harmful VOCs flow through the purifier unit and are attracted to 'adsorption' sites within the carbon, thus becoming stuck in the micropores[51].

4.2.3 HEPA (High-Efficiency Particulate Air) Filters

A HEPA filter is widely defined as follows: a filter capable of capturing at least 99.97% of particulate >0.3 microns in diameter[52]. The filter structure involves an outer filter stopping and trapping larger particles, prior to the air approaching a second filter in which the more microscopic bacteria and debris are captured. Despite, by definition, HEPA filter's remarkable efficiency- these filters are unable to kill bioaerosols, instead, they become trapped and unable to continue within the flow of air through the purification unit. Readers should be aware of the marketing tools used by companies to advertise their air purifiers as being "HEPA-type," "HEPA-like," or "99% HEPA," as these refer to HEPA filters which perform below industry standards outlined above[53].

4.2.4 UV-C Irradiation

UV light refers to ultraviolet light, an invisible form of electromagnetic radiation just outside the visible spectrum to humans (with a shorter wavelength than visible violet humans can see). More specifically, UV-C waves refer to an obscure part of the ultra-violet section of the spectrum and are distinctive from

[49] Srivastava et al. 2015
[50] Bessonneau et al. 2013
[51] Zheng et al. 2004
[52] Sehulster et al. 2004
[53] Yadav et al. 2015

UV-A and UV-B both due to their comparatively greater energies and shorter wavelengths (between 100 and 280nm).

Most importantly, however, UV-C can be created artificially by humans and is extremely effective at destroying genetic material. It is hence that UV-C emitting bulbs are crucial to any effective air purification units' internal technology. UV-C waves are able to destroy cells by disrupting their DNA - deeming them unable to go on performing their vital functions following exposure. This means UV-C can effectively kill bacteria, viruses, and mould particles passing through the chamber. Importantly, UV-C emitting bulbs within air purification units are not released externally (outside the constraints of the unit's internal infrastructure) meaning their use is safe to the user.

4.3 The importance of UV-C irradation integration

UV-C irradiation is widely considered an extremely effective method of air purification. The high energy wavelengths emitted in this process (of between 200-280nm) are capable of damaging the DNA or RNA of microorganisms such as bacteria and viruses, deeming them no longer able to perform their vital functions. In the case of DNA, after exposure, the collision of photons in the cell causes their energy to become absorbed by the nucleic acids. Following this, pyrimidine dimers lead to a change in the DNA structure, followed by mutation and ultimately the death of the cell[54].

The effectiveness of four different UV-C emitting purification units was tested individually for their ability to disinfect bio-aerosols of air-borne bacteria. The bioaerosols used for testing were vegetative cells of the following: *Escherichia coli*, *Micrococcus luteus*, *Pseudomonas fluorescens*, *Staphylococcus aureus*, and endospores of *Bacillus Subtilis*. Results showed all four units were able to kill in excess of 99% of all the airborne vegetative bacteria tested and over 75% for the *B. Subtilis* Endospores. This study concluded the use of this technology an important addition to any purification unit, whilst highlighting that such a process bore no utilisation risk to the user[55].

[54] Jafari et al. 2018
[55] Green et al. 2001

Despite the extensive research-based evidence validating this technology, many purification solutions do not utilise UV-C radiation. This omission is detrimental for a number of reasons.

To begin with, viruses are amongst the most harmful particulate matter encountered via airborne transmission. Many virus particulates measure submicron diameters- reaching the size of 0.12-0.16 diameter in the case of COVID-19[56] . Because of this, a HEPA-filter (which by definition filters >99.97% of >0.3 microns) will not always be sufficient as a means of purification. This is because the efficacy of HEPA filters below this level is dependent on a less consistent particle-capturing mechanism, namely 'diffusion' due to the 'Brownian dominant' motion of particles at this size[57]. UV-C, however, has proved effective at deactivating such viruses from contaminated air at extremely high efficacy[58].

UV-C irradiation effectiveness is proportional to the wattage of the UV-C bulbs used in the purifier[59] . As such, not only is the presence of UV-C capability imperative, as well as the careful integration of these bulbs into the design engineering of a purifier but also important to consider is the strength of these bulbs (measured in wattage). Existing models on the market vary from a low of 10W up to an impressive 24W. Furthermore, dust agglomerations can impact the efficacy of the UV because such particulates impact the UV light's potential penetration[60]. Having considered the above insights, it may be beneficial to utilise a unit capable of relatively higher UV-C irradiation wattage.

5 Air Purification — Practical considerations

Current Public Health England 2020 guidelines indicate a need for 6 air changes (ACs) per hour in areas in which a known infected individual is located (Public Health England 2020). It is therefore important to consider the throughput capability of a purification unit in order to avoid undershooting these parameters, a situation likely to put healthcare workers and residents at risk.

Many companies who engineer air purification units measure their abilities to purify an indoor area in terms of a m^2 metric. This, however, is confusing because it does not tell the user the number of ACs expected within a given hour. A unit that claims to be capable of purifying a room of $60m^2$, may only actually achieve 2.5 ACs (this AC undershoots the above targets indicated by Public Health England[61] . Instead, the maximum throughput of an air purification system should be measured in m^3/hour, this allows one to calculate the number of times the air within a room, of given dimensions, will be 'turned-over' per hour. Assuming a medium-sized communal care home area of 5m by 5m, and a ceiling height of 2.5 m, we can estimate a total room volume of $62.5m^3$.

[56] Ward et al. 2020
[57] Perry et al. 2016
[58] Kim et al. 2018
[59] Kujundzic et al. 2007
[60] Van Osdell et al. 2002
[61] Public Health England B. 2020

Thus, a unit capable of say 600m^3/hour could achieve well over 9 air change per hour, delivering purified air, mitigating against the threat of low IAQ. In the context of the ongoing COVID-19 pandemic, selecting a unit that delivers under-performance could be detrimental as air reminds stagnant, with high levels of airborne contaminants suspended within it[62] .

Having considered the importance of the maximum capabilities of an air purifier, it is also important that the unit is not running at full capacity indefinitely. Such over-use will lead to increased stress on the machine, leading to issues such as increased repair requirements and unpleasantly high noise levels. As such, it is advisable to purchase a unit capable of throughput far in excess of required capability — thereby allowing the unit to run at a considerable margin below its full capacity and still achieve AC targets). Under such a scenario, noise levels shall be much lower and, in many cases, hardly noticeable. Furthermore, the optimum number of AC required to prevent airborne infection are unknown in their entirety (although speculated), thus a unit should be capable of exceeding guidelines to future-proof against possible increases in these recommendations as more research becomes available[63].

6 Concluding remarks

This white paper considered research specifically undertaken with the care home environment to understand the damaging role low IAQ can have upon resident's and care workers' health. Such a field is of particular concern during the ongoing COVID-19 pandemic. In line with the well-researched IAQ solution known as 'air purification', this paper takes a more in-depth look at the potential of air purification units to provide a healthier indoor environment, by removing contaminants. The technologies commonly integrated within such solutions are evaluated both theoretically and practically, with a focus on UV-C irradiation as an essential component of any complete air purification solution. It is the intention of the author that such a paper will allow the reader to make a more informed decision regarding the implementation of technologies to counter air-quality issues in care homes. Further, the ultimate goal of this paper is to contribute towards overall improved air quality, and thus the overall health and well-being of all those with a care home environment.

[62] GE et al. 2020
[63] Eames et al. 2009

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