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ARCHITECTURE AND HEALTH IN TRADITIONAL BUILDINGS

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PREFACE

Older housing is sometimes portrayed as damp, dark, uncomfortable, and often unhealthy. This view has suited many interests over the years and while true to a degree, in some instances, by the late 19th century there was a reasonable understanding on how buildings that were healthy should be configured, designed, and constructed. Many building types from this period are popular today with residents and contribute to sustainable urban and rural communities. While appropriate refurbishment is an imperative which the heritage sector should embrace, there are limits to how far this can go in terms of cost, expended carbon, and changes to indoor living conditions. The matter of internal health has always been important but has been subordinate to requirements of reduced operational energy consumption and high airtightness. Recent events with Covid-19 have demonstrated how buildings and the way they are occupied are at the core of public health. As older buildings are a considerable proportion of the housing stock in the UK (approximately 20% in Scotland are from pre-1919), how they are used and upgraded is of considerable importance.

This paper explores issues around infection control in pre-antibiotic times and identifies features from the past that are not only healthy but are low carbon too. These qualities are a mix of passive ventilation, material characteristics, and quality of internal space. Their retention in refurbishment must be a core principle and their application in new build should also be considered. Some of these principles allow for a reduced carbon intensity of plant and equipment that has become dominant in refurbishment and new build in all sectors. That such an approach has had no champion, with little product to sell, has meant that this hitherto has had no voice; many of these benefits have been known for a long time, anecdotally as it were, but as they had no numbers behind them, they had no traction. By way of illustration, the alterations to older school buildings in the 1980s, where ceilings were lowered, windows covered with blinds, and ventilation all but eliminated, shows how far views had changed since the building-conscious design of their inception. Such modifications made them ill-equipped to cope with the new conditions of climate change, often related to overheating, and the conditions required to minimise virus transmission risk. This paper raises issues of how thermal comfort and health is delivered in our homes and seeks to show that past approaches have relevance today.

SUMMARY

While older buildings are often characterised as substandard, they have many beneficial features. Many of the issues now surrounding health in housing were confronted and dealt with by experts and practitioners a century ago. When they were working in this field, respiratory infections were known to be caught indoors. Common diseases of the period, such as tuberculosis, were thought to be airborne, so ventilation was considered a priority. It is becoming so again, as it is now recognised that the SARS-Cov-2 virus is spread by the airborne route.

Housing has been a major factor in the Covid-19 pandemic. Unfortunately, newer housing has not been designed to prevent airborne infection. Another related health hazard in modern housing is poor indoor air quality. New building materials, tighter construction, and reduced ventilation rates can combine to concentrate pollutants. These can react with each other to create further harmful products. In the past, when architects designed indoor environments, they took an integrated approach to ventilation, heating, and lighting. Today, this is less evident. As such, Scotland's historic housing may provide better protection from current and future threats to health than newer dwellings. However, an older one will only confer this protection if used and refurbished appropriately, maximising its designed benefits and improving aspects of performance where needed. Such an approach is not incompatible with current energy and environmental targets.

CONTENTS

1 INTRODUCTION

Throughout history, housing has been arranged to try to stop the spread of diseases. A preventive approach informed the architecture of many cultures, including those of India, China and Imperial Rome. Equally, Scotland has a tradition of building for health. It came to the fore during the 19th century when Scotland's cities grew dramatically. As elsewhere in Britain, public health and hygiene became pressing concerns. Disease, and the fear of it, prompted investment in sewerage, clean water and housing regulations. A Scottish doctor played a leading part in these reforms. Then, Scottish architects began arranging hospitals and schools for hygiene and health. They took the same approach to housing design and continued to do so into the 20th century.

One major influence on housing from this period – which sets it apart from later designs – was a widespread appreciation of the dangers of poorly ventilated spaces. By this time, many common life-threatening respiratory infections, such as tuberculosis, rheumatic fever and measles were believed to be transmitted through the air. So, architects and legislators put measures in place to reduce the risks of such infections. They were based on practical experience rather than on hard scientific evidence. Unfortunately, this meant they could be ignored or dismissed when the focus of attention moved elsewhere. Changes in medical philosophy have, at times, cast doubt on the health benefits of fresh air, daylight, and hygiene in buildings. Even today, the transmission of infectious diseases indoors remains poorly understood. However, the Covid-19 pandemic has given new impetus to what has been a long-neglected area of research. Significantly, recent scientific findings support the thinking behind many of the design principles that were once thought to prevent disease and promote health in the housing of the late 19th century and this thinking deserves review and application.

2 BACKGROUND: THE WORK OF DR WILLIAM DUNCAN

This report takes as its starting point the 1st January 1847, when Liverpool appointed Dr. William Duncan (1805-1863) as its (and Britain's) first Medical Officer. Born of Scottish parents who moved to Liverpool from Dumfriesshire, Duncan studied medicine at Edinburgh University. He qualified in 1827 and moved back to Liverpool to begin work in general practice. By this time, the city was one of the fastest growing, and one of the unhealthiest, in Britain. Liverpool was second only to London in the number of its inhabitants and remained in second place until the 1860s when Glasgow surpassed it. In 1801, some 82,000 people lived in the city and by 1861 this figure had risen to 444,000 (Halliday, 2003).

The working poor flocked to Liverpool's slums, including many thousands of immigrants from Ireland after the potato famine of 1845. There was little investment in public health to cater for this growing population, so Liverpool suffered epidemics of cholera, diarrhoea, typhoid and typhus which claimed many thousands of lives. During William Duncan's first year as Medical Officer, some 21,000 people died.

Unusually for the time, Dr. Duncan recognised the link between living conditions and the outbreak of epidemic disease and, in particular, cholera. He carried out a survey of the sanitary conditions in Liverpool and found that less than half the street mileage of the city had any sewerage. Families were living in small windowless cellars with no water, sanitation, or fresh air. In all, one-fifth of the working population lived this way, often deep in sewage. Others lived in overcrowded housing built around closed courtyards, where it was common practice to empty privies over the courts. It was not until 1846 that houses were allowed to connect their cesspools or drains to the sewers. With the help of Liverpool's borough engineer James Newlands, Duncan began a long campaign for improved housing and sanitation for the poor of the city (Halliday, 2003).

In 1840, Duncan had reported the findings of his survey of Liverpool's sanitation to the Poor Law Commission. Two years later, the secretary to the commissioners, Edwin Chadwick, published his landmark Report on the Sanitary Condition of the Labouring Classes of Great Britain. Chadwick, like Duncan, believed that improving the environment in cities would prevent infectious disease and that housing was key to this. Chadwick's report of 1842 was radical for the time in that it called for health promotion rather than reactive medicine. The motive was financial: a preventive approach to public health would lower the costs of poor relief. Also, better housing for workers would improve their health and, thus, would increase their productivity (Richardson, 1887). So the idea that safe and sanitary homes were essential to public health can trace its roots via Chadwick back to Duncan.

3 SANITARY HOUSING AND FLORENCE NIGHTINGALE

Following these initiatives, housing for what was termed “the working poor” became more of a priority. At the start of the 19th century, Robert Owen (1771-1858) had already established his pioneering community at New Lanark, between Edinburgh and Glasgow. The millworkers’ housing at New Lanark was designed for health and was a significant advance on what was available elsewhere in industrial Britain. One thing Owen insisted on was adequate ventilation in dwellings (Owen and Claeys, 1991). His work inspired other enlightened industrialists to build and plan for health. The Cadbury brother’s Bournville Village, and William and Lever’s Port Sunlight were two notable examples. The Garden City Movement (explained further later in the text) and, later, the Modern Movement emerged to improve ordinary people’s living conditions. But it was Florence Nightingale (1820–1910), one of the leading social reformers of the mid-19th century, who set out what these conditions should be and then promoted them.

Florence Nightingale regarded sanitary housing as essential to public health. An early disciple of Edwin Chadwick, by the 1860s she was at the forefront of several fields, including hospital planning, public and military health, medical statistics and nursing training. Like Chadwick, she campaigned for health promotion and preventive medicine. Nightingale’s concept of public healthcare was centered on housing rather than hospitals. She believed the sick were better off cared for at home with visits by nurses and doctors. Hospitals were too dangerous because the risk of infection was so high. So, in her view, investing in sanitary housing was a far better way to improve public health than spending money on hospital construction:

> *`...in all European countries, more sickness, poverty, mortality and crime is due to the state of our poor men’s dwellings than any other cause. And I would rather devote money to remedying this than any institution.’* (McDonald, 2003, p. 171)

In her *Notes on Nursing* of 1859, Nightingale identified five requirements for health in a house: pure air; pure water; efficient drainage; cleanliness; and daylight. She believed good design shortened the course of diseases and promoted health.

Nightingale was highly critical of the way in which hospitals were being built at the time because she felt they put the patients’ health at risk. They were often overcrowded, badly ventilated, and poorly lit. She believed the sick needed pure air, sunlight, and variable conditions, if they were to have the best chance of recovery. Sickrooms in houses and hospital wards had to provide patients with fresh air through open windows. The air indoors had to be as pure as it was outside.

> *‘Always air from the air without, and that, too, through those windows, through which the air comes freshest.’* (Nightingale, 1859)

Like other Sanitarians, Florence Nightingale believed that infectious diseases were transmitted by the air in and around buildings. They could travel long distances, carried in the `bad air' from sick rooms. They could also come from rotting matter, filth, and sewer gases. This provided the rationale for the construction of closed sewers and drains. It was also why Nightingale argued that hospital wards should be one or two-storey pavilions built on spacious grounds and cross-ventilated. Big windows on both sides and tall ceilings facilitated natural ventilation and helped reduce infection. Figure 1 shows what is often termed a 'Nightingale Ward' in Ward 15 of the Royal Infirmary of Edinburgh, built in 1879 and one of the largest voluntary hospitals in the United Kingdom at this time.

Figure 1 - Ward 15 in the Royal Infirmary of Edinburgh in 1917. Note the high ceilings and windows on both sides for cross ventilation. © Survey of Private Collection. Dr G L Malcolm-Smith album. Courtesy of HES.

4 THE TRANSMISSION OF INFECTION

Within the scientific community, the modes of transmission of respiratory diseases have been the subject of discussion and debate for more than a century. In Nightingale's day, dust was considered to be a hazard. Respiratory infections were thought to be due to the inhalation of infective dust suspended in the air. By the 1890s, tuberculosis was recognised as an infectious disease. Dry tuberculous sputum was believed to be particularly dangerous and, so, tuberculosis sanatoria were designed to reduce the amount of dust in the air and on surfaces to a minimum. Many of the leading figures of the Modern Movement were involved in sanatorium design. One of the principles of Modernism was that mouldings and decorative detail in interiors posed a threat to health because of the accumulation of infective dust. So did heavy furniture. This had to be lightweight and hygienic to prevent dust and bacteria gathering on or beneath it (Hobday 2006).

However, medical thinking changed in the early years of the 20th century. Dust was no longer considered important. Research seemed to show that large expelled droplets were the main route of transmission. The findings suggested that infections occurred at close distances. They came either directly from the inhalation of droplets from contagious individuals when they coughed or sneezed or through contact with surfaces freshly contaminated by them. Gradually, airborne infection became less important and fewer precautions were taken to prevent it (Hobday and Dancer, 2013). Antiseptic and aseptic procedures assumed greater importance than damp-dusting and cross-ventilation in the battle against contagion. Also, bacteriology and germ theory moved attention away from the built environment, towards individual infectious agents and to the patient, rather than the ward. By this time, infectious diseases posed less of a threat to public health than they had done. At the end of the 19th century, they accounted for a fifth of all deaths, down from a third from 50 years earlier (Galbraith and McCormick, 1997, p. 3).

Although medicine was moving away from the environment towards reactive medicine, some public health experts still argued that the priority should be to get rid of the slums of cities with their overcrowded tenements, sunless rooms and lack of ventilation. Money should be spent on eliminating the conditions that caused diseases such as tuberculosis; not in building and maintaining sanatoria. At the end of the First World War, Lloyd George launched the `Homes fit for Heroes' campaign. Much of the thinking on healthy housing at this time was formulated by Raymond Unwin, the pre-eminent architect of the Garden City Movement, whose work can be seen in Gretna (Rosenburg, 2016).

Although many architects and others were planning housing for light and air at this time, there was less emphasis on it in hospitals. By the 1930s, architects were starting to design hospital wards with small bed bays. Hospitals became more compact and were no longer restricted to two floors, as they had been. However, fresh air continued to be thought important in tuberculosis sanatoria (Hughes, 2000). But in the decades that followed, the design of housing and other buildings to prevent infections became less of a priority.

Dust was still considered dangerous; but infections caused by it were hard to prove. During the 1930s, scientists discovered that small droplets, or `droplet nuclei', could remain suspended in the air for long periods and cause infections. But the prevailing orthodoxy remained then – as it still is today – that large droplets are the primary route of transmission of respiratory infections (Hobday, 2020). Somewhat ironically, research is now showing that the old idea that dust transmits respiratory infections may be valid after all. The results of experiments published in *Nature Communications* 2020 prove that influenza viruses can spread through the air on dust, on fibres and other microscopic particles, and then infect (Asadi et al., 2020). If this neglected mode of infection gets wider recognition, it will change infection control protocols (Hobday, 2020). This could, in turn, influence building design and refurbishment.

5 OPEN AIR AND VENTILATION

During the late 19th and into the 20th century, there was a widespread belief in the disinfecting and healing properties of outdoor air. Hospital wards and sanatoria were designed for high ventilation rates to exploit both. There was little hard scientific basis for this practice. The open-air regimen, which became the mainstay of tuberculosis therapy, was never investigated by scientists to any great extent. Yet, it was used for decades, until antibiotics became available. There were many examples of such buildings in Scotland. The sanatorium called Nordrach-on-Dee, built in 1890, was designed by a local doctor, Dr David Lawson of Banchory, around provision of light and air for the healing of tuberculosis patients (Figure 2).

Figure 2 - Nordrach-on-Dee Tuberculosis Sanatorium opened in 1890 (destroyed by fire in 2016).

During the First World War, military surgeons routinely used open-air therapy on British casualties; as did those in other countries. The open-air regimen was reported to be particularly successful during the 1918 influenza pandemic. Seriously ill patients nursed outdoors recovered in greater numbers than those nursed indoors (Hobday and Cason, 2009).

Many of the temporary, prefabricated hospitals used during the First World War were specially designed for open-air therapy and this regime was widely adopted in civilian hospitals (Figure 3). They had their origins in the Crimean War where the world's first prefabricated hospital proved particularly successful. It was designed and built by Isambard Kingdom Brunel (1806-1859) who, like Nightingale, went to great lengths to ensure that patients in his hospital's wards enjoyed copious amounts of fresh air to help them recover (Merridew, 2014).

Figure 3 - Open-Air Therapy, Princess Margaret Rose Hospital, Edinburgh. © The Scotsman Publications Ltd. Licensor www.scran.ac.uk.

As the practice of opening the windows or nursing patients on verandas and balconies became common, these features became an important part of the hospitals' design at the time, as seen at the Elsie Inglis Memorial Hospital in Edinburgh, in about 1935 (Figure 4).

Figure 4 - Sunlight and Open Windows at the Elsie Inglis Memorial Hospital, Edinburgh taken around 1935. © Lothian Health Services Archive. Licensor www.scran.ac.uk.

These open-air and ventilation principles used in medicine also became part of the domestic building design. Figure 5 is a simplified cross-section of a traditional dwelling showing ventilation routes, where a central mechanism for air movement is the chimney. There is also movement and infiltration of air through cracks and gaps, and diffusion of water vapour through the building fabric and construction materials (shown as oscillating lines).

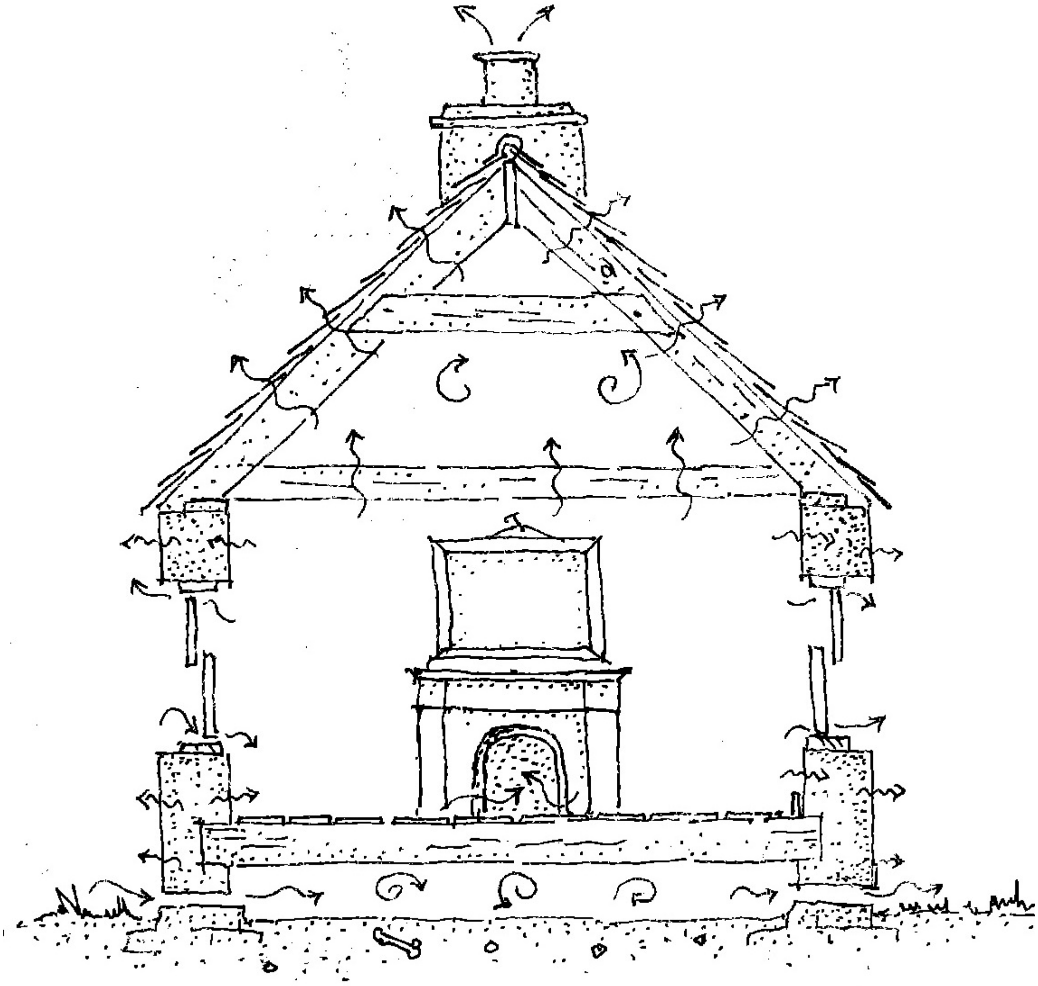


Figure 5 - A simplified cross section through a notional traditional building, showing advection, infiltration and fabric diffusion paths.

Big windows and tall ceilings, as used in Nightingale Wards, were combined to facilitate high air change rates without draughts. Equally, some stairwell cupolas, often a feature of Scottish tenements, provided light and were fitted with vents to disperse warm humid air that rose up the stairwells (Figure 6). This helped draw the air from the flats up the stair and out at the top. If these vents are shut or removed, stairwells can often become hot or odoriferous.

Figure 6 - A passive ventilation cowl can be seen at the top of a stairwell in Edinburgh and to the right a modern mechanical installation.

6 VENTILATION AND THE CONTROL OF INFECTION

In the 1960s, a series of experiments performed by Ministry of Defence scientists at Porton Down demonstrated that rural outdoor air kills airborne bacteria and viruses. When they exposed them to the open air outside a building, both died off rapidly. However, the lethal effects were greatly reduced when samples of the same pathogens were tested indoors (May and Druett, 1969). They also disappeared swiftly in any form of enclosure. The findings suggested that the chemical agent responsible for this germicidal effect, which they called the `Open Air Factor', was stable in free air but was nullified once it came into contact with surfaces. Further research at Porton Down showed this Open Air Factor could be fully retained in experimental containers if ventilation rates were high. Significantly, the rates of fresh air needed for full preservation of it were comparable to those typical of old cross-ventilated hospital wards with large windows and high ceilings (Hobday, 2019).

In more recent times, the idea that a hospital or a house can promote health has become less of a focus. Fresh air is no longer thought to have curative properties and open-air treatment was abandoned in the 1960s, when antibiotics became the dominant treatment route and open-air therapy was discontinued. Over time, creating comfortable conditions became more important than providing a germ-free therapeutic environment. However, recent research recognises that if the air coming into a building is clean, higher ventilation rates can have health benefits. Research in homes, schools and offices shows that a good supply of fresh air can reduce asthma, Sick Building symptoms, and sick leave (Shrubsole et al., 2014; Milner et al., 2015).

Unfortunately, antibiotics are no longer as effective as they were. Antimicrobial resistance is now described as a global crisis (Aslam et al., 2018). In April 2019, the UK's Chief Medical Officer described the threat from drug-resistant bacteria as being as big as that of climate change (Harvey, 2019). So, there are good grounds for reviewing how bacterial infections were dealt with in buildings before antibiotics were discovered. The disinfecting properties of fresh air have been largely overlooked since the 1960s, but there is robust scientific evidence that outdoor air can kill pathogens.

A recent study of ventilation and infection rates in different rooms occupied by tuberculosis patients has shown that pre-1950 hospitals with high ceilings and large windows offered the best protection (Escombe et al., 2007). Whether this was simply due to high ventilation rates diluting and dispersing tuberculosis in the air or to the Open Air Factor, remains uncertain. But it is possible that the latter was responsible for some of the protective effect. Also, case studies show that cross-ventilation was an effective way of controlling SARS infections in hospitals during the 2003 pandemic (Qian et al., 2010). As yet, no tests have been carried out to determine whether open air is lethal to airborne pathogens in hospital wards. But apparatus has been developed which replicates outdoor air's germicidal properties indoors. Such equipment has been tested as an air disinfectant in hospitals (O'Brian et al., 2012). A greater understanding and appreciation of the Open Air Factor will help in an era of evolving antibiotic resistance and new virulent infections.

Understanding how pathogens spread indoors is now central to global public health, given the threat of existing and future pandemics. Unfortunately, the indoor transmission of infectious diseases is poorly understood (Hobday and Dancer, 2013). Outbreaks of respiratory infections, such as the severe acute respiratory syndrome (SARS) epidemic in 2003, the H1N1 influenza epidemic in 2011 and the emergence of Middle East respiratory syndrome (MERS) in 2014 have raised awareness of the importance of ventilation in removing and diluting pathogen-laden air (Qian and Xiaohong Zheng, 2018). The Covid-19 outbreak heightened this, following evidence of airborne transmission of the virus (Morawska et al, 2020). However, the field has been under-researched for decades. Significantly, current minimum ventilation rates to prevent infections in hospitals, or elsewhere, have no scientific basis. There is not enough data to establish what they should be (Li et al., 2007; Qian and Xiaohong Zheng, 2018).

Recent research suggests that between a quarter and half of influenza contracted in housing may be transmitted by the airborne route (Cowling et al., 2014; Cowling et al., 2013). Infections caught in homes have been a major factor in the Covid-19 pandemic (Haroon et al., 2020; Grijalva et al., 2020). How much of this illness was passed through the air is uncertain. But guidance is now in place to encourage better ventilation in houses and elsewhere (Anon, 2021).

Prior to the pandemic, standards and building regulations had not addressed the threat of infections in housing for decades. Throughout most of Europe, the minimum ventilation rate for new mechanically ventilated buildings is around 0.5 air changes per hour (ACH), while in North America it is between 0.30 and 0.35 ACH (Levasseur et al., 2017). It is questionable whether such air change rates are sufficient to dilute and disperse viruses or other pathogens. Historical evidence and recent research suggest that the minimum ventilation rates needed are far higher (Hobday, 2019).

7 VENTILATION RATES AND CO2 LEVELS

In a study of newly built, naturally ventilated Scottish homes, all of the occupants experienced periods where CO2 levels in bedrooms were significantly above 1000 ppm. Dwellings averaged close to twice this threshold in many cases (Sharpe et al., 2015). The planned trickle ventilation from windows adopted in these dwellings proved largely ineffective. Windows were the preferred means of ventilation by occupants. But the occupants tended to open them to control indoor temperatures, rather than improve air quality. In 2013, researchers from the University of Strathclyde who had measured CO2 levels in newly completed Scottish homes stated that reducing ventilation without providing a planned and effective ventilation strategy was likely to result in a toxic and more hazardous indoor environment (Howieson, Sharpe and Farren, 2013).

The case put for planned natural ventilation with trickle ventilators over adventitious leakages is that trickle ventilators can be located and controlled where they are needed (Kukadia et al., 2012). However, the findings of the Strathclyde University study shows this is not sufficient. Similarly, research on mechanical ventilation has shown it to have severe limitations in newly built Scottish homes (Kukadia et al., 2012). As dwellings become more airtight, any failure of planned natural or mechanical ventilation becomes a health issue. If occupants cannot rely upon uncontrolled infiltration to remove pollutants, it has been suggested that some form of fail-safe strategy should be put in place. It remains to be seen how this would work in practice and what ventilation rate would be considered fit for purpose.

Current ventilation standards in Europe and North America mainly set ventilation rates that address the risks of discomfort from unpleasant odours and unacceptable air quality, as perceived by occupants and visitors to buildings (Carrer, de Oliveira Fernandes and Santos, 2018). In 2018, the pan-European `HealthVent' project proposed a base ventilation rate of 4 L/s per person. However, the findings of other reviews of the scientific literature on ventilation rates propose much higher rates to eliminate health risks (Carrer, de Oliveira Fernandes and Santos, 2018). Currently, these appear to be underestimated.

8 OPEN FIRES AND RADIANT HEAT

Before central heating became popular in this country, radiant heating through open fires and high ventilation rates via a chimney were the norm. They were considered beneficial to health. During the 1920s, the then leading authority on indoor health, Sir Leonard Hill, stated that the ideal method of warming and ventilating rooms would give occupants:

> *`… radiant heat, a warm floor, and agreeable movement of cool air – the conditions of a sunny spring day out of doors.'* (Hill, 1925, p.37)

Both infiltration and diffusion achieved a moisture equilibrium that ensured the fabric of the building did not decay, as well as giving beneficial conditions for occupants. Florence Nightingale stated how important chimneys were as ventilating shafts, as Hill did. This thinking, while old, is not obsolete. Humidity is a feature of the British climate and one function of the open hearth would have been the removal of moisture. This idea was revisited in the 1990s, when it became clear that that the declining use of open fires and tighter building envelopes were causing ventilation problems; in particular, the removal of moisture generated by household activities. At the time, one solution put forward to remedy the moisture problem was passive stack ventilation (Stephen, Parkins and Woolliscroft, 1994).

Open hearths and unblocked flues remain an effective aid to ventilation, but heat losses are a concern because an appreciable amount of warm, conditioned air can pass up a domestic chimney (Iles, 2015). Nevertheless, a balance must be struck between health on one side and energy thrift on the other. Such losses are less problematic in buildings arranged for radiant heating.

One major advantage of heating with a radiant heat source is that it allows indoor air temperatures to be kept lower than is the case with convective heating. With radiant heating, room air is not the main medium of heat transfer to the occupants. A radiant source heats internal surfaces and the warmer the internal surfaces of a room are, the cooler the air can be while still maintaining comfortable conditions. Less energy is also needed to heat incoming outdoor air to a comfortable temperature than with heat supplied by convection because the room air is not `conditioned'. Consequently, ventilation heat losses are not as significant as they are with warm air heating. This, in turn, means air change rates can be higher without losing too much heat and energy.

One source of radiant heat in buildings is sunlight. Many older buildings were designed to admit solar radiation to supplement the heating and to take advantage of the health benefits. Where space allowed, vernacular buildings were often orientated to maximise solar gains in the winter and to dry out the masonry on the principal elevations. Following the repeal of the Window Tax in 1851, there were more opportunities to get sunlight into buildings.

It was thought that radiant energy from a fire could make up for any absence of radiant heat from the sun. Hill had concluded that in a damp climate, like ours in Scotland, the healthiest approach was to combine the radiant heat of an open fire with the ventilation provided by its chimney, and by an open window when needed.

This finds some support in recent historical review of heating and ventilation in British homes. The author suggests it is natural to prefer radiant heat from an open fire in an unpredictable climate with 'notably limited sunshine' (Rudge, 2012). Hill's conclusions are further supported in a technical paper written for Historic Scotland in 2011, titled 'Keeping Warm in a Cooler House', in which the benefits and techniques of radiant heating are examined. The authors argue that by using lower background-temperature heating and local warmth from supplementary radiant heaters, it is possible to provide comfortable conditions, low energy costs, and low carbon dioxide emissions in homes (Humphreys, Nicol and Roaf, 2011).

It is, in effect, a revival of an older approach to heating which does not try to provide a uniform indoor temperature. Instead, it creates thermal micro-climates to which the occupants are constantly adapting. This is what central heating replaced. It is worth noting that Professor Hill had strong reservations about central heating, which was being proposed when he was active in research in the 1920s. The monotonous, over-warm atmosphere it produced would not promote health in people who spent too much time indoors. Indeed, Hill thought a sedentary life in such conditions increased the risk of tuberculosis and other illnesses. Hill made a clear distinction between comfort and health in buildings: the aim should not be to pander to people by giving them over-warm, comfortable indoor conditions, but to keep them strong and fit. Such warmth was only appropriate for the elderly or infirm:

> *'The hothouse conditions of life suitable for the failing powers of the aged, the injured in a state of shock and those in the last stages of wasting disease are mistakenly supposed to be suitable for the young and healthy.'* (Hill, 1920)

Hill's thinking was that humans have an inherent need to exercise and challenge their thermoregulatory system. In recent years, there has been a revival in research in this field. The health benefits of adapting to changes in indoor conditions are gaining greater recognition (van Marken Lichtenbelt et al., 2017). Florence Nightingale also recommended radiant heating in houses and hospital wards, rather than warm air. Like Hill, she believed that keeping patients in warm air at a fixed temperature, day and night, was harmful. For many years, the comfort standards set in buildings limited opportunities for the thermal stimulation occupants may need for health (Stoops, 2006). Fortunately, current international standards do make provision for an adaptive approach to thermal comfort. However, they treat thermal comfort, air quality and other factors separately; an integrated approach is lacking (Khovalyg et al., 2020).

The central heating systems that Hill objected to transfer heat mostly by warming air. But historical and recent evidence suggests that radiant heating is healthier than convected air in a number of ways. Radiant heating can provide more uniform floor-to-ceiling temperature gradients than convective heating. Warm air rises; radiant heat does not. Keeping a floor warm can quicken blood flow in the feet through vasodilation. This, in turn, can improve some vascular-related disorders (Song, 2008). Keeping feet warm also raises the temperature of the nasal mucosa (Assanasen et al., 2003; Abbott et al., 2001). This improves the ability of the nose to condition air as it is inhaled. Conversely, if the feet get cold, this can cause the blood-vessels in the nose to constrict. Such constriction of the upper airways has been proposed as a mechanism that reduces our defence against the germs that cause respiratory infection. It cuts off the flow of blood that supplies the white cells that fight them (Johnson and Eccles, 2005).

Another benefit of radiant heating is that infrared radiation penetrates deeply into the body and can stimulate healing processes. Red and near-infrared spectrum irradiation has been used to treat a range of injuries and chronic diseases. There is growing evidence of positive effects on a range of conditions including heart disease, diabetes, central nervous system disorders and autoimmune diseases (Heiskanen, Pfiffner and Partonen, 2020).

9 SUNLIGHT AND HEALTH

As with outdoor air, by the middle of the 19th century, there was a growing realisation that getting sunlight into buildings was better than keeping it out. Florence Nightingale insisted on sunlight in wards and homes at a time when others thought it was harmful. She considered this as second only in importance to pure air in sick rooms.

We now know that many of the claims she made for sunlight were correct; sunlight disinfected the air and it helped patients recover. In 1877, Dr. Arthur Downes and Mr. Thomas Blunt reported to the Royal Society that sunlight killed bacteria and it did so through glass. Then in 1890, the German physicist and bacteriologist Robert Koch who identified the tubercle bacillus, or Mycobacterium tuberculosis bacteria, disproving the widely held belief that it was an inherited and non-infectious disease, announced that sunlight was lethal to the tubercle bacillus; again through glass. The next breakthrough came in 1903, when Niels Finsen was awarded the Nobel Prize for Physiology and Medicine in recognition of his success using sunlight and ultra-violet radiation from lamps to treat tuberculosis (Hobday, 1997).

Another example of sunlight used for the health in buildings is the formerly common childhood illness ‘rickets’. This was the most common childhood disease in the polluted industrial cities of Europe and the United States; and endemic in Britain for over 200 years. In 1921, clinical research work showed lack of exposure to sunlight, which resulted in vitamin D deficiency, was the cause. Prior to this, in 1918, a British Medical Research Committee had tried to find out why rickets affected so many children. The thinking was that if bad housing and lack of fresh air and exercise were factors in the cause of rickets, they could expect to see less of it under better living conditions; this was shown to be the case (Findlay et al., 1918).

10 DOMESTIC ARCHITECTURE AND SUNLIGHT

Cleanliness and sunlight were now the first line of defense against tuberculosis and all of the many other communicable diseases linked to bad housing (e.g. diphtheria, smallpox, scarlet fever, rheumatic fever, whooping cough, measles, and pneumonia).

Architects started producing buildings that were well sunlit to promote health and hygiene (Hobday, 1997). They had a relatively high window-to-wall ratio, as shown by houses of various types for both the upper and working classes around Scotland. This design allowed taking advantage of the sun by admitting natural light in, supplementing the heating, and the additional health benefits gained. Bay windows, sun lounges and sash windows became popular features in houses.

From the turn of the 20th century onwards, dark cluttered interiors were no longer thought to be safe. Instead, the airy, austere sunlit rooms became the ideal. Thanks to advances in glass manufacture people could afford to get some daylight and fresh air into their properties. Urban planners laid out streets and open spaces so that city-dwellers could get access to sunlight when it was available.

Figure 7 - Modern type housing from the 1980s seen next to a 19th century colony flat in Stockbridge, Edinburgh. Note the low ceiling height and relatively smaller windows in the newer building.

In contrast, many of the houses built over the last 30 years have comparatively small windows, partially due to reduced room (and therefore window) height, safety regulations for minimum sill height, as well as efforts to improve energy efficiency. Overheating caused by solar gain (through window glazing), has been addressed by reducing window size. This reduces heat gains without incurring the cost of providing shading to the windows (Ministry of Housing, Communities and Local Government, 2021) (Figure 7). However, it is increasingly recognized that a reduction of available light can have adverse effects on the inhabitants' health and wellbeing (Osibona, Solomon and Fecht, 2021). It can also affect the biology of buildings (Fahimipour et al., 2018).

11 SUNLIGHT AND INDOOR PHOTOCHEMISTRY

In 2013, scientists showed for the first time that sunlight can trigger hydroxyl (OH) radical production in a building. The results of tests in a school classroom in Marseilles, France found OH levels peaked when sunlight came in through the windows and pollutants were present. The chemical reaction ceased when the classroom was purged with fresh air. This highlights the importance of ensuring adequate ventilation levels in sunlit spaces. It also demonstrates the effectiveness and necessity of purging indoor spaces when there are harmful substances in the air (Gómez Alvarez et al., 2013).

More recent research has confirmed that photolysis processes indoors can generate significant levels of hydroxyl and peroxyl radicals (OH and HO2, `HOx') and secondary species (Kowal, Allen and Kahan, 2017). It has been suggested that reactions with such oxidants could be of equal or greater importance indoors than those with ozone (Young et al., 2019). Yet, indoor photochemistry was recently referred to as a largely unconsidered potential source of such products (Blocquet et al., 2018). Another recent paper on photolysis indoors noted that the increased use of `green' building materials and cleaning products can introduce additional oxidative capacity indoors. Furthermore, secondary emissions are rarely considered in product evaluation and labelling (Young et al., 2019).

It would appear that sunlight is capable of initiating cascades of chemical reactions in indoor air, just as it does in outdoor air. This is of particular relevance to the upgrading of historic buildings, many of which have extensive glazing; notably those from the late 19th and early 20th century. If the permeability of these structures is altered and ventilation rates reduced, sunlight penetration could actually have harmful effects.

The available evidence suggests lighting and ventilation strategies must be considered together; as was once the case. If not, adverse chemical reactions may occur, and sunlight can trigger them. Electric lighting can too; it can produce enough light at the right wavelengths to trigger photochemical reactions indoors (Kowal, Allen and Kahan, 2017). Further research work is urgently needed to clarify how lighting and ventilation strategies affect indoor air quality in homes built and refurbished to current standards.

12 THE MICROBIOLOGY OF THE BUILT ENVIRONMENT

There is evidence that infectious conditions indoors are not only created by the presence of harmful viruses and bacteria – but also by the absence of other species. Until recently, micro-organisms in hospitals and houses were thought to play a purely negative role. They were pathogenic, or infectious, and a threat to health. But it is now clear that microbes can have health benefits indoors. This has prompted researchers to investigate whether indoor environments can be designed to prevent diseases in new ways. It seems that encouraging a wide range of bacteria and viruses indoors can stop the proliferation of harmful micro-organisms (Horve et al., 2020). Such microbial diversity depends on a number of factors, including ventilation rates. Research has shown that mechanically ventilated rooms contain less diverse microbial communities than window-ventilated rooms. In addition, reducing ventilation rates reduces the diversity of the indoor microbiome (Kembel et al., 2012).

The way houses are built also influences the indoor microbiome. Until recently, homes were constructed with traditional materials to which humans have spent millennia adapting. By contrast, modern building materials may have an adverse effect on the microbiome indoors and then on us:

> *`…modern buildings are constructed with synthetic materials, plastics, and concrete, and the timber and cardboard are treated with adhesives and biocides, and the buildings are ventilated by air conditioning systems. When these modern structures degrade, become damp, or accumulate condensation in cavity walls, they do not become colonised with the bacterial strains with which we coevolved. They become habitats for unusual strains that we did not encounter during our evolutionary history, some of which synthesise toxic molecules that we are unable to inactivate.’* (Rock, 2013, p. 18364)

13 INDOOR POLLUTION

Typically, the air inside a home is contaminated with a mixture of particulates, gases such as ozone, nitrogen dioxide, carbon dioxide and carbon monoxide, volatile organic chemicals (VOCs), moisture and biological agents. Pollutants come from outside and from various indoor sources. The latter include construction materials, the occupants, pets, household items, carpets, furnishings, heating appliances, cleaning, cooking and home repair. Personal exposure to pollutants has increased because of increased time spent indoors and reduced air change rates (Spengler and Adamkiewicz, 2009).

Many of the VOCs commonly found indoors, such as benzene and formaldehyde, are toxic or carcinogenic, or both. Some of these chemicals reach higher concentrations in indoor air than outdoors because they are present in consumer products or are off-gassed from building materials. The health effects of exposure to indoor pollutants range from irritation of the skin, and the worsening of asthmatic symptoms, to premature deaths from lung and heart disease (Kukadia and Upton, 2019). There are calls for more research into the biological mechanisms by which polluted air damages human health, and into the acute and long-term effects of exposure (Wells et al., 2017; Zhang et al., 2019).

Currently, information in the UK and worldwide on recommended standards and concentration guidelines for indoor air pollutants is limited (Kukadia and Upton, 2019). Few studies have examined their effects on human health and, in particular, the impact of mixtures of them (Zhang et al., 2019). Evidence is emerging that the adverse effects of air pollution persist at levels below current regulatory standards. For example, for many years it was thought that carbon dioxide levels had to reach concentrations of at least 5,000 parts per million (ppm) before becoming a threat to human health. Yet new research suggests CO2 levels much lower than this can cause inflammatory conditions, cognitive impairment and other serious health problems, even if exposure only lasts for a few hours. Chronic exposure to CO2 at levels between 2,000ppm and 3,000ppm may result in kidney calcification, bone demineralisation and other health problems (Jacobson et al., 2019). Low building ventilation rates and prolonged periods spent indoors increase the risks of exposure. CO2 concentrations, which are relatively easily measured, are also a proxy indicator for the presence of other contaminants, such as those mentioned above. Also they are now used as a way of judging indoor air quality with respect to Covid-19 infection risk (Piscitelli et al., 2022).

14 INDOOR CHEMISTRY

Air pollution outdoors has long been recognised as a dynamic process: a cascade of chemical and physical processes driven by the Earth's climate and solar radiation. By contrast, until the 1990s, the science behind indoor pollution did not consider chemical reactions between primary pollutants. So, the secondary pollutants these reactions produce were largely overlooked (Salthammer et al, 2018). Research now shows there are more pollutants in buildings than there were 50 years ago and that they can react with one another to produce highly reactive compounds in what has become known as \`indoor chemistry' (Weschler and Carslaw, 2018).

Until recently, much of the chemistry in buildings was thought to be the result of reactions with ozone, which is a highly reactive oxidant. Ozone is a constituent of clean air which forms in the upper atmosphere. However, ozone is also created at ground level by photochemical reactions. This so-called \`bad ozone' is formed in polluted air when nitrogen oxides (NOx) and volatile organic compounds react in the presence of solar radiation (Gaffney and Marley, 2003; EPA Office of Air and Radiation, 2003). Ozone can infiltrate buildings at levels capable of triggering chemical reactions. There are more chemicals that react with ozone in buildings than there are in outdoor air. Therefore, the inhalation of the products of these reactions is far greater indoors than the intake outdoors (Weschler, 2006).

Many indoor pollutants have been identified that can react with ozone. During the 1990s, reactions between ozone and pollutant VOCs were identified, which can produce a further powerful oxidant, already discussed above, the hydroxyl radical (OH). The production of hydroxyl radicals indoors poses a threat to health because they can oxidise VOCs to form secondary gases and aerosols. Secondary emissions are a concern because they are potentially more harmful than primary sources (Weschler, 2011). Also, the hydroxyl radical can react with some indoor VOCs faster than ozone (Weschler, 1996). Investigating indoor chemical processes such as these is difficult, because they generate products that can only be measured with highly sophisticated equipment (Wells et al., 2017). In addition, both ozone and OH may also produce so-called \`stealth' products that cannot be measured with current technology. In addition, the low ventilation rates in low-energy buildings are an emerging area of interest to researchers, as they allow more time for gas-phase indoor chemistry to occur (Weschler and Carslay, 2018).

15 INTEGRATED DESIGN

Given all the factors that have to be considered, it is useful to examine how they were brought together in the design of buildings during the 19th and into the 20th century. Considerable progress was made in identifying what constitutes a healthy indoor environment in homes. It is noticeable that pioneers in this field, Florence Nightingale, and later Sir Leonard Hill, took what would now be called an integrated or holistic approach to the subject (Nightingale, 1863; Hill and Campell, 1925). They considered the combined effects of sunlight, heating, and ventilation on building occupants' health and it did so in an integrated manner. So did many leading architects in the decades that followed (Hobday, 2006; Rosenburg, 2016).

For the designers of social housing in the early 20th century, the provision of windows for natural light and the ventilation they gave was a big focus. In Scotland, during the 1930s, Edinburgh's City Architect Ebenezer James MacRae was the leading Scottish figure in planning housing for health. In 1935, he was a member of a Department of Health fact-finding team that inspected continental housing estates and he contributed to the subsequent report which informed local authority housing in the late 1930s (Anon, 2011).

Figure 8 - Social Housing units in Edinburgh designed by the City Architect Ebenezer MacRae in 1936; a traditional style with modern elements.

During the interwar years, MacRae designed many housing projects around Edinburgh. His work, and that of others, blended traditional Scottish architecture with newer building techniques to produce mass housing of good quality. This meant ample provision of light, air, modern sanitation, and largely radiant heat from what were then coal fires. Fenestration was a dominant part of the architecture (Figure 8). The `four in a block', or cottage flat, was particularly successful (Figure 9).

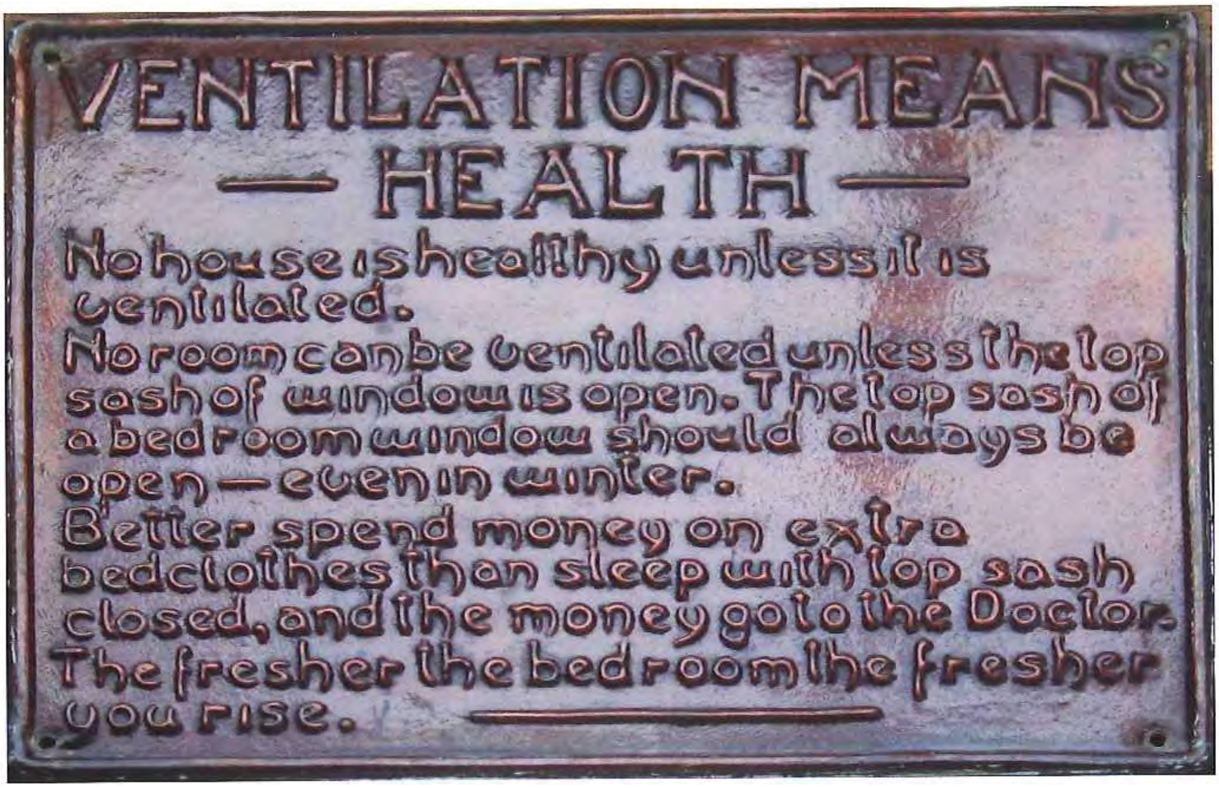
Figure 9 - A 'four in a block' type house designed for social housing in Scotland in the inter war period.

Another housing development that takes this integrated approach was built for Alexander Bell, a distiller from Perth. In the housing scheme he commissioned for workers at his distillery, health and wellbeing were a priority. This estate of over 150 homes, built from 1927 to 1937 in a detached cottage style, followed Garden City principles overall (Figure 10). Bell put great emphasis on the design of the houses, which included all living rooms facing south-west to take advantage of sunlight, and in common with others of the period, a focus on ventilation. This approach was made clear on notices in every kitchen (Figure 11) and every room was ventilated either by windows and a hearth or an inbuilt ventilator in the ceiling (Duncan, 2012).

The Gannochy Trust, who manage these properties today, deliver energy retrofits that follow Alexander Bell's principles of indoor health and amenity (HES, 2015). It is worth noting that the Trust also follows the same approach to the internal climate in more recent new build properties they commissioned.

In recent times, creating healthy indoor conditions has not been addressed in an integrated way. Government agencies have placed greater emphasis on reducing energy use and the carbon footprint of dwellings, than on securing and promoting health. One consequence of this is that a holistic approach to health in buildings is less evident than it was a century ago. Currently, heating and ventilation are considered separately, even though they are clearly related (Kukadia et al., 2012).

Figure 10 - One of the cottages built by Alexander Bell on the edge of Perth. Image © The Gannochy Trust



VENTILATION MEANS
— HEALTH —

No house is healthy unless it is ventilated.
No room can be ventilated unless the top sash of window is open. The top sash of a bedroom window should always be open — even in winter.
Better spend money on extra bedclothes than sleep with top sash closed, and the money go to the Doctor.
The fresher the bedroom the fresher you rise.

Figure 11 - The pressed tin sign fixed to the wall of every kitchen in Alexander Bell's housing scheme. Image © The Gannochy Trust

Also, knowledge about healthy indoor environments has become fragmented. An understanding of the many individual factors that comprise a healthy building, and how the occupants influence them, has been lacking for many years. To illustrate the point, the findings of what may be the first ever collaborative exercise aimed at giving a holistic perspective on indoor environmental research was published as recently as 2018 (Wierzbicka et al., 2018).

This work, which brought together technical, behavioral, and medical experts was undertaken in Scandinavia. It was also in Scandinavia, in 1980, that the first statutory requirement for air-tightness for dwellings was published. The Swedish Building Code (SBN 1980) is credited with introducing the concept of `Build Tight Ventilate Right' which was later promoted in the UK (Perera and Parkins, 1992; Kukadia et al., 2012). In Scandinavia, and other severe climatic regions, combining air-tight building envelopes with mechanical ventilation heat recovery systems is an effective way to save energy. However, the benefits of adopting this approach in the Scottish climate are not clear. The impact on health is uncertain, too. In 2017, a report by Scotland's HEMAC network identified a pressing need for an evidence base on the relationships between indoor air quality (IAQ), ventilation and health in UK homes (McGill et al., 2017). Data on indoor pollutant exposures in homes and the health effects of them are limited. The preference for mechanical systems overlooks the benefits of passive ventilation; one of which is the opportunity for adaptive thermal comfort rather than a more static thermal environment (Roaf and Nicol, 2020).

16 RETROFIT AND REFURBISHMENT

Whether a tight building envelope provides a healthy living environment in the Scottish climate has yet to be determined. There has been a dearth of information on the subject for more than a decade. The impact of refurbishment on indoor air quality was raised by Historic Scotland in a report in 2009 (Halliday, 2009) and another in 2011 (Hobday 2011). Yet, as recently as 2017, only ten scientific studies had been published on IAQ in Western Europe, including newly built and retrofitted buildings. Furthermore, as these studies did not address directly comparable factors related to IAQ it is not possible to draw meaningful conclusions from the findings (Debez et al., 2018). Nevertheless, an upgrade of nearly all dwellings will be required if the UK government's energy efficiency targets are to be met. In 2015, researchers at University College London referred to this undertaking as `one of the largest natural experiments in the indoor environment in the coming decades' (Hamilton et al., 2015). They also noted that these upgrades are likely to have major impacts on the indoor environment and population health. If properly designed and implemented, they argued, an upgrade could have major health benefits. However, they also noted there were risks involved. Poorly designed or modern interventions using inappropriate materials or coatings can lead to sub-optimal conditions which could have unintended consequences on both the health of the occupants (Ibid) and the building fabric (Jenkins and Curtis, 2021).

So, at this point, it is worth summarising the Scandinavian experience, as reported in the findings of the multi-disciplinary research study of 2018, cited earlier. This concludes that higher standards for insulation and air tightness can lead to poor internal conditions due to mould growth, as well as indoor air quality issues. The authors stated that concentrating on energy efficiency risks losing sight of factors necessary for occupant health. They also discuss the potential risks of using materials whose health effects on building occupants have not been tested (Wierzbicka et al., 2018). Some of the concerns raised in this paper are not new to Scotland. Several authors have linked health problems to housing refurbishment. Notably, the increase in asthma rates in Scottish homes in recent years has been linked to it and this has been investigated by Howieson (2005).

There are other health issues that have not been fully addressed in the context of refurbishment. As noted above, carbon dioxide may pose a greater threat to building occupants than previously thought. Similarly, chemical reactions that take place indoors when pollutants are present may have negative health impacts and light can trigger them. There are also concerns about the threat to building occupants' health from infectious diseases and from changes to microbial activity indoors. Some of these health threats could be exacerbated by summertime overheating. Taken together, low ventilation rates in refurbished buildings may be far more hazardous than previously thought.

17 OVERHEATING

As noted above, one indication that an integrated approach has not been taken during new build and refurbishment projects is summertime overheating. This growing threat to public health was discussed in a Historic Scotland report on refurbishment, published in 2011 (Hobday, 2011). At the time, overheating was generally considered only to be problematic in southern English cities. However, a paper published in 2016 reviewed the findings of a number of studies and found overheating was by no means limited to the south; it can also be a problem in Scotland. When insulation levels are high and buildings are sealed, overheating can occur as far north as Inverness (Lomas and Porrit, 2016). This situation may not get better; a changing climate could lead to increased summertime temperatures in Scotland (UKCIP 2021).

It seems the insulation of existing homes has improved and air infiltration has been reduced, without due consideration of summertime heat gains. Unfortunately, the build-up of heat can affect the health and wellbeing of occupants adversely in many ways. One of the most significant of these is disrupted sleep. Also, in extreme cases, the heat stress caused by overheating in buildings can result in premature deaths, especially among the elderly and other vulnerable members of society. The 2003 pan-European heatwave caused 20,000 such deaths. Design guidance has since been published to address the problem of summertime heat gains in British homes (Dengel et al., 2016). However, this can be difficult to achieve in buildings refurbished primarily for the retention of winter heat.

18 CONCLUSION

When Scotland's homes and public buildings were constructed, infectious diseases were the leading cause of sickness and death. Following the repeal of the Window Tax and public health reforms, the architecture of hospitals, schools and homes began to change. New buildings had tall ceilings and often windows on more than one wall to get high ventilation rates and to admit daylight and outdoor air. A healthy indoor environment comprised fresh air through open windows, cross ventilation, sunlight penetration and a radiant heat source. The latter also provided, thanks to its chimney, a further means of ventilating rooms. The first consideration was preventing disease, rather than comfort or energy efficiency. Tuberculosis and other airborne infections were more of a concern for architects and planners then, and they had to know how to deal with them. Science is now showing that much of what they did had a sound basis.

The available evidence suggests lighting, heating and ventilation strategies must be integrated to achieve healthy conditions indoors. Scotland's traditional housing may be better placed to deliver this than newer designs. Radiant heating and high ventilation rates are not obstacles to reaching energy and environmental targets. On the contrary, they offer an alternative approach to achieving them. This may become more attractive if infections become more common, or more difficult to deal with, and if Scotland's weather becomes warmer in the summer. Clearly, more research work should be undertaken to clarify how lighting, heating and ventilation strategies affect indoor air quality and health in Scottish homes being refurbished to current standards. Meanwhile, older ones may offer some useful insights into how best to achieve a healthy indoor environment.

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