NATIONAL ENGINEERING POLICY CENTRE

ROYAL ACADEMY OF ENGINEERING

Rapid review of engineering factors that will influence the spread of COVID-19 in hospital environments

Executive summary

The spread of COVID-19 in hospitals is a complex problem influenced by the virus transmission routes, the hospital environment and how it is used, and how external people and services interact with it. In light of the challenges from COVID-19, Public Health England reviewed the infection protection and control (IPC) guidance to ensure best practice is deployed to help prevent the spread of COVID-19 in hospitals and keep people safe.[1] The primary strategy for controlling transmission in hospitals is following this guidance on cleaning of surfaces, hand hygiene and use of personal protective equipment (PPE). However, engineering solutions play a role to enhance these measures at multiple points in the system, through environmental decontamination, personal and respiratory protective equipment, hand hygiene and environmental design.

Shining a light on this challenge has already created space for innovation but these solutions should not be developed with engineers alone. Instead it is critical that the engineering and healthcare communities collaborate on this challenge and include human factors expertise, statisticians and epidemiologists for a holistic approach.

Taking time to understand/identify the lessons learned from this pandemic will be a critical step to inform how future hospitals are designed and built for resilience and how the healthcare system approaches preparedness.

This paper is a rapid review of engineering factors that will influence the spread of COVID-19 in hospital environments. The review is not meant to be comprehensive; it is part of the engineering community's input to government and is intended to inform further discussion and development of advice. The ideas and suggestions included in this document have been gathered from discussion with stakeholders, including partners to the National Engineering Policy Centre. It is not formal National Engineering Policy Centre guidance.

Introduction

Hospitals are on the frontline of the COVID-19 crisis, providing critical care. Because of the high numbers of infected patients and exposure of healthcare workers to high viral loads, there is a significant risk of viral transmission within hospitals. To reflect this risk, Public Health England

[1] Public Health England (2020) Guidance: [Reducing the risk of transmission of COVID-19 in the hospital setting]

has updated its guidance for reducing the risk of transmission of COVID-19 in the hospital setting.[2]

The engineering profession was consulted to understand the role of engineered systems to support the risk mitigation. This process identified potential engineering solutions to limit hospital onset infection, outlining those already in operation in many hospitals (in the UK and internationally), near term innovations that could support the COVID-19 challenge, and longer-term considerations. Where they are not already in use, these innovations should be considered to be additional to specified hospital cleaning protocols, not as an alternative. Many of the individuals and organisations consulted are focused on just one component of this complex problem but how these processes are integrated is critical to their success.

The review is not meant to be comprehensive, instead it collates the thoughts of relevant individuals and organisations on areas where technology and design solutions may help prevent the spread of hospital onset COVID-19.

Hospital onset infection

Hospital onset infections pose a risk to patients, staff and visitors and are typically estimated to affect 6.4% of patients.[3] From an engineering perspective, hospital onset infection is a complex problem that depends on:

1. the characteristics of infections and how they spread
2. the design, use and maintenance of hospital environments
3. user behaviours
4. interactions with external elements such as the delivery of food and other services.

Each of these considerations is multifaceted with opportunities for engineering design or technology solutions to either increase or suppress the number of hospital-acquired infections. Similar considerations will apply in the social care environment. However, the behaviours of users and external actors are critical to the success of any engineering intervention. These complex interactions mean that a systems approach to reducing the rate of hospital onset infection is crucial.[4] By this, we mean a prevention approach centred on people and an understanding of their needs, which is iterated with stakeholders before implementation and proactively manages risk.

COVID-19

There are engineering design and technology dimensions to infection transmission in hospitals informed by the characteristics of the disease, how it spreads, and the design use and maintenance of hospitals. Providing advice on a COVID-19 specific response relies on an understanding of the disease's transmission, on which information is still emerging. An international roundtable of engineering academies on PPE, convened by our Academy called for better global sharing of data and evidence on virus survival times to try to build consensus on treatment standards and temperature thresholds for disinfectant.

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[2] Ibid
[3] National Institute for Health and Care Excellence (2016) Healthcare-associated infections
[4] Royal Academy of Engineering, Royal College of Physicians, Academy of Medical Sciences (2017) Engineering better care

The scale of the COVID-19 outbreak has highlighted clinical needs that much of the engineering community may not have previously been aware of. This has already resulted in industry-academia partnerships to adapt existing technology and prototype new ideas.

In order to ensure the efficacy of solutions, scientists and engineers must work in partnership with social scientists, psychologists and users in order to fully understand the behavioural aspects of how people use buildings and how technologies for infection control can help. The engineers also need to work with clinicians, healthcare practitioners and patients to understand how solutions play out in practice on busy wards or care homes with competing demands.

In its COVID-19 guidance, the First Affiliated Hospital, Zhejiang University School of Medicine, has published a detailed *Handbook of COVID-19 Prevention and Treatment*.[5] This includes guidance on prevention and control management including: isolation area management; staff management; personal protection management; hospital practice protocols; and digital support for epidemic prevention and control. This illustrates that taking a joined-up approach across many of the elements affecting hospital onset infection may be beneficial.

The role for engineering solutions

There are a range intervention points where engineering design and technology can play a role. These have been identified as hand hygiene, environmental design, personal and respiratory protective equipment, and environmental decontamination. The prevalence of these solutions and the ease of implementation varies, and their adoption will impact patients, staff and visitors differently.

1. Hand hygiene

Wash-hand basins should be accessible at frequent intervals throughout the patient care and visitor pathways and designed to be contact free. The effectiveness of handwashing is reliant on the healthcare professional following the WHO handwashing guidance.[6] There are innovative solutions available such as Sloan Water Technology taps that deliver water with soundwaves and microscopic bubbles.[7] This combination creates a microscopic scrubbing action that cleans without requiring the behaviour change expected with a 20 second wash. A National Institute for Healthcare Research (NIHR) pilot had been planned for summer but has been put on hold because of COVID-19, despite potential benefits to the wider impacts of the virus if it proves successful.

2. Environmental design

There is a significant body of research on the design of hospitals and, in 2013, the then Department of Health published a series of *Health Building Notes* highlighting good design practice to minimise hospital onset infection.[8] Many of the issues highlighted by the engineering

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[5] Handbook of COVID-19 Prevention and Treatment
[6] World Health Organization Clean care is safer care
[7] Sloan Water Technology Ltd.
[8] Department of Health (2013) Health Building Note 00-09: Infection control in the built environment

community below are covered in this guidance. Implementing these classic engineering design solutions may prove challenging or disruptive at a time of crisis.

Ventilation – In the UK natural ventilation can prove highly effective, allowing access to fresh air at high air change per hour rates to increase the dilution. Local extract ventilation and avoiding recycling of air from one space to another could also be effective in limiting airborne infections. Federation of European Heating, Ventilation and Air Conditioning Associations, (REHVA), has published ventilation guidance for COVID-19.[9] This includes practical modifications that both healthcare and other buildings can make to help control COVID-19. The Specialised Ventilation for Healthcare Society has issued guidance on healthcare ventilation that focuses on theatres and other controlled spaces. However, ventilation of all hospital spaces including waiting rooms should be assessed. Any changes to ventilation design should be carefully considered in the context of the neighbouring spaces to ensure that there are not inadvertent effects such as changing the pressurisation.

Layout – Hospitals and field hospitals should have high ceilings with a mixture of narrow plan and open plan spaces. The layout, pressurisation of the space, fresh air supply and extraction process must all be considered to deliver effective hospital ventilation strategies. Patient isolation with en-suite single-bed rooms can limit the spread of hospital onset infections. However, the movement between rooms and the number of visitors create risks for hospital onset infection. Wash-hand basins should be frequent and designed to be contact free. The provision of natural light can have beneficial effects on patients' health and the healing process and can help reduce errors in administering medicines and other mistakes related to the staff visual performance. For field hospitals the infectious patients will be in multibed rooms; in this case anterooms may need to be used when doffing PPE to reduce levels of environmental contamination. The creation of a temporary negative-pressure multibed ward for emergency use has been tested in San Francisco.[10] There will be opportunities to learn from successful international examples.

Clinical waste disposal – Adequate facilities should be in place to store waste, as well as arrangements for waste to be removed for incineration or rendering safe. These systems should be designed to be easy and safe to use. The use of colour coding helps with segregating between different types of medical waste to ensure that each type is discarded, transported, and destroyed properly, preventing larger health issues arising from mislabelled medical waste. Staff training is important to ensure successful implementation.

Drainage – Effective drainage systems should be designed to ensure the venting to atmosphere has been considered. Pressure fluctuation in pipes can cause water traps to be 'pulled', leading to open air paths between drainage pipework and habitable spaces creating a transmission route for airborne viruses. To effectively manage positive and negative air pressure transients within the pipework, PAPA (positive air pressure attenuator) drainage systems may prove beneficial.

Plumbing – The introduction of hand sanitiser has reduced the number of wash-hand basins and the frequency at which they are used. This can result in water stagnation and a risk of bacterial growth; this problem is exacerbated if the water temperature is not kept below 20

[9] REHVA (2020) [COVID-19 Guidance]
[10] Miller et al. (2017) [Implementing a negative-pressure isolation ward for a surge in airborne infectious patients]

degrees. Looped or daisy chain pipework can encourage full circulation of water through the system and pipe insulation, system wide temperature monitoring or a circulating return domestic wholesome water system can maintain appropriate temperatures. Copper pipework should be used between the wholesome water pipework and the sanitary fittings to further reduce infection.

3. Personal and respiratory protective equipment

PPE – There is engineering expertise in the materials and designs for masks as well as gloves, aprons, visors and so on, which must be designed with the fit and comfort of the user in mind. Donning and doffing are the riskiest times for virus transmission for health workers and therefore need effective design solutions. Globally, the engineering community has rapidly responded to the demand for PPE, which has contributed to the design and production of medical grade PPE, creating novel solutions that lend themselves to reuse. There will be lessons to be learned, especially as the designs navigate the regulatory and standards hurdles.

Intubation shields – These can be used to control the risk of infection through aerosols generated during the intubation or extubation of breathing support devices such as ventilators. To minimise the risk of exposure to COVID-19 for frontline staff involved in both the intubation and extubation processes, the Manufacturing Technology Centre, working in collaboration with expert medical consultant practitioners and Rolls-Royce and supported by Innovate UK, has prototyped, developed and tested a new intubation shield for use with ventilators.[11]

Intubation enclosure – The *New England Journal of Medicine* published an update from the Boston Medical Centre on the use of a barrier enclosure during endotracheal intubation (e.g. for use where clinicians have inadequate access to PPE). The barrier studied was an 'aerosol box' that consists of a transparent plastic cube designed to cover a patient's head and that incorporates two circular ports through which the clinician's hands are passed to perform the airway procedure. This was reported to significantly reduce the area contaminated when patients cough during procedure (from a test using a mannequin).[12]

4. Environmental decontamination

Air cleaning – Ultraviolet germicidal irradiation lamps are part of a strategy to reduce contact between hospitalised patients and microbial agents by decreasing the concentration of infectious airborne organisms. These are commonly installed on the upper side of rooms with careful installation of lamp fixtures to prevent patients being exposed to stray UV-C rays. The effectiveness of ultraviolet lamps is dependent on their interaction with heating, ventilation and air conditioning (HVAC) systems, as high relative humidity can attenuate UV and different air flows can expose more or less air volume to direct UV irradiation in the upper side of rooms.[13] These devices should not be used for hand or skin sterilisation. There are a range of portable air cleaning and disinfection technologies that remove microbial particles from the air, which could be appropriate to boost the effectiveness of ventilation in smaller rooms.

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[11] Manufacturing Technology Centre (2020) Intubation shield: supporting our frontline NHS workers

[12] Canelli et al (2020) Barrier Enclosure during Endotracheal Intubation

[13] Commission Internationale de l'Eclairage (2010) UV-C Photocarcinogenesis Risks from Germicidal Lamps.Tech. rep. Commission Internationale de l'Eclairage

Room decontamination – Chemical cleaning is the primary decontamination mechanism, but this is supported by a series of other technologies. Many hospitals already use UV robots to clean and sterilise rooms between patients. An Innovate UK funded company has developed FinsenTech THOR UVC, which delivers UVC light to hard-to-reach places using radar technology to map its surroundings to establish that it is clean and eliminate human error.[14] Additionally, hydrogen peroxide vapor systems are used, filling the room and distributing evenly through the space regardless of the room configuration. However, this can damage equipment and requires closed rooms. Robotic fogging devices are being explored but have not been widely deployed in clinical settings yet. These can be further aided by cold plasma technology, a form of advanced electric air filtration that can be used alongside ventilation to collect and kill air contaminants.

Equipment decontamination – Decontamination of equipment used to treat patients, such as ventilator suction units, must be carried out in approved sterile services departments. If a shortage of single use items arises because of the number of patients needing treatment, there is a risk of clinical staff asking for such items to be reprocessed. Reprocessing of single use equipment is not permitted by UK regulation. In critical situations advice should be sought from the sterile service department personnel and the authorising engineer.

Laser UV-C decontamination – Working with the University of Strathclyde and University of Southampton, M Squared Lasers has developed a novel UV-C laser light source for decontamination. Early stage tests suggest that this laser delivers seven times higher power density than typical UV-C lamps, allowing rapid disinfection. The lower wavelength is also safer for the user. Methods have been developed to integrate the novel laser technology with existing equipment sterilisation biosafety boxes to explore faster decontamination of PPE, ventilators and other tools. The integration of a novel laser backend with already deployed sterilisation solutions for hospital room sterilisation is currently being explored.[15]

Materials – Material choice can limit hospital onset infection through improving ease of cleaning or actively destroying the infection. Silver and copper have previously proven effective at preventing the spread of respiratory viruses such as severe acute respiratory syndrome (SARS)[16]. There may be a role for antimicrobial materials in certain circumstances, particularly in devices that are very close to patients.

Coatings – There are a range of antimicrobial-impregnated products available such as paints and curtains and powder coatings that can be used for bed rails and toilet handles.[17] These coatings often also come in gel and liquid form that can be sprayed on. The application mechanism can affect the effectiveness of the coating.

Digital tools – The University of Quebec in Montreal has developed and implemented a disinfection needs identification tool (DNIT). This is a digital interface that coordinates cleaning teams to ensure timely and appropriate levels of cleaning and disinfection within hospitals and medical facilities. The Health Standards Organization reported that the DNIT improved efficiency

[14] FinsenTech THOR UVC
[15] More information available on request
[16] www.sciencedaily.com/releases/2015/11/151110102147.htm
[17] University of Birmingham (2019) New antimicrobial coating could be key in fight against hospital-acquired infections

of operations, reduced errors and confusion, and improved safety for patients all at relatively low cost.[18]

Future research considerations

The lessons learned from this pandemic should be used to provide much greater engagement between the engineering and healthcare communities. Understanding these problems and developing useful future solutions necessitates multidisciplinary collaboration. For example, collaboration between engineering and mathematicians and epidemiologists offers the potential to quantitatively link environment design and practice to risk.

There are several areas where research is currently underway that may inform the strategy to limit hospital onset infection in future pandemics:

- **Point of care diagnostics:** to prevent virus transmission, it would be advantageous to have early warning of which infections patients, visitors or staff may be carrying through more extensive real-time testing.[19]

- **Biosensing**: developments in this area would provide benefits for those looking to manage infection sources in the environment.

- **Digital technology**: engineers are investigating the role of sensors to allow adaptive control of healthcare environments to detect and respond to threats. This data collection will improve the ability to model scenarios to aid both the design for, and the management of, infection.[20]

- **Ventilation modelling:** theoretically based modelling work on designing for infection control and optimisation could play a useful role in informing both ventilation and energy efficiency measures. Modelling touch contact transmission may also help enable PPE considerations to be simulated. [21]

- **New biomaterials and coatings**: identification of new materials and coatings to provide antibacterial function and surface technologies for a range of clinical applications.

- **Robotics**: increased use of robotic systems to disinfect continuously and/or within hard to reach or dangerous settings, monitor temperature in public areas and points of entry, assist with testing (e.g. swabbing and transport of samples) and help keep non-COVID-19 patients out of hospital are all under investigation.[22]

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[18] Health Standards Organization DNIT project
[19] Department of Health and Social Care (2020) Coronavirus (COVID-19) Scaling up our testing programmes
[20] Adhikari et al. (2019) Fast and near-optimal monitoring for healthcare acquired infection outbreaks
[21] University of Leeds Hospital Environment Control, Optimisation and Infection Risk Assessment research programme
[22] Yang et al (2020) Combating COVID-19—The role of robotics in managing public health and infectious diseases

- **Future hospital design or retrofit**: consideration of how hospitals are designed to adapt in emergency scenarios.

- **Future preparedness**: understanding the generalisable lessons for this and any future pandemics in terms of creating more resilient environments.

There will be lots to learn from international comparators. However, it is important to remember that the operational context matters, and solutions may not be directly transferable because of physical (e.g. climate), operational or behavioural contexts.

Working collaboratively on these engineering themes will ensure new innovations meet the necessary clinical need, building resilience into the UK health service.

Contributors

This rapid review conducted by the Royal Academy of Engineering draws on input from a range of sources outlined below.

- Academy Fellows with expertise spanning clinical engineering, systems design, lasers and utrasonics.
- Wider Academy networks including Enterprise Fellows, research awardees and other identified experts covering antimicrobial resistance, hospital design, ultraviolet decontamination and airflow modelling.
- Chartered Institution of Building Services Engineers
- Institute of Healthcare Engineering and Estate Management
- Institution of Mechanical Engineers
- Institute of Physics and Engineering in Medicine
- An Academy roundtable discussion on personal protective equipment (PPE) attended by representatives of 15 international Academies of Engineering