Development of Intelligent Early Detection and Monitoring of Air-Borne Infection in British Hospitals

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Abstract:

Hospitals are closely fitted buildings encompassing a wide range of specialized and highly serviced spaces which can be a reservoir for potentially infective agents which need to be controlled and managed effectively. They are highly digitised incorporating sophisticated monitoring and control systems.

This paper assesses the *rasion detre* for developing sensors-based detection and monitoring system of air-borne infection (ABI) in British hospitals; it seeks to examine the effectiveness of incorporating such a system in selected critical hotspots of mechanical ventilation systems in hospital environment to increase resilience in tackling sporadic outbreaks. A Predictive Infection Criticality model (PICM) for assessing the risk was developed, solely based on the overall risk weighting of four key environmental parameters including air temperature, Relative Humidity (RH), air velocity and dust accumulation.

The main findings is that effective incorporation of an intelligent monitoring may contribute in mitigating such endemic problem.

Keywords: MRSA, Infection control, Dust accumulation, Digital relaying, BIM

1.0 Background Studies:

Hospitals are very complex organisations and highly serviced ones, which make them very difficult to manage. They can be depicted as an array of many interdependent and interwoven technologically complex services and environmental control systems and their many processes, interactions and interfaces. They are invariably in influx of change as they are encompassing a complex matrix of activities and accommodate a diverse range of users including

visitors, patients and staff. Adding to that hospitals require a more robust around-the-clock management input to ensure effective functionality and quality maintenance of both assets and services systems adding to the complexity involved. Equally, a hospital environment can be a reservoir for potentially infective agents as shown in figure 1, which needs controlled and managed effectively.

Figure 1 – Thick dust accumulation and discolouration at critical junction of Mechanical ventilation and A/C ducting system as stipulated by the Energy Performance in Buildings Directive (EPBD)

Research regarding cross-infection is fragmented, which makes it difficult for those seeking timely information. The spread of infection in hospitals is a complex process and difficult to manage. As shown in figure 2, it relies mainly on trio of factors: i) source, ii) mode of transmission and iii) susceptible recipients). The source can be a person, which could be a patient and/or staff in an outbreak scenario, object, environment or substance from which the infectious agent is transmitted to the host (NHS 2010). The relationship between host and the internal environment is quite complex and critical as this might contribute to and accentuate "Health Care Acquired Infections"(HCAIs). Several influential design factors for the outbreak of HCAIs have

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Modes of Transmission	Possible Culprits	Current Technological Intervention
Direct Contact	Carriers (patient, staff, visitors) furniture, room equipment, curtains,	▪ **Screening upon admission** ▪ **Hard surface detection**
	Infectious Agent (organic substance)	▪ **Decontaminating, sterilising and disinfecting**
	Objects	
Cross-contamination	Equipment/ devices (ventilator, peripheral catheter, urinary catheter, mechanical ventilator, parenteral nutrition, blood pressure cuffs, stethoscope)	▪ **Silicon membrane** ▪ **Long-term, hard- wearing surfaces which contain anti-bacterial properties (copper, silver coating technologies)**
	Sanitary appliances	▪ **Antibacterial and disinfectants products**
	Floors, walls and other hard surfaces	▪ **Smart paints and antibacterial emulsion**
Air-Borne	Hospital dust circulated through mechanical ventilation & Ac systems (filters, internal wall of ducting, diffusers)	▪ **Design of isolation rooms held at negative pressure to reduce aerosol escape to those outside the room.** ▪ **Higher air-change rate to allow rapid removal of aerosols.**
	Air pressure differentials in areas where infected patients is kept [1]	▪ **Use of Germicidal Ultra-violet Irradiation (GUVI)**

Figure 2 – Mode of Transmission of Infection

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[1] Techniques such as aerosol particles tracer sampling and computational fluid dynamics can be applied to study the performance of negative pressure rooms and to assess how design variables can affect their performance.

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Higher levels of HCAIs were recorded in General Acute Speciality Hospitals (HPA, 2006, 2010); Intensive care units (ICU), endoscopy units, accident and emergency (AE) and internal wards. These were identified to be more susceptible to HCAIs than other healthcare areas like outpatients and paediatric wards (HPA, 2006, 2010).

Several environmental factors including indoor relative humidity (RH), air temperature, air velocity, surface humidity, surface porosity and cleanliness were identified as triggers for colonisation and the spread of infection (Cornet, *et al*, 2007; Fleischer, *et a*l, 2006; Makison, 2006). There is growing recognition that (RH) level and air temperature in particular are more pertinent for the growth and the spread of HCAI; both act as triggers facilitated by air circulation; both might be critical to the colonisation and the spread of infection on internal surfaces of ducting systems? Ward (2008) argued that failing to maintain an appropriate relative humidity (RH) in a building can be as much of a risk to health as airborne particles. For example, when the RH is above 60% people feel uncomfortably hot and restless beyond what would be expected from the actual temperature. RH below 40% affects our mucous membranes which start drying out, causing a feeling of constant thirst and leaving us more vulnerable to infection by airborne pathogens (Ward, 2008; Skoog, 2006; Cornet, *et al*, 2007). In the same vein, environmental conditions can affect the survival and persistence of microorganisms on surfaces of the indoor environment (e.g. walls, ceilings, floors, furniture, door knobs and keyboards, monitors) or through airborne dispersal. Controlling indoor relative humidity (RH) to acceptable levels significantly minimises microbial growth. There is a growing consensus that RH below 60% significantly reduces the potential for microbial growth in buildings (Kilcoyne, 2006; Skoog, 2006; Cornet, *et al*, 2007, Fleischer, *et a*l, 2006). Humidity levels are known to influence MRSA survival and growth, in particular, and its ability to persist in the ambient environment (Makison & Swan; 2006) In theory, the accepted limits for ventilation and air-conditioning [2] are 21° C to 24° C at 40% to 60% relative humidity; but in reality humidity levels can be much lower than 40% in many hospital wards (NHS, 1994, Humidity Group of HEVAC, 2008; WHO, 2002). Non-humid environment at RH below 40% appears to be optimal for MRSA to thrive. These temperature and RH thresholds can be considered as a reliable measure of the risk involved of air-borne infection associated with hospital environment incorporated for measuring risks involved

This is particularly relevant given that the comfort zone 21° C to 24° C which is well within the MRSA survival temperature range of 18-37° C (Dancer, 1999). On the contrary, TB thrives on a relatively higher RH above 60% and a temperature range below 16° C.

Clearly, environmental conditions can affect the survival and persistence of hazardous micro-organism on surfaces or indoor environment and could potentially affect indoor air quality and increase the spread of HCAIs. This is particularly significant given that patients spend around 90% of their time indoor. The need for

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[2] A typical air-conditioning system includes air filters, air cooling, chilled water systems de-humidifiers, humidifiers, duct work, dampers and diffusers, fire dampers and sound attenuators.

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more energy efficiency has led to hospitals becoming more air-tight which exacerbates the problem further, compromising indoor air quality (IAQ).

Dust accumulation has widely been factored in HCAIs. Much of the emphasis was on internal surface cleanliness for breaking the chain of air-borne transmission. Of particular importance to this research is hospital dust from dry skin flakes, hair, cotton lent and tissue papers accumulated in internal surfaces of ducting system, fire dampers and return diffusers in particular (Dancer, 1999, 2007; Shabha & Higgins, 2011). There is a growing recognition that higher accumulation of hospital dust will be conducive for HCAIs spreading. Dancer (1999; 2007) stressed that MRSA in particular is a frequent component of hospital dust as it can easily circulate through the supply and return ducting network in ventilation and air-conditioning systems. This is a major logistical management challenge to hospital as most ducts are hidden behind walls, floors and ceilings and they are heavily used at higher frequency and intensity which makes them more prone to wear and tear, malfunction or faulty operation. Most are largely overlooked and ignored as they are "out of sight and out of mind" despite mounting evidence indicating a higher risk in spreading air-borne infections (NHS Estate, 1993,1994; Ward, 2008; Van Enk, 2006; McNevin; 2004; McRay 2008; McDowell, 2004; Skoog, 2007; Shabha,2008, 2009; Shabha & Conway, 2016, HEVAC, 2010; Shabha & Higgins, 2011).
23.

This study argues that the dust thickness is a valid and reliable indicator of bacterial colonisation. This implies that greater is the thickness of dust the higher is the amount of organic matter contained and the greater is the level of risk involved- According to TR19 there are two ways of assessing cleanliness: i) using a dust thickness meter DTT and ii) by vacuuming a known area into a filter and weighting the mass VT. The standards are shown in table 1 below

Systems Type	Surface Contaminant Limits	Test Method (VT Vacuum test)
Extract	6g/m2 180µm	V.T.
Re-circulation	1g/m2 60 µm	V.T
Supply	1g/m2 60	

Table 1: Surface Deposit Limits- TR19 Section 5

Dust accumulation up to 2 mm thickness was in ducting extract system of a few critical health area which were examined by the authors during the pilot study where no cleaning regime been put in place.
Again this study argues that dust accumulation is conducive to bacterial colonisation and further hypothesises that this is a key contributory factor to air- borne transmission. Again this relies greatly on air velocity and the pattern of flow in the ducting system. A higher air velocity can cause more disruption to dust particles exasperating the situation further. The pattern of flow can be envisaged within the context of fluid dynamics; laminar flow (or streamline flow) occurs when a fluid flows in parallel layers and cause the least disruption between layers. At low

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velocities, the fluid tends to flow without lateral mixing and adjacent layers slide past one another like playing cards."

Smooth transition is pivotal as any disruption of the air flow which is Omni-directional could potentially lead to cross contamination in critical clinical environment. This is particularly true in OT and ICU. Both temperature and humidity level (RH) are equally significant to the spread of air-borne infection if the threshold is breached or exceeded.

Removal of such hazardous accumulation should be a matter of course in any effective cleaning and decontamination strategies and interventions but this has largely been ignored given the cost implications and the level of disruption to patients. However, when these interventions are implemented they were purely on *ad hoc* basis and mostly reactive in dealing with particular outbreak situation; many are superfluous. Their long-term effectiveness remains to be seen; this is particularly alarming given the lack of robust and reliable early detection and monitoring system in place. Other possible management strategies for tackling the risk of **air borne infection** in ducting system include mainly I) filtration, ii) deep cleaning via steaming and iii) UVGI regime (Ryan et al, 2011) and "Kill Tunnel" by Sterile air (2016).

Again the efficacy of these methods and their robustness is determined by accessibility to the Labyrinth of mechanical ducting which proved to be problematic. Current cleaning strategies do not incorporate any reliable functionality for detection apart from recording the sequence and frequency of cleaning based on purely prescriptive criteria such as "box ticking" nor provide any utility to inform the FM team about any potential infection hazard in mechanical ventilation systems.

2. Rational and Justifications:

The continuing problem of healthcare acquired infections (HCAIs) in British hospitals has prompted the search for an effective infection control monitoring strategies over the last few years to alert both hospital team and FMs to potential hot spots and hazards area which was implicated in the air-borne transmission of *Mycobacterium tuberculosis* (TB), "nosocomial" MRSA, *Aspergillus fumigatus*, *Serratia marcescens*, norovirus and other air-borne HCAIs (Dancer, 1999) This study argues that dust thickness is indicative of lack of cleanliness of internal surfaces within mechanical ventilation systems which merits consistent monitoring. It further argues that RH and air temperature are equally significant indicators for gauging the level of risk associated with airborne infection. Current monitoring methods are highly fragmented and limited in their scope and a new risk assessment tool is therefore needed. The need for monitoring is based around the old dictum "prevention is the mother of all cure" and so by developing a proactive approach, just- in- time cleaning and or decontamination interventions can be commenced when the alarm is raised.

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2.1 Aims and Objectives:

The primary aim of this research is to develop a robust intelligent monitoring management tool as a novel approach for tackling the spread HCAI in British hospitals. This can be used to monitor hotspots in mechanical ventilation in higher

risk health care areas.

Three key objectives have been identified and will be pursued: i) to assess the technical feasibility of incorporating wireless smart sensors using purpose built 3-D building Information modelling software for mechanical ventilation into the monitoring process and ii) to assess the efficacy of the newly developed tool by further testing and piloting on selected hospitals in the Midlands Region and iii) to develop new infection control management tool.

2.2. Theoretical Framework:

In the light of the complexities and the multi-facetted mode of transmission involved in air-born infection a theoretical model depicting the process of the spread of infection in critical healthcare areas was developed using criticality of infection- traffic light model. The model is solely based on overall level of risk measurement- weighted scores obtained from key environmental parameters and cleanliness indicator.

This study advocates collecting real-time data for monitoring and assessing the overall impact of interrelated RH level, air temperature, dust accumulation in hotspots in particular mechanical ventilation which can equally applied to other services systems such as air-conditioning (AC) and plumbing systems. The gathered data are obtained via off-the-shelf currently available smart sensors technology which are tested and validated.

A Predictive Infection Criticality Method (PICM) is developed by the authors and further fine-tuned to provide easy to grasp mechanism for alerting hospital team about potential hazardous. Similar model was developed by NHS Estates, albeit generic using a 3 x 3 matrix for determining services system failure; this was subsequently used by BSRIA for measuring failure of services items or elements of an installation (BSRIA, 2012).

Suffice to mention that models are essential tools to understand processes, identify relationships, associations and causality which can help to explain data, as well as inform the deployment and location of digital smart sensors by identifying hotspots and areas of interest where data collection may achieve the best results.

The authors argue that in order to determine the level of risk due to colonisation in mechanical ventilation systems, four environmental parameters need to be measured and analysed, i) Thickness of dust; ii) air temperature; iii) RH and iv) air velocities. Any changes below or above the prescribed threshold will potentially increase risk and trigger an alarm which vary from yellow to orange. The authors

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further advocate risk based analysis in order to determine "Risk Worth" as a key criteria for assessment. This is wholly based on overall effect weightings.

These risks are then given a numbers for the calculation of level of risk using 4 x 7 matrix as shown in table 2. A risk factor based on numerical index is given to each of the environmental parameter. Thresholds for each parameter are based on the literature analysis underpinning these weightings and an algorithm embedded in the computer model.

	Slightly Harmful	Moderately Harmful	Extremely Harmful
Temperature	19-21 °c <	22-24 °c	24°c >
Humidity	40-60 %		60%> 29 % <
Dust Accumulation	<0.05- 0.1 mm> minor accumulation	0.10 – 1.00 mm	1.00 mm> major accumulation
Air Velocity	0.3-0.5 m/s<	<0.5-0.9 m/s>	1.00 m/s>
Highly Unlikely	1	2	3
Unlikely	4	5	6
Likely	7	8	9

Table 2 – PICM Risk Matrix Depicting the Key Environmental Parameters

The authors argued that this model is most appropriate and easily manageable; it is underpinned by Reliability Centred Maintenance (RCD) method in tackling a complex and multi-facetted problem which is essentially metamorphous and a moving target problem. RCD lends itself to formulate an objective assessment of the likelihood and probability of infection spreading via mechanical ventilation (MV) systems.

Sensors Types	Green Status	Yellow Alert Status	Orange Alert Status	Red Alert Status
Temperature	16-18 °c	19-21 °c	22-24 °c	24°c>
Humidity (RH)	40%-60%	<35%-40%>	<29%-35%>	29%< or 60%>
Dust	<0.01	<0.01-0.1 mm>	<0.1-0.9 mm>	1.00mm>
Air Velocity	0.1-0.3 m/s	0.3-0.5 m/s	0.5-0.9 m/s	1.00 m/s>

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Table 3 - Alert Conditions

Such a holistic tool for monitoring and detecting ABI in MV systems can provide a real-time condition-based feedback about critical hot spots concomitant with time-based none- invasive visual inspection if practically accessible.
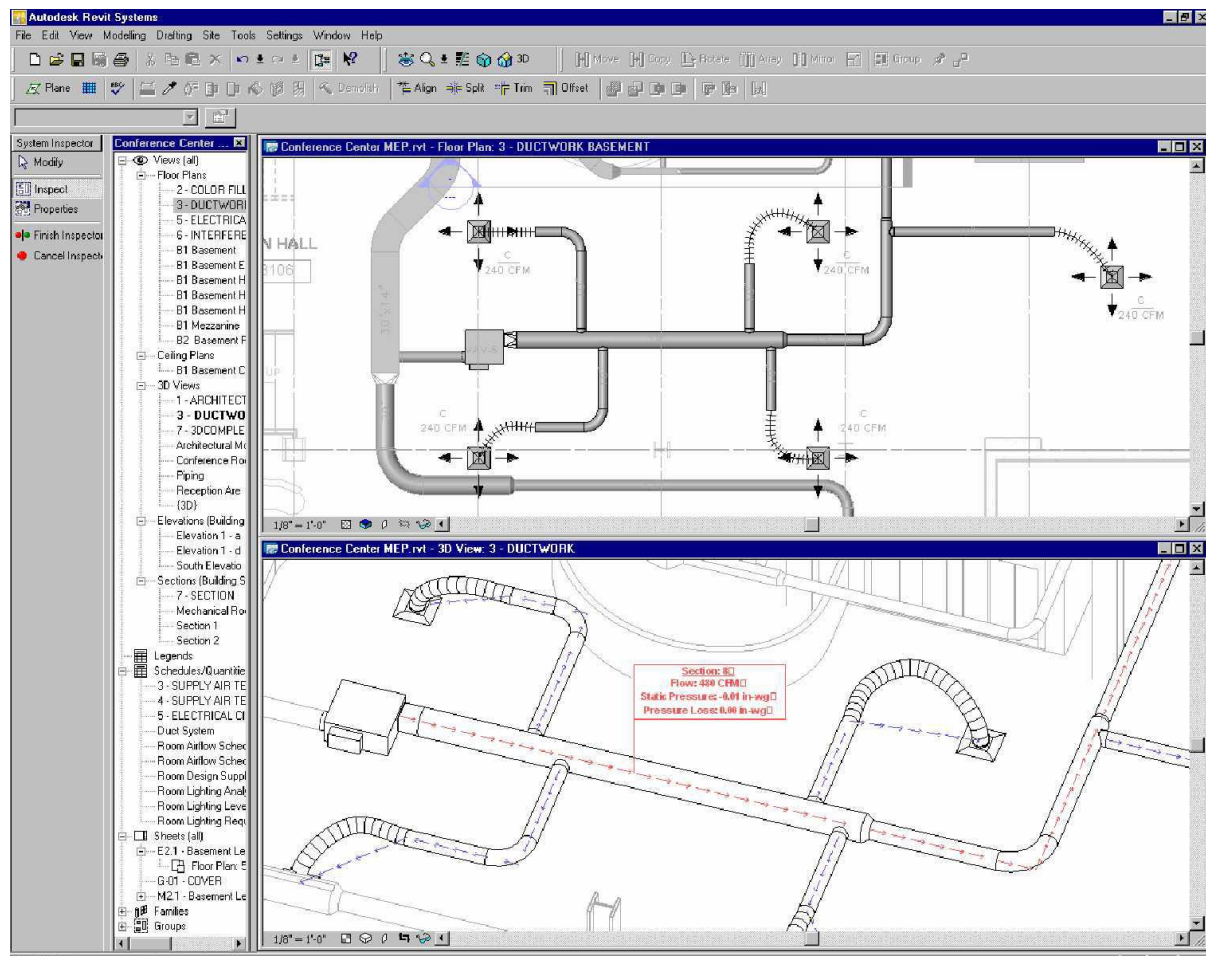
3. Methodology

3.1 Study sample:

The study sample was selected from two NHS trusts in the Midlands Region (A & B). Both Trusts were initially approached to participate into this study. The key selection criteria is based primarily on i) risk and criticality; ii) frequency of occurrence and iii) susceptibility to HCAIs based on the complexity of MV services involved. Historical data was analysed together with secondary data based on the findings of prevalence survey of HACI by the Health Protection Agency. Two higher risk healthcare areas were selected per Trust. These include, *inter alia,* private rooms, endoscopy units, internal wards, operating theatres (OT) and intensive care units (ICU).

3.2 Methodology:

A pilot study was conducted on a selected sample where embedded smart sensors for measuring dust accumulation were installed into MV critical and higher risk areas. 3-D BIM drawings of MV systems were used for setting up an early detection and monitoring in these critical areas. Wireless smart sensors were embedded into critical points/junctures of MV for measuring and relaying information about air velocity rate, relative humidity (RH), ambient air temperature and dust accumulation in critical ducting areas including elbows and T- junctions, return diffuser and ducting shutter. These are remotely accessed using web-based technology. This enables multiple critical health areas to be monitored simultaneously from one location, which overcomes any manual checking and reduces human errors to ensure data consistency. The distance between sensors is shown in appendix A.

Real-time-data of critical points of MV were collected, recorded and collated on a daily basis over two months periods; it is hoped that this can be extended to another four months. The data can be presented in frequency graphs, histograms and trends to generate a customised monthly report. The gathered data can provide a full audit trail and empirical data for further analysis to aid developing the new monitoring tool. Operational limitations and technical glitches were overcome during the pilot study in terms of reliability and efficacy of the sensors, type and quality of data collected were regularly assessed and fine-tuned.

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Figure 3: A 3-D BIM modelling which illustrates design integration with services achieve a higher level of modular coordination.

4. Findings and Discussion

Following from the pilot study and the data collected it becomes apparent that both orange and red alarm triggers were raised and activated on 7 occasions where the threshold was exceeded above critical point which merited intervention. A combination of more one or two methods might be appropriate cost permitted. Cyclical duct cleaning is needed to dislodge accumulation of dust most of which will be of a higher proportion of organic compounds (OC) including hair and skin flakes-the main nutrients for micro-organisms.

4.1 Outcomes and Benefits

Many benefits could accrue to patients the ultimate beneficiaries of this project. Other intended beneficiaries are NHS policy makers, NHS and PCTs managers, medical staff, FM professionals in proactively addressing the complexity of HACIs spreading in the light of the wealth of knowledge base generated over the last five years as follows

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1. Developing an innovative and technologically driven tool which can be deployed in critical healthcare areas for tackling HCAIs. Such a predictive tool for monitoring, detection and management of infection in MP systems can provide a reliable real-time condition-based monitoring and early alarm system against ABI and HCAIs

2. Providing predication about the likelihood of infection spread in critical care areas in British hospitals. The value of prediction, however, is in creating scope for dealing with similar problems. This might have a wide ranging of implications to commercial and leisure facilities as much as to food industry, which encompasses dairies, abattoirs, breweries and soft drink plants amongst many others.

3. Developing an integrative approach to the current technologies and techniques for cleaning, disinfecting and decontaminating of HCAIs which are largely conducted on ad hoc basis hence mitigating the likelihood of micro-organism from being transferred via MV services. This will contribute further in reducing the risk of contagious bacteria being transferred through internal hospital environment.
An automated system for processing, calibrating and recording data is needed as this might affect the outcome.

Monitoring and assessing risk due to ABI needs to be part of IAQ monitoring regime in healthcare places in tandem with other measurable evidence-based data physiological parameters and comfort/wellbeing indicators need to be incorporated into building management systems, which will require a paradigm shift. The old adage of an IAQ (indoor air quality) adequate for 'comfort' must be intertwined with 'IAQ to mitigate the risk of ABI which ultimately improves patients' health'.

4.2 The Potential impact on NHS

The primary impact is to develop an intelligent predictive real time monitoring method that can be used by infection control staff and FM team in British hospitals for tackling airborne infection. This can be achieved by providing rapid response to hot spots within MP in particular at critical junctions, distribution and outlets points of the services systems- become prone to dust accumulation and blockage. This would eliminate the need for costly and unnecessary outsourced services for inspection and conformance and would significantly reduce downtime and airborne infection. An automated system for processing, storage, analysis, validation, and presentation, will also be needed, and for calibrating and recording data, which might affect the outcome. A number of other potential impacts can be envisaged as follows:

Versatility of the devised technology which can be wirelessly integrated into BIM to monitor varying critical healthcare areas some of which are in greater daily demand and difficult to access for maintenance and cleaning as in OT, Isolation rooms and ICU.; these are barely unoccupied long enough to be visually inspected either. Could be problematic for setting up the piloted particle counters???

Automated monthly reporting of cleaning and maintenance activities which can be tracked in real-time monitoring of internal surfaces of MEP. This provides a reliable

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systematic assessment of any hotspots in critical healthcare areas with strict cleanliness requirements.

Easily managed and practical in-house system facilitated by web-enabled CAFM/BIM solution which provides adaptable and easy to use platform to proactively tackle any lurking problem allowing infection control staff members ample of time for rapid response to cleaning and decontaminating affected internal surfaces of mechanical and plumbing including underside and inaccessible surfaces.

Benefit to patients and the NHS might include, *inter alia,* reduced risk of air-borne infection a well as cross-infection due to residual action of pathogen. This will contribute to the prevention and spread of HCAIs between hospitals, ambulances and the care sector increasing confidence in current patient care provision and boosting moral of care providers including clinicians, nurses and healthcare managers at large.

Acknowledgements

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Government target has led to higher bed occupancy whilst staff shortages and increased use of unqualified staff have compounded strict hygiene protocols. (www.bbc.co.uk/health/ 2009)

'Single speciality' Trusts- (Trusts undertaking orthopaedics, or cancer or children health services).

Specialist' Trusts- (Trusts with specialist services which receive patients referred from other Trusts for these services).

'General Acute' Trust- (Trusts providing general acute healthcare services). The highest in HCAIs.

Ward speciality can be categorised into medical, surgical, obstetrics and gynaecology, critical care medicine amongst many others specialties. (Hospital Infection Society and Infection Control Nurses Association, 2007:9)

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