Modeling the Contact Propagation of Nosocomial Infection in Hospital Emergency Departments

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***Abstract*—The nosocomial infection is a special kind of infection that is caused by microorganisms acquired inside a hospital. In the daily care process of an emergency department, the interactions between patients and sanitary staff create the environment for the transmission of such microorganisms. Rates of morbility and mortality due to nosocomial infections are important indicators of the quality of hospital work. In this research, we use Agent Based Modeling and Simulation techniques to build a model of Methicillin-resistant Staphylococcus Aureus propagation based on an Emergency Department Simulator which has been tested and validated previously. The model obtained will allow us to build a contact propagation simulator that enables the construction of virtual environments with the aim of analyzing how the prevention policies affect the rate of propagation of nosocomial infection.**

***Index Terms*—Agent Based Modeling and Simulation; Nosocomial Infection; Hospital Emergency Departments.**

I. Introduction

The nosocomial infection is a kind of infection that is caused by microorganisms acquired inside a health care environment. It is the most common type of complication affecting hospitalized patients. Inside a health care environment we can find several microorganism that can be causative of a nosocomial infection, but our work has focused in the propagation of the Methicillin-resistant Staphylococcus Aureus (MRSA), one of the most common and dangerous microorganisms in this environment. The presence of these bacteria could mean serious health problems for a patient. It is a common cause of skin, wound and, most seriously, blood stream infections as it may be responsible for a greater hospital length of stay, expensive treatments and an increased mortality [1]. MRSA is a bacteria usually resistant to conventional antibiotics that makes it very difficult to treat. These bacteria live in the skin of some patients and could be transmitted to another patient by physical contact through the interaction between patients, healthcare staff and environment. The most common transmission vias are: healthcare staff's hands, contaminated medical equipment and objects in the hospital room environment. The risk of MRSA acquisition is particularly high in elderly patients, severe underlying disease, prolonged hospitalization (especially in ICUs, surgery and burns units), use of invasive medical devices, previous antibiotic treatment and exposure to infected or colonized patients [2].

An emergency department is undoubtedly one of the most complex and dynamic areas in a hospital. Its operation is not linear and depends on several factors. This way, we can conclude that an emergency department can be classified as a complex system. When we work with complex systems, one of the strongest problems is how we can represent human behaviors that cannot be predicted using conventional methods such as qualitative or statistical analysis. Modeling techniques using agents can bring the most benefit when applied to human systems, where agents exhibit complex and stochastic behavior and the interaction between agents are heterogeneous and complex [3]. In our research, we make use of an Agent Based Model and Simulation (ABMS) to create a contact propagation model of MRSA inside a emergency department. For this purpose, we defined all actors involved in the emergency departament process and their specific function and behavior: patients, doctors, nurses, admission staff, laboratory technicians, auxiliary personnel and cleaning staff. Every person who has a role in the emergency department is defined as an active agent in our model. It is very important to take into account the environmental objects that healthcare staff use in the process of attention patient because our model is focused on the transmission by contact and this transmission could be between active agents (direct transmission) or between active and passive agents (indirect transmission). Each one of the agents who is interacting in a emergency department can be a multiplier of MRSA bacteria, which depends on the condition of *colonized* or *infected*, in the case of active agents, or the condition *contaminated* in the case of passive agents. In all cases, we apply the term ”transmission vector” to any agent capable of transmitting MRSA bacteria and ”susceptible” to any agent that has risk to adquire the infection.

Some health services have implemented concrete actions that attempt to control the rate of propagation of nosocomial infections. These actions are called ”prevention policies” and are represented in our model through the definition of behaviors performed by members of the sanitary staff.

The remainder of this article is organized as follows: the previous emergency department model is detailed in Section 2. Section 3 describes the related and previous works. Section 4 the proposed contact propagation model of nosocomial infection. Finally, Section 5 closes this paper with future works and conclusions.

II. Emergency Department Simulator. Previous Model

We based our model in a previous emergency department model (ED-Simulator) that had been developed as part of a previous research work [4][5][6] in our research group.

This model considers the emergency department divided into two zones, A and B. The patients are divided in 5 acuity levels according to the Spanish Triage System [7], very similar to the Canadian Triage System. Acuity level I means that the state of patient is very serious and a patient with acuity level V is the patient with the least severity. Patients with acuity level I, II and III are located in zone A, and patients IV and V are located in zone B. The agents are divided into active agents and passive agents. The active agents represent people who act upon their own initiative and passive agents represent systems that are solely reactive, such as patient information system and diagnostic services (radiology service and laboratories). Each agent has variables and behavior. The behavior depends of the kind of agent and the interactions between agents allow a system behavior to emerge. The behavior of agents has been modeled using Moore State Machines [8]. In each state, the agent has a set of probable outputs. Each state of the state machine for a specific agent has been defined on basis of the values of state variables of each agent at a certain time. Moreover, each one of the state variables could have more than one possible value. The agent will remain in a specific state until, through interaction with other agents, they receive an ”input” (an output generated by other agents), which could cause a change in the state of such agent and generating an ”output” sent to the agent with whom they are interacting. The agents state machine will move to the next state following the transition, which may be another state or the same one in which the agent was before the transition.

With this background, our proposal is obtain an efficient model of the propagation of MRSA by adding new features to the actual model through the use of ABMS technics.

Propagation of nosocomial infections has already been widely studied using different techniques. In this section, we will refer to some relevant papers relating to the modeling of the transmission of MRSA with ABMS techniques. These investigations focus on contact transmission of MRSA mainly through the interaction between patients, doctors and nurses, other members of healthcare staff are not included. The interaction between patients or healthcare staff with the environmental objects or medical equipment have only been dealt with in three research papers. In general, the patients are divided into colonized or infected patients and the healthcare staff are divided into colonized and non-colonized or transiently colonized. Neither considers the severity level of the patients and only two members of healthcare staff are included in the simulation, doctors and nurses. All of these features are resumed in the Table I.

TABLE I: COMPARISON BETWEEN OUR RESEARCH AND RELATED RESEARCHES.

Characteristic / Researches		8	9	10	11	12	Our work
Interaction between patients and...	Doctors	x	x	x	x	x	x
	Nurses	x	x	x	x	x	x
	Others healthcare staff						x
	Equipment and objects			x			x
Prevention policies		x	x		x	x	x
Patient risk adquired NI		x		x	x		x
Transmission probability			x		x	x	x

In Barnes et al. [9], MRSA transmission reduction using agent-based modeling and simulation is presented. The environment of this simulation is a hospital ward. Two types of interactions are modeled: patients-healthcare staff, and patients-visitors. The interaction between the members of the healthcare staff is considered unnecessary for the model. Patients are generated continually and are housed in a waiting room until replacing the discharged patient, so hospital wards are always full. Admitted patients can take one of two states: susceptible or colonized. It is not taken into account the possibility that the patients come as infected but they can develop infection during their stay. Members of the healthcare staff are created at the beginning of the simulation and are all considered as being in an uncolonized state. During the simulation the healthcare staff could be susceptible or colonized. This research includes visitors as agents and they have a colonized status (non-colonized, colonized); therefore, they can transmit the infection. The visitors only have interaction with the patients. The transmission of MRSA between agents is based on the risk level of the patient to becoming infected and the behavior of the healthcare staff members who visit the patient.

In Milazzo et al. [10], the following factors are taken into account: the status and the movement of each agent, the contacts between individuals during a ward round, the hand hygiene compliance for each agent, and the control measures applied. The environment of the simulation is a hospital ward. The main parameters that characterize each agent, patient and healthcare staff, are: the colonization status, the transmission probability, and the compliance factor. The transmission dynamics of the infection is based only on transmission from patient to patient via healthcare staff. The model does not take into account the direct transmission from patient to patient or the indirect transmission from patient to patient via environmental surfaces. The healthcare staff may become transiently colonized and carry MRSA on their hands if their compliance with hand hygiene is poor.

The model proposed by Meng et al. [11] is a propagation model in a single hospital ward divided into bays, with some isolation rooms. Transmission is modeled by pairwise interaction between colonized and non-colonized patients, patient and healthcare staff (nurse and doctor) transiently or permanently colonised, patient-to-patient contacts and transmission from a contaminated environment. This model takes into account the susceptibility of the patient to colonisation. Some possible states are defined for the patient: colonisation, detection, decolonisation treatment and location status. This model includes the time required to treat colonization or infection carried by the patient and a metric that assesses the patient's susceptibility to acquire a nosocomial infection. This model therefore assumes that a susceptible patient may acquire MRSA due to the presence of colonised patients in the vicinity, regardless of the mode of transmission.

According to Raboud et al. [12], a Monte Carlo simulation was used to model MRSA transmission in a hospital ward. They used the simulation to study the impact of different components of infection control programs on the propagation of MRSA on a hospital ward representative of a general hospital ward. Visits from healthcare staff to patients were simulated and MRSA was assumed to be transmitted from patient-to-patient via healthcare staff. Once colonized, healthcare staff remained colonized until they next washed their hands. The model did not address transmission related to healthcare staff who chronically carry the organism or to contaminated environment surfaces or equipment.

In Barnes et al. [13], a dynamic patient network model is defined through ABMS techniques. The environment is a hospital unit. They explicitly define only patients as agents. Patients have a single boolean state that indicates whether or not a patient is infected or colonized with some type of pathogen. In the simulation, two healthcare staff types are defined, nurses and doctors that they are not modeled as agents but they are implicit through the transmission mechanism. Each patient has a primary nurse and a primary doctor who provide care a patient during the hospital stay. There is an underlying network that connects patients who share nurses and a separate network for patients who share doctors. A patient could be infected only if there is a source patient who shares a nurse or doctor. Patients who are connected by a nurse and a doctor have an increased probability of transmission if one of them becomes infected. A single parameter called virulence defines the probability of an infected agent transmitting the microorganism to a susceptible agent.

III. Model of the Propagation by Contact of Nosocomial Infection

As explained above, the model proposed in our research has the advantage of being developed based on a previous emergency department model and previous emergency simulator, both of which have been developed as part of previous research works [4][5][6] carried out with the collaboration of healthcare staff at the Emergency Department of Hospital Universitari Parc Taulí. This previous model used ABMS techniques to define the full attention process of an emergency department. Some agents defined in this model can be used as part of the model of propagation by contact, but we need to add more passive and active agents. In the same way, it is necessary to add new variables and behaviors in all agents, in order to represent MRSA transmission between a transmission vector and a susceptible host.

A. Transmition Forms

There are two forms of contact transmission, direct transmission and indirect transmission. In both cases we need a transmission vector.

1) Direct transmission: When MRSA bacteria is transmitted from an active agent (transmission vector) to another active agent (susceptible agent). For instance, when an infected/contaminated patient is touched by a member of healthcare staff without a physical barrier.

2) Indirect Transmission: When an active agent (transmission vector) touches medical equipment or objects in the hospital environment and MRSA bacteria is transmitted to the object, later, a susceptible agent (patient or healthcare staff) has contact with the same object and acquires the microorganism.

In the real process, for the first time to diagnose an MRSA infection or colonized , it is necessary to apply a laboratory test. Many laboratory test options exist but we mention two: culture testing and polymerase chain reaction (PCR). The culture testing is a conventional laboratory test, which has a low cost but the results are available in 72 or 96 hours (3 or 4 days). In contrast, PCR has a high cost but the results are available in a few hours (2-6 hours) and it may be more sensitive [14]. The time required to obtain results is an important factor in the attention process because the length of stay (LoS) of the patient in an emergency department is usually short. On the other hand, the long wait for the result of the laboratory test could contribute to increasing the rate of propagation of nosocomial infection.

To make a model about the indirect transmission, it is necessary to bear in mind the lifetime of MRSA on dead surfaces. There is scientific evidence that suggest that bacteria can live more than 90 days on different surfaces [15]. If we consider that the time of the attention process of the ED changes in function of the illness severity of the patient and availability of the healthcare services, in all cases it is less than 90 days, then we can assume in our model that the lifetime of MRSA bacteria is unlimited on dead surfaces (objects and medical equipment) but can be eliminated through a disinfection process carried out by cleaning staff.

B. Agents and Behaviors

Frequent interaction between patients and healthcare staff is the principal way to MRSA propagation. To combat MRSA, some healthcare services implement prevention polices to control transmission. These prevention policies are a set of concrete actions and behaviors that healthcare staff perform to control the rate of propagation. Some of these actions are: handwashing, use of hydroalcoholic solution and use of isolation material. Healthcare staff are required to practice the handwashing and use of hydroalcoholic solution every time

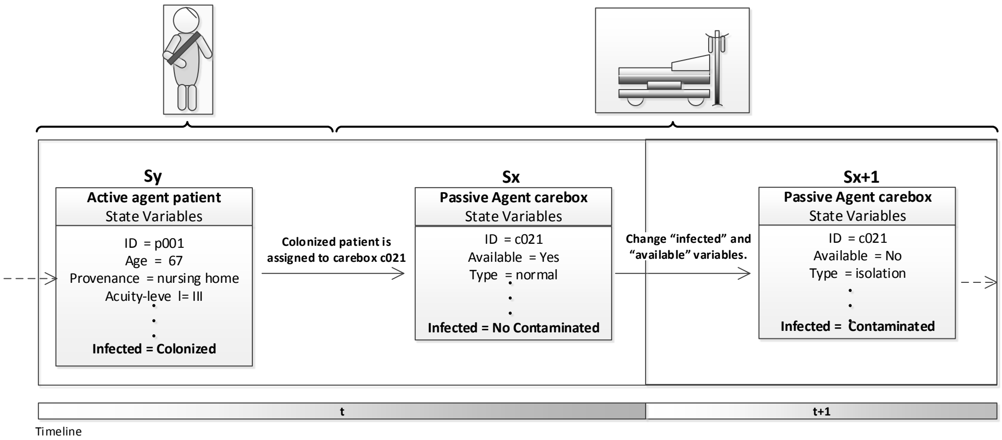

Fig. 1: Interaction between colonized patient and carebox.

that they attend a patient, but the use of isolation material is required only when they attend an isolated patient.

1) Passive Agent: Passive agents are agents that do not have their own initiative, they are solely reactive. All passive agents react to an action of an active agent or time. The actual model of ED has some passive agents such as information system. For our purpose, we added the passive agent ”Carebox” in order to represent the interaction between active agents with the environmental objects.

Carebox: The carebox is the physical space where the patient is accommodated during the treatment and diagnosis process. In the model, once it has been confirmed that a patient is a transmission vector we have the possibility to isolate the patient in a carebox. All careboxes could be transformed in isolated careboxes. We use the infected variable to reflect whether a carebox is contaminated with MRSA or not. The possible value for infected are: *non-contaminated* or *contaminated*. When an MRSA patient is assigned to a carebox, the infected variable takes the value *contaminated* (see Figure 1), and it will remain at such a value until a disinfection process has been carried out. This process can only be executed when the MRSA patient leaves the emergency department and releases the carebox. The disinfection process is carried out by cleaning staff. The isolated carebox contains the entire equipment needed for patient care, which means that we have a lot of objects likely to be a vector of transmission, though all these objects are usually inside the same carebox, therefore we consider them as a single object. In extreme cases, where all carebox are busy, it is possible to use ”a virtual carebox”, which are additional spaces located in the ED. The main difference between a virtual box and a carebox is that the virtual one does not have the same level of isolation, which is why the probability of MRSA propagation is higher.

2) Active Agents: Any actor who has the ability to act by himself/herself is an active agent. The propagation model includes the interaction between patients and some agents of healthcare staff, such as doctors, triage nurses, nurses, admission staff, auxiliary personnel and cleaning staff (see Figure 2). For the purpose of our propagation model we can devide all these active agents in two cathegories: Patient and Healthcare Staff.

Patient: In order to properly define the propagation model of MRSA, it is important to consider that the patient on arriving to an emergency department, regardless of their acuity level, has a probability of being a transmission vector (infected or colonized) of MRSA. It means that the patient has a probability of being a carrier a microorganism causative to nosocomial infection. MRSA bacteria could live in the skin of some patients without their knowledge it and without any symptoms. However these patients could transmit the bacteria to another patients by physical contact.

In our model, we use the infected variable to show if the patient is *non-colonized*, *colonized* or *infected*. All non-colonized patients are susceptible to acquiring a nosocomial infection. We can classify patients in two groups: 1) patients that do not have a clear possibility of being colonized or infected with MRSA bacteria. In this case the healthcare staff assumes that this patient is non-colonized; 2) patients that are known or can be assumed to be colonized or infected with MRSA. If a patient has had a previous admission, the ED has their clinical history and knows if they had or have MRSA (during the admission process). In such cases the patient is classified as colonized, because a patient who has previously been colonized has a higher risk to a new colonization [16]. However, if it is the first time that the patient attends the emergency department, healthcare staff evaluate the MRSA Risk Factor (RF) of the patient.

In some health services, when it has been confirmed that a patient has MRSA (on the basis of the doctor's exploration and laboratory test results), this patient is immediately isolated in a carebox.

The MRSA risk factor is a metric that allows us to give the patient a level of probability (P(RF)) of being a transmission vector. With the purpose of calculating the risk factor, we can ask about several factors associated with a higher risk of acquisition of MRSA [17], but our research focused on three

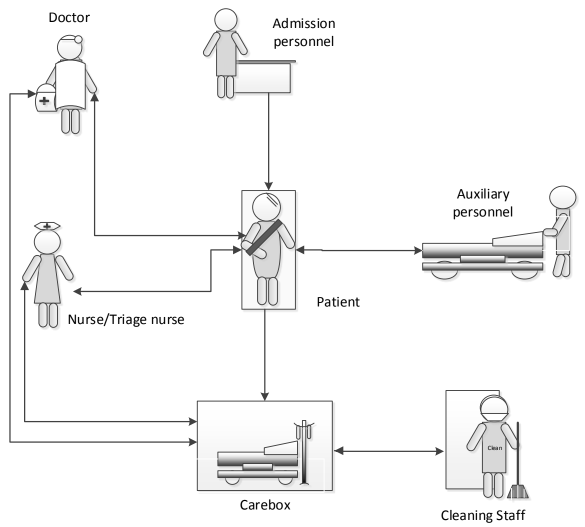

Fig. 2: Diagram of physical contacts of the patient with other actives and passives agents.

aspects that we consider require special attention:

- Patient age: patients over 65 years old have more probability of being an MRSA patient carrier because their immunological systems are usually weakened due to several illnesses or extended treatments.
- Place of residence: when patient is an institutionalized patient, sharing their residence with many people, such as a nursing home, prison, etc.
- Acuity level: usually patients with acuity level I, have more probability of acquiring a nosocomial infection because their immunological system is weakened.

$$P(RF)= f(\text{Age},\text{PlaceResidence},\text{AcuityLevel})$$

When the risk factor is high then we assume that there is a high probability that the patient be colonized. The patient can be considered infected only when the diagnostic can be supported by the results of laboratory tests. It is very important to ensure the results because if one positive case escapes, we have a transmission vector together with susceptible patients, and on the other hand, if one negative case is assigned as positive, the patient will receive an unnecessary treatment that will increase the cost.

It is very important to differentiate between infected and colonized patients. Colonized patients carry MRSA on their skin, but they are asymptomatic and therefore require laboratory tests for it to be detected. If MRSA bacteria get inside the body, the patient will develop an infection, becoming a symptomatic carrier, which is called an *infected patient*. However, the doctor needs to apply a physical examination and laboratory test to support the diagnosis. Both colonized and infected patients may transmit MRSA bacteria to susceptible patients and this can lead to infections with serious consequences.

Healthcare Staff: In this model we study the interactions with some active agents of healthcare staff: admission staff, triage nurses, patients, doctors, nurses, laboratory technicians, auxiliary personnel and cleaning staff. Each of these agents has a specific function in the attention process. The healthcare staff agent has the infected variable with three possible values: 1) *non-carrier*; 2) *carrier*; 3) and *colonized*. A member of the healthcare staff could be a *carrier* when they acquire temporarily bacteria. This happens when they have physical contact with a transmission vector and acquire the bacteria. Later, if the healthcare staff complies with the prevention policies, the bacteria will be eliminated and the healthcare agent will return to non-carrier. The accomplishment level of the healthcare staff agents with the prevention policies is measured by the *accomplishment factor* (AF).

This metric measures the probability that a member of the healthcare staff transmits the bacteria to a susceptible agent. This probability (P(AF)) will be calculated on the basis of the accomplishment level of prevention policies/actions. The three prevention actions that are evaluated in this research are:

- Handwashing: the most important of the actions. The healthcare staff is required to do it, before and after they have a physical contact with a patient.
- Sanitizing hand: with a hidroalcoholic solution. It is necessary to do it before and after they have physical contact with a patient. There is no substitute for handwashing and it is better if both actions are done.
- Using isolated material: this is required only when they attend an isolated patient.

$$P(AF)= f(\text{Handwashing},\text{SanitizeHand},\text{IsolatedMaterial})$$

C. Propagation of Nosocomial Infection by Contact Model

The model takes into account the parts of the overall process in which contact propagation can take place. For this it is necessary to clear the entire care process. This section is dedicated to describing the emergency attending process and identifying in which parts of this process a transmission vector can be in contact with a susceptible patient.

Attention Process: When a patient arrives in the emergency department they approach the admissions zone. Here the admissions staff ask for their health card and registers their arrival. Then the patient waits in the waiting room for the triage process. When the triage nurse is available, they call the patient and takes their vital signs and asking for some additional information in order to identify the acuity level of the patient. The acuity scale applied in Spanish ED considers five different values, from I until V, with I being the highest level, and V the lowest. If acuity level assigned to the patient is IV or V, they will wait for diagnosis and treatment process in a waiting room, but patients with acuity level I, II or III will be assigned immediately to a carebox and diagnosis and treatment phases should be done inside such a carebox, with the exception of some specific tests. The diagnosis and treatment process is divided in 3 phases: 1) laboratory test; 2) treatment; 3) Exit from ED. When a doctor is available, they call the patient and decide what the next step is. Laboratory test and treatment can be carried out several times.

TABLE II: POSSIBLE WAYS OF TRANSMISSION BETWEEN ACTIVE AGENTS.

Agent1	Agent2
Carrier healthcare staff	Susceptible patient
Carrier healthcare staff	Passive agent
Infected/colonized patient	Passive agent
Infected/colonized patient	Healthcare staff
Passive agent	Healthcare staff
Passive agent	Susceptible patient

When the treatment has finished and an additional laboratory test is not necessary, the doctor will prescribe that patient leaves the ED. In the case of patients IV and V, the interaction with the doctor will be carried out in attention boxes, and the patient will remain in a specific waiting room while there is no interaction (between each one of these phases). We focus on the stages in which agents have physical contact with other agents, that is, when patients have interaction with healthcare staff. The MRSA transmission is possible in one of several ways (Table II). If patient is a transmission vector and has contact with a susceptible agent, transmission is probable [17], in which case the susceptible agent will change their state. The variable "infected" is used to reflect changes in the state of agents. To decide if one agent acquires the MRSA bacteria, we will use a probabilistic distribution based on the likelihood of the transmission vector transmitting the microorganism, and the probability of a susceptible patient acquiring the microorganism.

IV. Future Work and Conclusions

As a result of our research, we proposed an agents-based model of the contact propagation of MRSA in emergency departments. This model has been designed based on an emergency department simulator, ED-Simulator, developed in previous research and which has the advantage of having been verified and validated in several cycles or iterations, taking into account a wide variety of data and configurations, and with the participation of ED staff at the Hospital of Sabadell (Spain). Based on such an ED-Simulator and after a careful analysis of the care process, we have established in which parts of the process there is risk of infection and which agents have to be added in order to complete the propagation model. We have enhanced the model by including new agents, and by adding new variables and new behaviors in all the agents that participate in the transmission process. In this way, we have obtained a model of contact propagation of MRSA. Our future work is to implement the contact propagation model of MRSA in the ED-Simulator in order to obtain the computational model of the contact propagation. The next step will be the execution, validation and verification stages for improving the model. The computational model will allow the ED managers to analyze and evaluate potential solutions (the possible effects of applying the control policies' actions) for propagation of nosocomial infection in a virtual environment and to evaluate the effectiveness of different combinations of laboratory tests, isolation, and other control policies, with the purpose of identifying the best infection control policy.

Acknowledgment

This research has been supported by : MINECO (MICINN) Spain under contract TIN2011-24384. Ecuador government. SENESCYT, under contract 2013-AR7L335.

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