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Agent Based Model and Simulation of MRSA Transmission in Emergency Departments

Cecilia Jaramillo[1], Manel Taboada[3], Francisco Epelde[2], Dolores Rexachs[1], and Emilio Luque[1]

[1] Department of Computer Architecture & Operating Systems
Universitat Autonoma de Barcelona, Bellaterra, 08193, Barcelona, Spain
cjaramillo@caos.uab.es, dolores.rexachs@uab.es, emilio.luque@uab.es
[2] Medicine Department, Hospital Universitari Parc Taulí
Universitat Autonoma de Barcelona, Sabadell, 08208, Barcelona, Spain
fepelde@tauli.cat
[3] Tomas Cerda Computer Science School
Universitat Autonoma de Barcelona, Sant Cugat, 08714, Barcelona, Spain
manel.taboada@eug.es

Abstract

In healthcare environments we can find several microorganisms causing nosocomial infection, and of which one of the most common and most dangerous is Methicillin-resistant Staphylococcus Aureus. Its presence can lead to serious complications to the patient.Our work uses Agent Based Modeling and Simulation techniques to build the model and the simulation of Methicillin-resistant Staphylococcus Aureus contact transmission in emergency departments. The simulator allows us to build virtual scenarios with the aim of understanding the phenomenon of MRSA transmission and the potential impact of the implementation of different measures in propagation rates.

Keywords: Agent Based Modeling and Simulation, MRSA Transmission, Emergency Department, Complex System.

1 Introduction

Methicillin-resistant Staphylococcus Aureus (MRSA)is one of the most common and most dangerous microorganisms that we can find in a healthcare environment and it is an important cause of nosocomial infection. A nosocomial infection has been defined as a infection caused by microorganisms acquired within healthcare environments [4]. MRSA bacteria could mean serious health problems for patiens and it means a longer hospital stay, expensive treatments and increased mortality and morbidity rates [5]. MRSA bacteria is resistant to conventional antibiotics and they can live permanently on the skin of some people without showing any symptoms,

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making them colonized, or temporarily converting them into carriers and people that show symptoms are known as infected. However, all these people could transmit MRSA to another person by physical contact. Some researches suggest that the most common transmission vias are: the transiently colonized hands of healthcare staff, contaminated medical equipment and objects[11]. In an emergency department (ED), this transmission could be through the interaction between patients, healthcare staff and the environment. The risk of MRSA acquisition is particularly high in elderly patients, in patients with severe underlying disease, patients with open wounds or external devices, among other reasons [6].

The aim of ED is to take care of patients who arrive with some kind of illnesses and/or injuries that require immediate medical attention. In an attempt to control MRSA transmission rate, some concrete actions are performed in ED such as hand washing, hand disinfection and the use of isolation material, all of which are called Prevention Policies. The ED is one of the most complex and dynamic areas in a hospital because its operation is not linear and depends on several factors such as the acuity level of the patient, the configuration of the healthcare staff, the physical facilities of the ED among other factors. So, we can conclude that an ED is a complex system.

Agent-based modeling and simulation (ABMS) allow us to model complex systems as a collection of autonomous decision-making entities called agents. Each agent individually assesses its situation and makes decisions on the basis of a set of rules[2]. This work uses ABMS to create a contact propagation model and simulator of MRSA in ED. It is worth noting that MRSA bacteria is transmitted only through physical contact, when someone touch a person who carries the bacteria or when someone touch something that an infected person touched, therefore, this work focused only in this kind of transmission. Our model is based on the definition of active and passive agents and their interactions. Active agents are the people involved in the attention process, patients and healthcare staff with their specific function and behaviors. Passive agents are the environmental objects and equipment used in the attention process. Our model takes into account the direct and indirect MRSA transmission by physical contact. Direct transmission is represented through the interaction (person-to-person), between patients and healthcare staff and indirect transmission represents the MRSA contact transmission between patients and healthcare staff through the environmental objects and equipment. This research is carried out with the collaboration of healthcare staff at the Emergency Department of Hospital Universitari Parc Taulí, one of the biggest hospitals in Catalonia - Spain. It is worth noting that our work has been developed based on a previous ED model and a previous ED simulator, both of which have been developed as part of previous works [3][13][8] by our research group. These previous works describe the full attention process of an ED.

The remainder of this article is organized as follows: Section 2 describes some previous works about nosocomial infection simulation. The Modeling of MRSA propagation is detailed in Section 3. Section 4 shows the Simulator of MRSA transmission and its configuration and input values. Some experimental results are detailed in Section 5. Finally, Section 6 closes this paper with conclusions and future works.

2 Related and Previous Works

MRSA is a subject of global interest. There is no healthcare environment which is free of complications related to the presence of this organism. So, this topic has already been widely studied using different techniques. In this section, we will refer to some relevant papers relating to the modeling of the MRSA transmission.

In Barnes et al.[1], the authors presented a MRSA transmission reduction using agent-based

modeling and simulation. This simulation is developed in a hospital ward which has a different function to ED. The Model shows the interaction between patients-healthcare staff, and patients-visitors. Patients can take one of two states: susceptible or colonized. The patients never arrive as infected but they can develop infection during their stay. Our work classified the patients as non-colonized, colonized and infected. Healthcare staff agents are created at the beginning of the simulation in an uncolonized state and during the simulation could be susceptible or colonized. Unlike our work, visitors are included in the simulation, in the ED short stays of patients do not justify the inclusion of visitors in the simulation. In similarity to our proposal, 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.
According to Meng et al.[10], an agent-based-simulation is designed to determine how to reduce the transmission risk of MRSA in a hospital ward divided into bays, with some isolation rooms. The simulation divided patients who have MRSA in primary and secondary cases. Transmission is modeled by pairwise interaction between colonized and non-colonized patients, patient and healthcare staff (nurse and doctor) transiently or permanently colonized, patient-to-patient contacts and transmission from a contaminated environment is also considered. This model takes into account the susceptibility of the patient to colonization. A patient has some possible states: colonization, detection, decolonization treatment and location status. This work considers the disinfection process, since the environment of the simulation is a hospital, in ED these kinds of processes are not performed. The model assumes, unlike our model based on contact transmission, that a susceptible patient may acquire MRSA due to the presence of colonized patients in the vicinity, regardless of the mode of transmission.
In McBryde et al. [9], unlike our model based on agents, a stochastic mathematical model of MRSA transmission is presented. The environment of the simulation is an intensive care unit (UCI). The transmission model is based in mathematical formules. The model assumes that there was no direct patient to patient or healthcare staff agent to healthcare staff agent transmission. The model assumes that there is no environmental transmission and that all patients who were colonized were detected on admission.

These works focus on contact transmission of MRSA mainly through the interaction between patients, doctors and nurses, other members of healthcare staff are not included. These researches have different environment simulation such a UCI or a single hospital ward. In ge-

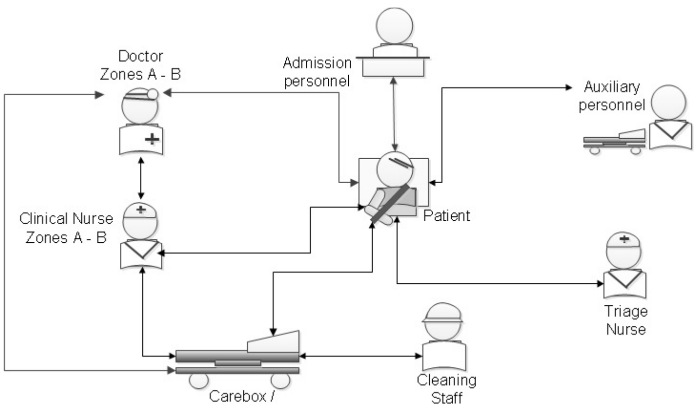


Figure 1: Possible physical contacts between active and passive agents.

neral, 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.

3 Conceptual Model of Transmission

The physical space in which the simulation takes place is the ED. It is devided in two zones according to acuity level of the patients. Zone A for patients I, II and III, and zone B for patients IV and V. The acuity level is decided in the triage phase according to the Spanish 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. More details about the organization of the physical environment are included in a previous research of our work group[13]. MRSA bacteria could be introduced in ED through colonized or infected patients that are admitted. These patients represent the percentage of transmission vectors ($Percen\_TV$) that arrive per day in ED. In addition, the model assumes that a percentage of total patients that arrive have a certain predisposition (*Percen_Predis*)to acquire MRSA.

3.1 Agents and their Behaviors

As mentioned above, two kinds of agents are defined, active and passive agents. Active agents have the ability to act by themselves, they are all people involved in the attention process. Passive agents do not have their own initiative, they are the medical equipment and objects of the healthcare environment(see Figure 1).

3.1.1 Active Agents

Active Agents are divided in two sets: patients and healthcare staff. It is necessary to make this classification because each group can take a different infectious status. The model uses *Infect_Status* variable to show the infectious status of active agents.

A **Patient** is any person who arrives at ED seeking healthcare. It is important to consider that each patient on arriving at ED, regardless of their acuity level, has a probability of being a MRSA transmission vector (*Primar_Status*). A patient who is identified as transmission vector at the admission time is labeled as a primary case, the *Primar_Status* boolean variable shows this condition and can take one of two values: true or false.

Our work classified patients, according their infectious status (*Infec_Status*), in non-colonized, colonized or infected. All non-colonized patients are susceptible to acquiring MRSA, but some of them could be more susceptible than others, such as patients with open wounds, external devices among other reasons. The *Predis_Status* boolean variable shows if the patient has a predisposition that could make them more susceptible to acquiring MRSA or not.

The model assumes that patients, who arrived as transmission vectors and patients who develop a colonization or infection during their length of stay (LoS) in the ED, remain in this infectious status until the end of simulation. The model does not take into account disinfection or decolonization process for patients because these processes usually have longer average length of time than the average of LoS of patients in ED.

Healthcare staff is divided in doctors, triage nurse, clinical nurses, admission personnel, auxiliary personnel and cleaning staff, each one of which has an *Infec_Status* variable. It has three possible values: non-carrier, carrier and colonized. A member of the healthcare staff could be a carrier when they acquire MRSA temporarily as a result of interaction with any transmission

vector, if healthcare staff complies with some action of the prevention policies, the bacteria could be eliminated and the healthcare agent will return to non-carrier. At the beginning, all healthcare staff agents are created as non-carrier. Doctor and clinical nurses are different for zones A and B, and are classified according to their experience in senior or junior.
Prevention policies are implemented in the model as behaviors performed by members of the healthcare staff. Three prevention actions can be evaluated in this model: hand washing, hand disinfection and use of isolation material. Healthcare staff have the oportunity to execute a hand wash and/or hand disinfection before they finish their interaction with a patient. The isolated material is required only when healthcare staff attend an isolated patient. The model allows us to define, at the beginning of the simulation, a likelihood of compliance for each action through the variables *HandW_Prob*, *HandD_Prob*, and *IsoMat_Prob*. Each of these actions can be executed with a higher or lower level of compliance (probability between 0 - 100), which influence the likelihood or not of MRSA transmission. The variables *Effec_HandW*, *Effec_HandD* and *Effec_IsoMat* are the effectiveness of each prevention action.

3.1.2 Passive Agents

Passive agents are inanimate objects of the environment that might have interactions with the active agents, but given that it is not possible to include all these objects and equipment, we consider all these objects as a single agent. So, we represent the interaction between active agents with the environmental objects through a single passive agent called *Carebox*.
The carebox is the physical room where a patient is accommodated during the treatment and diagnosis process. Each carebox contains the equipment needed for patient care, it meaning that when the patient is a transmission vector we have a lot of contaminated objects, though all these objects are usually inside the carebox, therefore we consider them as a single object. This carebox could be an isolated carebox, if the patient who is housed is a transmission vector. *CareB_Type* variable shows the type of carebox, isolated or non-isolated. The carebox has a infectious status and can be representated through *Infect_Status* variable, it can take one of two values, contaminated or non-contaminated. The main difference between carebox and isolation carebox is the value of transmission probability of each one. *Trans_Prob* variable represents this probability and it can take values between 0 and 100.

3.2 Direct and Indirec Transmission

Two kinds of contact transmission are defined between agents through their interactions, direct and indirect transmission. Direct transmission occurs when an active agent transmission vector has interaction with another active agent, which is not a transmission vector, and this active agent acquires MRSA bacteria.
Indirect transmission is when an active agent vector transmission has interaction with a passive agent (touching some medical equipment or objects in the hospital environment), and MRSA bacteria is transmitted to the object. Later, an active agent which is not a transmission vector has contact with the same object and it acquires MRSA.
In the indirect transmission it is necessary to bear in mind the lifetime of MRSA on dead surfaces. Considering that MRSA bacteria can live more than 90 days on different surfaces [12] and this period is very long compared with the LoS of the patients in the ED, 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.

3.3 Transmission Model

Frequent interaction between patients and healthcare staff is the principal way to MRSA transmission. Whenever an interaction between agents is given, we consider an MRSA transmission is likely. However, there is a wide variety of factors that will determine if the transmission has a direct impact on the infectious status of the susceptible agent and change it from non-carrier or non-colonized, to carrier, colonized, infected or whether in contrast, the bacteria are removed and the infectious status of the susceptible agent will not change. To assess the incidence of transmission, a mechanism to allow us to determine the probability of either alternative is required. Our model considers in each interaction the susceptibility of the agent who is at risk of acquiring MRSA. If the agent at risk is a patient, the analysis is based on the health state of the patient (predisposition, infected status), but if the agent at risk is a member of the healthcare staff, the analysis takes in account other values such as accomplishment and effectiveness of prevention policies (hands wash, disinfection hands, etc).

The model takes into account the parts of the overall attention process in which the agents interact with each other, because the contact propagation can take place in these moments. The process starts when a patient arrives in the ED and they approach the admission zone. Here the admission staff ask for their health card and register their arrival, if the patients had a previous admission, the ED has their clinical history and the infectious status of the patient is identified. After, the patient goes to the waiting room and waits for the triage process. When the triage nurse is available, they call the patient through the information system (IS), and take vital signs (interaction) and ask for some additional information in order to identify the acuity level of the patient, the infectious status, and other important data. If the acuity level assigned to the patient is IV or V, they wait for the diagnosis and treatment process in a waiting room (zone B), but patients with acuity level I, II or III are assigned to a carebox (zone A) and the diagnosis and treatment phases should be done inside such a carebox, with the exception of some specific tests. In the same way, when the infectious state of the patient is colonized or infected, IS registers this state and makes an alert in the clinical history of the patient.

The diagnosis and treatment process is divided in 3 phases: 1) Initial evaluation; 2) Laboratory test; 3) Application of medication or treatment. When a doctor is available they call the patient (through IS), perform the medical examination (interaction) and decide what the next step is. The IS shows the clinical history of the patient, including the infectious status, and the doctor has the opportunity to apply the prevention policies. The laboratory test phase is optional, and the doctor decides if it is necessary or not. The treatment phase and the take of samples for laboratory test are carried out by clinical nurses (interaction). Laboratory test and treatment can be carried out several times. When the treatment has finished and additional laboratory tests are not necessary, the doctor dicharges the patient from the ED. In the case of patients IV and V, the interaction with the doctor and nurses will be carried out in attention boxes of the doctor (zone B), and the patient will remain in a specific waiting room while there is no interaction (between each one of these phases). Whenever the healthcare agent finishes an attention task, they may or may not apply the prevention policies: hand washing, hand disinfection or using isolated material. The action that is executed can be effective or not. A full explanation of attention process is detailed in a previous work [7].

4 Simulator by Contact Transmission of MRSA

The implementation of the model is in Netlogo 5.1.0. simulation environment. The initial configuration is described in Table 1 and Table 2. Some initial simulation parameters for the model are input directly via a text file and others such as *HandW_Prob* and *Effec_HandW* can be set in the graphical environment. It is possible to give values for each one of the three prevention policy actions: hand washing, hand disinfection or using isolated material, and give a effectiveness value for each one action. At the beginning of the simulation the patient agents are created based on the real flow of patients in a single day in the ED with a distribution per hour($Averag\_Pat = 397$) and the healthcare agents are created based on the initial parametres of the text file (see Table 2).

The simulator has an initial value for the percentage of colonized or infected patients

Table 1: Example of quantity configuration of resourse for a single execution.

Description	No.	Description	No.	Description	No.
Admission Personnel	4	Junior Clinical Nurse Zone B	1	Junior Doctor Zone B	2
Triaje Nurse	4	Senior Clinical Nurse Zone B	2	Senior Doctor Zone B	2
Junior Clinical Nurse Zone A	1	Junior Doctor Zone A	3	Auxiliary Personnel	10
Senior Clinical Nurse Zone A	7	Senior Doctor Zone A	3	Carebox	60

Table 2: Input values for experiments.

Description	Variable	Value
Simulation Time	Simul_Time	1440 hours
Average patient arrive per day*	Averag_Pat	398
Percentage transmission vector that arrive ED	Percen_TV	2%
Percentage of patient with predisposition to acquire MRSA	Percen_Predis	20%
Hand wash probability	HandW_Prob	100%

*The flow of patients has a probability distribution per hour, considering hospital data.

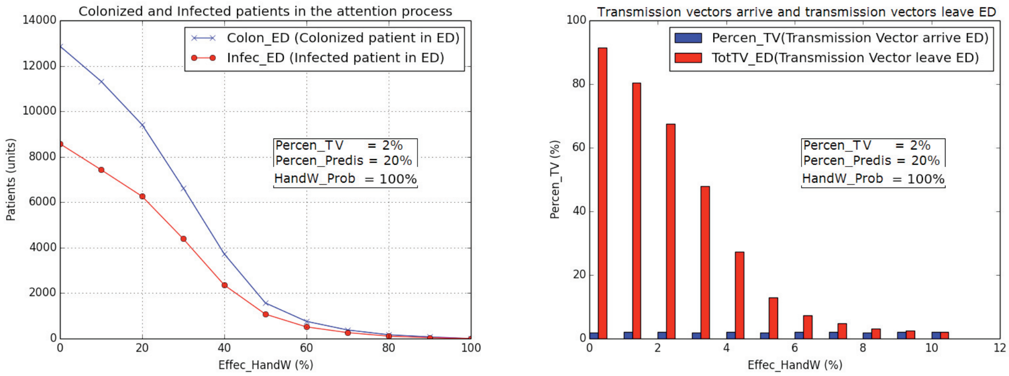
(*Percen_TV*) that arrive at the ED per day. This variable can take values from 0 to 10. The simulation gives a random value for the infectious state of each patient, taking into account the Percen_TV variable. In addition, the model assumes that 20% of the patients are more susceptible than others to acquiring a nosocomial infection because they have some specific condition such as open wounds, external devices, a weakened immune system as a result of a cronic illness, etc. The patient interaction with the admission staff is not taken into account in the simulation because the physical contact between them is negligible compared with the contact between patient and other members of the healthcare staff. In order to analyze in depth the transmission of MRSA person-to-person, in these executions we will assume that the only possible route of transmission is direct transmission between patients with triage and clinical nurses, doctors and auxiliary personnel.

5 Experimental Results

The input values for this experiments are detailed in Table 1 and Table 2. The experiments were executed parallel on a 10-node cluster. In order to analyse the impact of hand washing in MRSA transmission, we execute some experiments considering two specific variables, *HandW_Prob* and *Effec_HandW*. The first variable represents the probability that a doctor washes their hands after interaction with a patient, and the second variable represents the probability that this action is carried out correctly, in such a way that enough bacteria have been removed to prevent future transmissions. For experiments we keep a constant value for *HandW_Prob* = 100%, and we vary the values of *Effec_HandW* in a range of 0% to 100% with increments of 10% for each execution. The Table 3 summarizes the results of the experiments.

Table 3: Handwash Probability = 100%

Effec_HandW	**0**	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**100**
Colon_arrive	222	246	240	252	247	259	241	259	229	255	265
Infec_arrive	242	244	248	220	235	207	238	227	228	231	234
NonCol_arrive	23491	23467	23468	23483	23474	23490	23476	23469	23498	23471	23458
TotPat_arrive	23955	23957	23956	23955	23956	23956	23955	23955	23955	23957	23957
Percen_TV(%)	1,94	2,05	2,04	1,97	2,01	1,95	2,00	2,03	1,91	2,03	2,08
Colon_ED	12868	11326	9411	6634	3723	1568	757	379	169	74	0
Infec_ED	8573	7431	6258	4393	2355	1074	513	263	107	40	0
TotTV_ED(%)	91,44	80,34	67,44	48,00	27,38	12,97	7,30	4,71	3,06	2,50	2,08

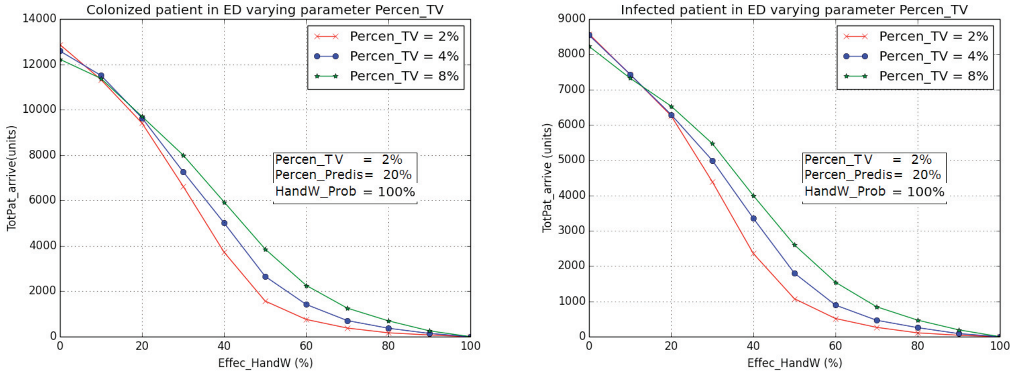


(a) Colonized and Infected patients in ED. (b) Comparison percentage of TV arrive and leave ED.

Figure 2: Colonized and Infected Patients with a hand wash accomplishment of 100% and differents values of effectiveness.

This experiment is a proof of concept whose aim is to analyse the behaviour of the propagation rate of MRSA assuming that healthcare staff always (*HandW_Prob* = 100%), wash their hands after an interaction with a patient. The average number of interactions between patients and health staff for each execution was 113872 interactions, meaning an average of 79 interactions per hour. The variation in the values of effectiveness, *Effec_HandW* = [0-100], influences the number of patients who were colonized and infected with MRSA during the attention process at ED, and these values are represented by *Colon_ED* and *Infec_ED* variables (see Figure 2). It is important to mention that the values obtained show a decreases in the number of colonized and infected patient when the effectiveness of hand washing increases.

The execution includes two extreme values for *Effec_HandW*, 0% and 100%. A value of 0% means that, although healthcare staff had practice hand washing after each patient interaction, this action is never executed correctly. Then in the next interaction with a susceptible patient, there is likely to be a transmission. A value of 100% means that each hand wash action is always well done, and takes into account that direct agent-to-agent transmission is the unique way of transmission, we can conclude that, in theory, the transmission rate of MRSA propagation in



(a) Colonized patient leave ED.

(b) Infected patient leave ED.

Figure 3: Influence of hand wash effectiveness in the number of colonized and infected patient with MRSA during the attention process at ED.

the ED will be 0, which equals the result obtained in our simulation. These two values for *Effec_HandW* are unlikely in the real world, but now, for us it is a way to validate that the behavior of the simulator is the expected.

Other executions were carried out assuming different values for percentage of transmission vectors that arrive daily at the ED (Percen_TV). A comparison of the obtained result of this executions is plotted in Figure 3 for Percen_TV of 2%, 4% and 8%. According to the values obtained, we can conclude that the percentage of transmission vectors, *Percen_TV*, that arrive daily at the ED has an important influence on the number of patients who acquire a colonization, *Colon_ED*, or infection, *Infec_ED*, during the attention process, unless the effectiveness of handwashing falls below 20%. Regardless of the input value of percentage of transmission vectors (2%, 4%, 8%), we can observe a significant decrease in the number of colonized and infected patients in the ED, *Colon_ED* and *Infec_ED*, from effectiveness of hand washing, *Effec_HandW*, of 60%.

6 Future Work and Conclusions

As a result of our research, we proposed an agent-based model and simulator of the contact propagation of MRSA in emergency departments implemented in Netlogo simulation environment. Our model includes the definition of active and passive agents, their variables and behaviors. Anyone who has a role in the attention process is defined as an active agent, and the objects and equiptment of the medical environment are defined as a passive agent. The transmission mechanism to the MRSA bacteria is the interaction between agents, as a result of attention process. The predisposition level of the patients and the accomplishment level of prevention policies of healthcare staff are evaluated in each interaction. The results of the simulation show that the percentages of patients that arrive as colonized or infected has incidence in the number of colonized and infected patients that acquire MRSA as a result of attention process in ED. The level of effectiveness of hand washing is a very important factor in the percentage of propagation of MRSA in ED, if hand washing effectiveness falls below 60% , it registers an important increase in the number of colonized and infected within the ED.

Our future work is to implement the full contact propagation model of MRSA, in order to obtain the simulation of direct and indirect transmission. The full computational model will allow us a better understanding of the MRSA transmission phenomena, as well as the impact of other prevention policies on transmission rates.

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