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Trained Nurse Location Model for In-Hospital Cardiac Arrest Survival

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Abstract

Survival and complete physiological recovery rates following In-Hospital Cardiac Arrest (IHCA) are poor in all age groups. For example, fewer than 20% of adult patients having an IHCA survive to go home. Medical authorities report that a victim of cardiac arrest has the best chance of survival without neurological damage if care is received within 3-5 minutes of occurrence. Nursing staff play a central role in the effective management of IHCA as they are often the first medical staff to arrive to a patient with IHCA. This paper proposes a new location model for nurses who are trained in Cardiopulmonary Resuscitation (CPR), defibrillation and In-Hospital Survival Chain (IHSC) processes to maximize the survival probability of patients.

Keywords: In-hospital cardiac arrest, survival chain, survival probability, covering problems
Introduction

In-hospital cardiac arrest (IHCA) is a major public health problem. Despite efforts to save more people who suffer from IHCA, survival rates following after in-hospital CPR are no better today than they were more than a decade ago (Ehlenbach et al., 2009). During 2005 and 2006, more than 21 000 in-hospital cardiac arrests were reported to the American Heart Association National Registry of Cardiopulmonary Resuscitation (AHA NRCPR) from approximately 10% of the hospitals in the United States (Peberdy et al., 2008). Based on the data from 14,720 in-hospital cardiac arrests in the NRCPR, Peberdy et al. (2003) reported an overall survival to hospital discharge of 17%. A total of 287 facilities reported 18 817 events to the NRCPR during 2009. The rates of survival to discharge after in-hospital cardiac arrest were 33% among children and 21% among adults. Of these, 95% were monitored or witnessed and 18% percent had ventricular fibrillation (VF) or pulseless ventricular tachycardia (VT) as the first recorded heart rhythm. Of these, 43% survived to discharge (AHA, 2011).

Patient survival following IHCA depends on a sequence of interventions. The Survival Chain is a metaphor used to organize and describe the integrated set of time-sensitive, coordinated actions necessary to maximize survival from cardiac arrest (see Figure 1). The use of evidence-based education and implementation strategies can optimize the links of that chain (Bhanji et al., 2010). The problem of IHCA is less well studied than the problem of cardiac arrest outside of hospitals but is nonetheless an important problem (Sandroni et al., 2007). This paper examines how staffing allocations for nurses who receive survival chain training can improve survival from IHCA.

FIGURE 1 NEAR HERE

Medical authorities report that a victim of cardiac arrest has the best chance of survival without neurological damage if care is received within 3-5 minutes of occurrence (Myers et al., 2009). Brain damage can start 4 to 6 minutes after the heart stops pumping blood. If a trained bystander is available to perform effective Cardiopulmonary Resuscitation (CPR) immediately after a sudden cardiac arrest, they can double a victim’s chance of survival (Abella et al. 2008). CPR is an important rescue skill used to treat cardiac arrest, a condition characterized by sudden, abrupt loss of heart function. CPR can stimulate a small amount of blood flow to the heart and
brain to "buy time" until a normal heart beat is restored by defibrillation or with the aid of drugs (Aufderheide et al., 2011). The concept of early defibrillation applies not only to the out-of-hospital setting but also to in-hospital resuscitation efforts. The International Liaison Committee on Resuscitation (ILCOR) strongly encourages the development of early defibrillation programs for nonphysician in-hospital responders (Kloeck et al., 1997).

Since nursing staff are frequently the first to witness or respond to an in-hospital cardiac arrest, they may play a central role in the effective management of IHCA (Gombotz et al., 2006). Nonspecialized nursing personnel cannot as a rule expeditiously perform the complex tasks of CPR. Accordingly, effective CPR is rarely begun before the arrival of experienced providers in the in-hospital setting (Weil et al., 2006).

This paper examines several facets of the problem of allocating nurses that are trained with CPR as well as defibrillation and IHCA Survival Chain processes. One facet is how to assign a limited number of nurses to different units in order to maximize the probability of patient survival following IHCA. We assume that the longer the response time by trained nurses, the lower the probability of survival. A variation on that problem is to maximize the number of units that are covered within a given time threshold (such as 3 minutes) in order to achieve compliance to standards for response thresholds. A second dimension that we explore is the relationship between the training of additional nurses in CPR and ICHA Survival Chain processes and the improvement in IHCA survival.

Our analysis determines the placement of nurses with CPR and IHCA skills to different units. The analysis accounts for patient occupancy and the number of beds in the units as well as the probability of IHCA, which may differ from unit to unit. The analysis does not provide a detailed rostering analysis for the assignment of individual nurses.

**Literature Review**

This article reports on a model developed to maximize the survival probability for IHCA by allocating trained nurses to hospital units. The mathematical model developed is a special case of a weighted resource location problem. Our work is linked to three main areas of research: location models, nurse staffing, and survival following cardiac arrest.

The assignment of specially trained nurses to units to maximize survival probabilities is a type of location problem. The main concern is to locate resources in a way to effectively address a
need. For example, many Emergency Medical Service (EMS) systems have performance measures based on the response time and the number of calls covered in a given timeframe (De Maio et al., 2003). Applications include ambulance location (Toregas, 1971, Church et al. 1974, Brotcorne et al. 2003, Goldberg 2004, Henderson et al. 2005, Gendreau et al. 2006, Andersson et al. 2007, Erkut et al. 2007 and Henderson et al. 2010, Amponsah et al. 2011) and defibrillator location (Myers et al., 2009). New models and algorithms keep appearing, as do surveys. We propose a trained nurse location model in order to improve the survival and the neurological outcomes from IHCA.

Previous research in the management science literature that involves nurses includes budgeting, scheduling, staffing and assignment problems (Punnakitikashem, 2007). Other nurse staffing work has focused on minimal staffing levels as a function of mean patient acuity, the number of patients, and the mean rate of change in patient acuities (Siferd et al., 1994). Much of this work studied nurse staffing ratios (De Véricourt and Jennings, 2011). Chapman et al. (2009) analysed qualitative data from interviews with healthcare leaders about the impact of nurse staffing ratios. Kane et al. (2007) demonstrate associations between increased registered nurse staffing and lower odds of hospital related mortality and adverse patient events. Griffiths (2009) confirms the association between nurse staffing levels and patient outcomes. Lavieri et al. (2009) proposed a linear programming hierarchical planning model that determines the optimal number of nurses to train, to promote to management and to recruit over a 20 year planning horizon in order to achieve specified workforce levels. Our study allows a decision maker to establish whether the available number of trained nurse can cover all the units in the hospital and how to assign them in order to improve IHCA survival probabilities. We also determine the minimum number of trained nurses needed to provide timely coverage for all areas of the hospital.

The literature on cardiac arrest outside of hospitals is quite rich, but IHCA is less thoroughly studied. Survival probabilities from studies of CA outside of hospitals (e.g. Erkut et al., 2007) are nonetheless relevant to our paper. Valenzuela et al. (2000) conducted a study in casinos and show that short response times improve survival rates of cardiac arrest patients. Security officers were trained to administer CPR and defibrillation. The exact time of collapse was determined from security videos and times from collapse to CPR were typically under three minutes. This separates this study from most others, where the time of collapse is either subjectively estimated by bystanders or ignored and times from collapse to CPR are considerably longer (Erkut et al.,
Patients who received defibrillation within 3 minutes after collapse had a 74% survival rate, while those who received defibrillation later had a 49% survival rate. A few studies reported response time distributions and estimated how survival depended on response time (Larsen et al. 1993, Valenzuela et al. 1997, Waaelwijn et al. 2001, De Maio et al., 2003).

Eisenberg et al. (1990) reviewed published reports from 29 cities on survival rates after out-of-hospital cardiac arrest. Factors besides response times that may influence survival rates include system design (how EMS staffs are trained; which procedures they perform) and the consistency with which procedures are applied.

This paper links to the literature on survival rates by accounting for nurse training and assignment to units, and how the transit time of a trained nurse in one unit to the site of a cardiac arrest links to the survival of patients that suffer IHCA.

**Trained Nurse Location Model for IHCA Survival**

This paper explores how to locate nurses that are trained in CPR, defibrillation and IHCA Survival Chain processes to improve the survival of patients that experience IHCA. Suppose that there are $M$ units in the hospital and the number of nurses that have CPR, defibrillation and IHCA survival chain allows for $N$ units at a time to be covered in the nurse staffing schedule. We define $X_j = 1$ if a trained nurse is based in unit $j$ and set $X_j = 0$ if a nurse is not based in unit $j$. We set $X = (X_1, X_2, \ldots, X_M)$.

The survival probability of a patient in unit $i$ that suffers from IHCA depends strongly on the response time of medical staff. If a nurse in unit $j$ is mobilized to respond to that patient, and the time to travel from unit $j$ to unit $i$ is $t_{ji}$, then we presume that the survival probability $F(t_{ji})$ of such a patient is given by the logistic regression of De Maio et al. (2003) who studied EMS response times

$$F(t_{ji}) = \left(1 + e^{0.679 t_{ji} + 0.262} \right)^{-1}$$

We assume that the nurse that maximizes patient survival is mobilized, so that a patient in unit $i$ that suffers IHCA has a survival probability

$$S_i (X) = \max_{j;X_j=1} F(t_{ji}).$$
This survival probability therefore explicitly depends on which units have trained nurses allocated to them.

Suppose that there are \( n_i \) patients and the probability of IHCA per patient per day in unit \( i \) is \( P_i \). The trained nurse location model for IHCA survival is the choice of \( X \) in order to maximize the expected number of patients per day that survive IHCA in the hospital. Formally, we call this optimization Problem (P1) and write it as follows.

\[
(P1) \quad J_1 = \max \sum_{i=1}^{M} n_i P_i S_i (X)
\]

subject to the following constraints:

\[
\sum_{j=1}^{M} X_j = N \quad (2)
\]

\[
X_j \in \{0,1\}, \quad j = 1,2,\ldots,M \quad (3)
\]

Constraint (2) controls the number of slots in the schedule for trained nurses in the solution (i.e., the number of units with a trained nurse assigned to it).

An interesting variation on (P1) accounts for regulations that may exist regarding staffing and response times to improve neurological outcomes. Suppose that there is a national target of having response times within \( T \) minutes. For example, the AHA (2000) recommends defibrillation within 3-5 minutes of cardiac arrest for emergency response outside the hospital. Recently published studies (Valenzuela et al., 2000) further support that recommendation, with results that show a 74% survival rate for victims defibrillated within three minutes.

To describe the number of units that are covered by a nurse in the same or another unit within \( T \) time units, we define the parameters \( a_{ji} \) to be 1 if unit \( i \) can be so covered by a nurse in unit \( j \) (that is, \( t_{ji} > T \)), and 0 otherwise, and we let \( Y = (Y_1, Y_2, \ldots, Y_M) \) be the vector of binary variables \( Y_j \) are 1 if and only if unit \( j \) is covered by a trained nurse in less than \( T \) time units.

With this notation, we can write a second objective function of interest which is the number of units that are covered within a given time threshold. The maximization of that objective function is the second optimization problem that we consider,

\[
(P2) \quad J_2 = \max \sum_{i=1}^{M} Y_j \quad (4)
\]

subject to the constraints in (P1) along with the following two constraints:
\[
\sum_{j=1}^{N} a_{i,j} X_j \geq Y_i, \quad i = 1, 2, \ldots, M
\]  
(5)

\[
Y_i \in \{0, 1\}, i = 1, 2, \ldots, M
\]  
(6)

Constraint (5) states that the unit \(i\) can only be covered if at least one nurse that cover \(i\) is selected.

**Computational results and discussions**

In this section we explore the nurse assignment model for IHCA survival that is informed by data from a large French hospital. We model \(M = 10\) of the hospital’s units and label them \(U_1, U_2, \ldots, U_{10}\). The choice of units is based on high levels of IHCA. The units include emergency, internal medicine/nephrology, four cardiac units (a cardiac intensive care, cardiology rehabilitation, and two cardiology units), and four other surgical units (digestive/vascular, orthopedic/trauma, ambulatory, vascular surgery and medicine). Table 1 summarizes some of the input data. We let \(n_i\) be the actual bed capacity in the units, as bed occupancy is high in the units (see Table 1) and the same solution of (P1) is obtained as the utilization of all units is scaled up or down together. Documents with values of the probability of IHCA per patient per day were available for units \(U_3, U_9\) and \(U_{10}\). The probabilities for the other units were estimated.

**TABLE 1 NEAR HERE**

Travel times were estimated from the layout of the facility to obtain distances, along with an estimated speed between the units (we used 2km/h for the trained nurses, to allow for identification of the nurse and any potential congestion in hallways and in some cases escalators). Note that we assume that the time to for a trained nurse to respond within his or her unit is not necessarily zero. For responses within a given unit we assumed that the response time is based on traversing half the width of the unit.

This hospital has many issues with IHCA, so they considered the use of Radio Frequency Identification (RFID) technology to locate the patients who have IHCA and to locate trained nurses. The proposed system is to place an Automatic External Defibrillator (AED) and RFID reader in each unit, to use an alarm to detect the signs of cardiac arrest (pulse and respiration), to
use active RFID tags to determine exact patient locations and to use a handheld (PDA, mobile phone, etc) equipped with an RFID reader to locate trained nurses. We performed an analysis for staffing that presumed that such as system could be put into place and that compliance for staff and patient use of the system were effective in rapidly determining the time and location of IHCA without an excessive false positive rate.

The main points of the experiments are to look at how to locate limited number of trained nurses to improve the survival to IHCA without increasing the cost of training and to determine how many nurses should be trained to improve survival and neurological outcomes from IHCA.

We Solve P1 for \( N = 1, 2, \ldots, 10 \) in order to explore the benefit of increasing the number of trained nurses? Table 2 summarizes the results.

### TABLE 2 NEAR HERE

The results indicated that the rate of expected survival to discharge can be improved by increasing the number of trained nurses. Table 2 also summarizes the vector \( X \) of how to optimally allocate the nurses to the 10 units. We observe that an allocation that greedily allocates slots for trained nurses to units with the highest expected IHCA rate, \( n_i * P_i \), is not optimal for P1. Such a greedy allocation would assign nurses to units 3, 1 then 2 (by inspection from the data in Table 1), whereas the optimal solutions assigns them to units 3, 1 then 9.

Figure 2 displays the expected number of IHCA per day (top line) and the expected IHCA survival with 0, 1, 2 and 3 minute response times (the three lower horizontal lines). The gap between the two top horizontal lines indicates that even immediate response times are not sufficient to improve survival beyond 35%.

### FIGURE 2 NEAR HERE

Figure 2 also displays a curved line that gives the expected survival as a function of the number of slots for trained nurses, assuming that the given number of trained nurses is assigned to those slots optimally as in Table 2. We observe marginal decreasing returns to assigning more trained nurses.

In a follow-up experiment, we compare the cost and expected benefit of adding more trained nurses with those of a pharmaceutical intervention that is designed to reduce the risk of cardiac
arrest. Fox et al. (2003) indicated that Perindopril can reduce the relative risk of cardiac arrest by 20%. It costs 3700£ cost/QALY for the patients at greatest risk of cardiovascular event and 31195£ cost/QALY for the patients in a lower risk group (Briggs et al., 2007). The cost effectiveness of training for CPR/Defibrillation is based on statistics for training and the calculation of QALYs gained from a survival from IHCA as follows. Gage et al. (2002) showed that staff CPR training per year costs 63618£ for 743 staff. Thus, CPR training for one staff per year costs 85.62£. It costs 513.72£ per slot for nurses (6 nurses) per year. We assume that staff CPR training includes defibrillation training and that the average incremental number of years following survival is 5 years. To calculate the QALYs gained from a survival from IHCA, we used the following formula from the National Center for Early Defibrillation (2002): Cost per life year gained = Incremental costs of the training per year / Number of lives saved x Average number of years of survival. The number of lives saved is taken from our analysis (Table 2). For example, the cost per life year gained from a survival from IHCA by training enough nurses to cover one slot in the schedule is 2568£/QALY.

Figure 3 shows that the cost/QALY is increasing as more nurses are trained. This is consistent with the observation that there are marginal decreasing benefits to additional trained nurses. Figure 3 shows that the first several nurses trained can be more cost effective than the use of Perindopril but that as more and more nurses are trained, the cost/QALY of an additional trained nurse is worse than that of the use of Perindopril as a risk reduction option.

FIGURE 3 NEAR HERE

Figure 4 shows the minimal number of units to be assigned a trained nurse in order to achieve coverage within T minutes in all units of the hospital. This is determined by solving problem P2 for \( N = 1, 2, \ldots, 10 \). In this example, 3 units should be staffed with trained nurses to cover all units within 3 minutes. For this facility, this would translate into 18 trained nurses (3 units per shift to cover, times 3 shifts per day, times 2 teams per week, given a maximum of 35 hours per week of work, some other work constraints, and a slight margin for potential absenteeism).

FIGURE 4 NEAR HERE
Figure 4 also shows that twice as many nurses (six slots instead of three) would be required in order to meet a threshold of 2 minutes rather than of 3 minutes.

Conclusions

We have formulated and solved a trained nurse location model to improve the survival and the neurological outcomes following IHCA. The aim was to look at how to assign a limited number of nurses to different units in order to maximize the probability of patient survival following IHCA or to maximize the number of units that are covered within a given time threshold (such as 3 minutes) in order to improve neurological outcomes following IHCA.

We observed that the optimal placement of trained nurses can improve both survival and neurological outcomes following IHCA. The benefits of training additional nurses have decreasing marginal returns. The training of an initial cohort of nurses in specialize survival training skills, accompanied by an effective IHCA detection and response system, can be more effective at improving survival than a risk reduction drug like Perindopril (based on estimate of the cost effectiveness of that drug found elsewhere). After a certain threshold in the number of trained nurses, additional training would be less cost effective than that drug. The combination of training and other targeted interventions of course can further improve health benefits.
References


Figure 1: Survival chain (Nolan et al., 2006)

Table 1 Number of beds and probability of IHCA by unit

<table>
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<tr>
<th>Units</th>
<th>( n_i )</th>
<th>( P_i )</th>
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</tr>
<tr>
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<td>10</td>
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</table>

Table 2 Best allocations and Expected Survival

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<th># of slots for nurses</th>
<th>Best allocations</th>
<th>( E[\text{survival}] )</th>
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<td>1.66</td>
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</tbody>
</table>
**Figure 2** $E[\text{IHCA per day}]$, $E[\text{IHCA Survival with 0, 1, 2 and 3 minute response time}]$ and $E[\# \text{ of patients that survive IHCA/day}]$

**Figure 3** Cost effectiveness of training to CPR/Defibrillation
Figure 4 Number of slots for nurses required
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