Predicting Survival From Out-of-Hospital Cardiac Arrest: A Graphic Model

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Study objective: To develop a graphic model that describes survival from sudden out-of-hospital cardiac arrest as a function of time intervals to critical prehospital interventions.

Participants: From a cardiac arrest surveillance system in place since 1976 in King County, Washington, we selected 1,667 cardiac arrest patients with a high likelihood of survival: they had underlying heart disease, were in ventricular fibrillation, and had arrested before arrival of emergency medical services (EMS) personnel.

Methods: For each patient, we obtained the time intervals from collapse to CPR, to first defibrillatory shock, and to initiation of advanced cardiac life support (ACLS).

Results: A multiple linear regression model fitting the data gave the following equation: survival rate = 67% – 2.3% per minute to CPR – 1.1% per minute to defibrillation – 2.1% per minute to ACLS, which was significant at $P < .001$. The first term, 67%, represents the survival rate if all three interventions were to occur immediately on collapse. Without treatment (CPR, defibrillatory shock, or definitive care), the decline in survival rate is the sum of the three coefficients, or 5.5% per minute. Survival rates predicted by the model for given EMS response times approximated published observed rates for EMS systems in which paramedics respond with or without emergency medical technicians.

Conclusion: The model is useful in planning community EMS programs, comparing EMS systems, and showing how different arrival times within a system affect survival rate.

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INTRODUCTION

Survival to hospital discharge from out-of-hospital sudden cardiac arrest depends in part on the time to three critical prehospital interventions: CPR, defibrillation, and advanced care (eg, intubation, medication).[1-3] The shorter that the time interval is between collapse and these three interventions, the higher is the probability of survival.[1-5] From the moment of collapse, the likelihood of survival decreases rapidly with each minute that elapses without initiation of life-saving procedures. Prehospital interventions typically occur in a sequence: CPR is started by bystanders or emergency medical services (EMS) personnel followed by defibrillatory shocks administered by emergency medical technicians (EMTs) authorized to defibrillate or by paramedics and then followed by advanced care administered by paramedics. The average time to performance of these critical interventions determines a community's overall survival rate from sudden cardiac arrest.

We developed a model that describes the relationship between a community's average time intervals to these three critical interventions and its overall survival rate. The model is easy to apply, and its lessons are readily interpretable.

MATERIALS AND METHODS

Since 1976, we have collected information on all patients with out-of-hospital cardiac arrests in King County, Washington, for whom emergency personnel attempted resuscitation (9,245). Data were obtained from multiple sources, including EMS run reports, hospital records, death certificates, and interviews with bystanders. Detailed methods of data collection are described elsewhere.[3-5] For all cases, we determined retrospectively the etiology of the cardiac arrest, whether the collapse was witnessed, and the cardiac rhythm associated with the arrest. For all witnessed cardiac arrests, we determined the time intervals to the three critical interventions: from collapse to CPR, from collapse to first defibrillatory shock, and from collapse to advanced care. Time of collapse may be biased by inaccurate recall of exact times surrounding a stressful event, such as a sudden cardiac arrest. In our data, however, time of collapse is gathered consistently from dispatcher recordings and paramedic on-scene reports. We expect neither the nature of this potential bias nor the method of estimating time of collapse to change in the future. Thus, the timing guidelines proposed by the model should be no different for future cases than they would be for the cases on which the model is based.

We estimated time intervals to actual treatment as follows: the time interval to bystander-initiated CPR was taken from interviews with the bystander or from the incident report prepared by EMS personnel; the time interval to EMS-initiated CPR was estimated from the EMS response time plus one minute (the time needed for EMTs or paramedics to arrive at the scene, reach the patient's side, and position the patient); and the time interval needed for EMTs or paramedics to attach the defibrillator and clear the patient for defibrillation once CPR was in progress was estimated to be two minutes past EMT arrival or one minute past time of initiation of CPR by EMTs. In our data, the time interval from arrival of paramedics to the initiation of advanced care was estimated to be two minutes past paramedic arrival if defibrillation had taken place before paramedic arrival, three minutes past paramedic arrival if defibrillation had not yet taken place, and four minutes past paramedic arrival if the paramedics were the only EMS providers on the scene. These intervals to interventions are the best estimates of EMTs, paramedics, and EMS medical directors.[1,2]

We recognize that "advanced care" by paramedics includes multiple interventions delivered over time (intubation, initiation of IV access, administration of multiple medications, rhythm assessment, hyperventilation). For simplicity of analysis, however, we focused on a single time interval, from collapse to the moment when paramedics were ready to perform advanced interventions.

To determine the effect of these three time intervals on survival, we selected a somewhat uniform group with a higher likelihood of survival: patients who had a witnessed cardiac arrest due to underlying heart disease, who were in ventricular fibrillation, and whose arrest occurred before arrival of EMS personnel (1,667). Survival was defined as discharge alive from the hospital.

We estimated the relative strength of influence of each time interval on survival using a multiple linear regression model with survival (discharge from the hospital) as the outcome and time interval from collapse to CPR (I_{CPR}), time interval from collapse to first shock (I_{DEFIB}), and time interval from collapse to advanced care (I_{ACLS}) as predictors. Age, sex, underlying morbidity, and time to various hospital procedures, although certainly relevant to the survival rate, were not included in the model because they were not considered to be under EMS control. The model is expressed as the following equation:

$$\text{Survival rate} = C_{COLLAPSE} + C_{CPR}I_{CPR} + C_{DEFIB}I_{DEFIB} + C_{ACLS}I_{ACLS} \quad (1)$$

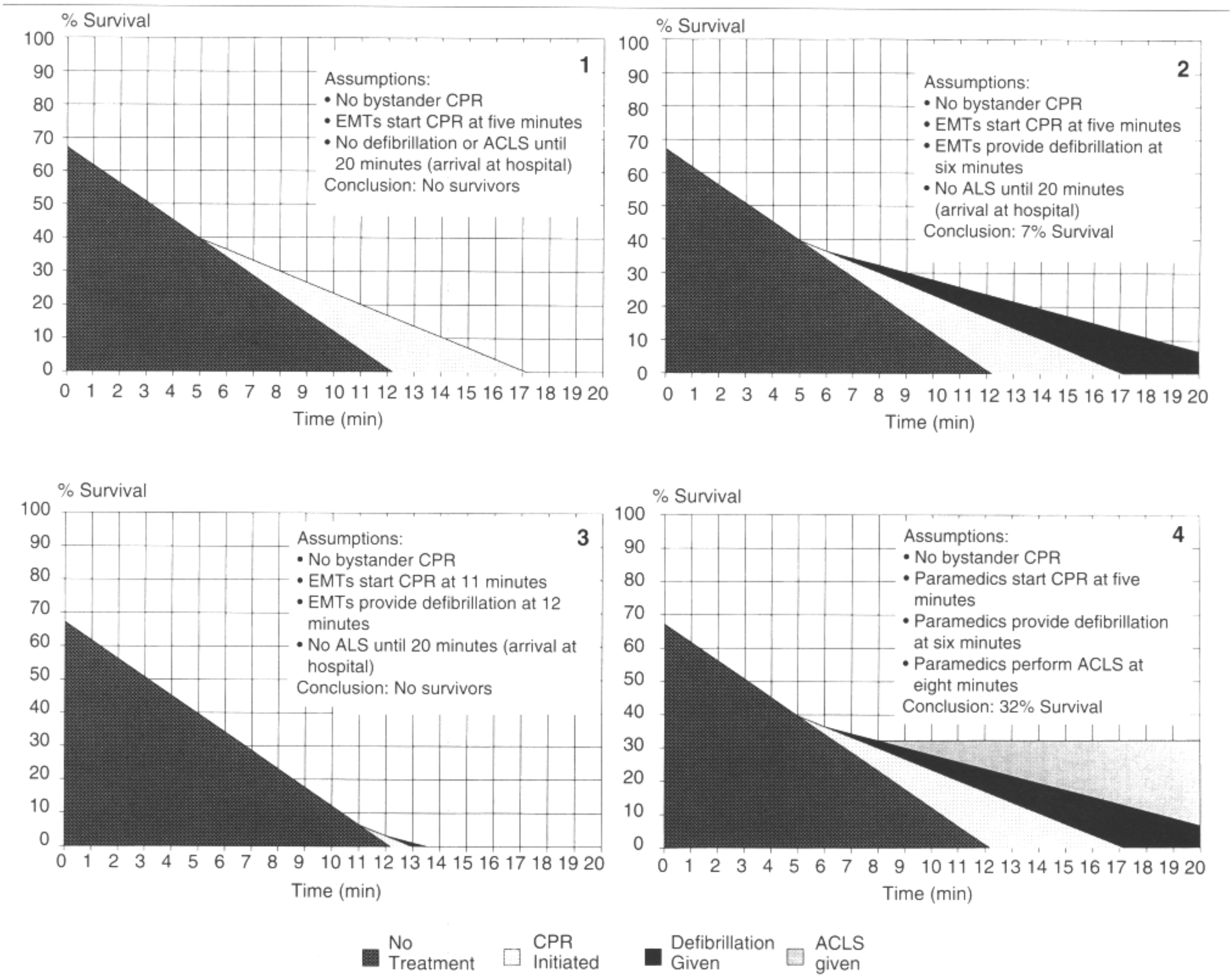
where C_{CPR}, C_{DEFIB}, and C_{ACLS} are the regression coefficients (relative strength of the effect) for the designated time intervals (I) and $C_{COLLAPSE}$ is the regression constant, which represents the survival rate expected when treatment is available immediately on collapse, ie, the hypothetical situation in which a patient went into cardiac arrest at the exact moment when an endotracheal tube was inserted, an IV catheter entered a vein, and defibrillator paddles were placed on the chest. Although a term to account for random measurement error generally is included in regression models, for simplicity we have omitted this term.

To test for the effects of interactions between terms or squared effects of any one term (a term multiplied by itself, such as $I_{DEFIB} \times I_{DEFIB}$), we also performed a stepwise linear regression using all possible products and squares of terms using a significance level of $P = .1$. None of these factors contributed significantly to the model, indicating that a simple, additive model was the most efficient.

All three time intervals, I_{CPR}, I_{DEFIB}, and I_{ACLS}, were limited to 20 minutes; cases with EMS arrival times in excess of 20 minutes were not included in the model. The survival rate is between 0% and 100% by definition. Within these limits, the model consists of a curve, the slope of which becomes more shallow with each intervention. Because the individual outcome measure is discharge alive from the hospital and we are assessing the effect of prehospital treatments only, the decline in survival is considered to be zero after the delivery of advanced care.

Figures 1-4.

Survival from cardiac arrest for 1) EMT system with response time of four minutes; 2) EMT-D system with a response time of four minutes; 3) EMT-D system with a response time of ten minutes; 4) paramedic system with a response time of four minutes.

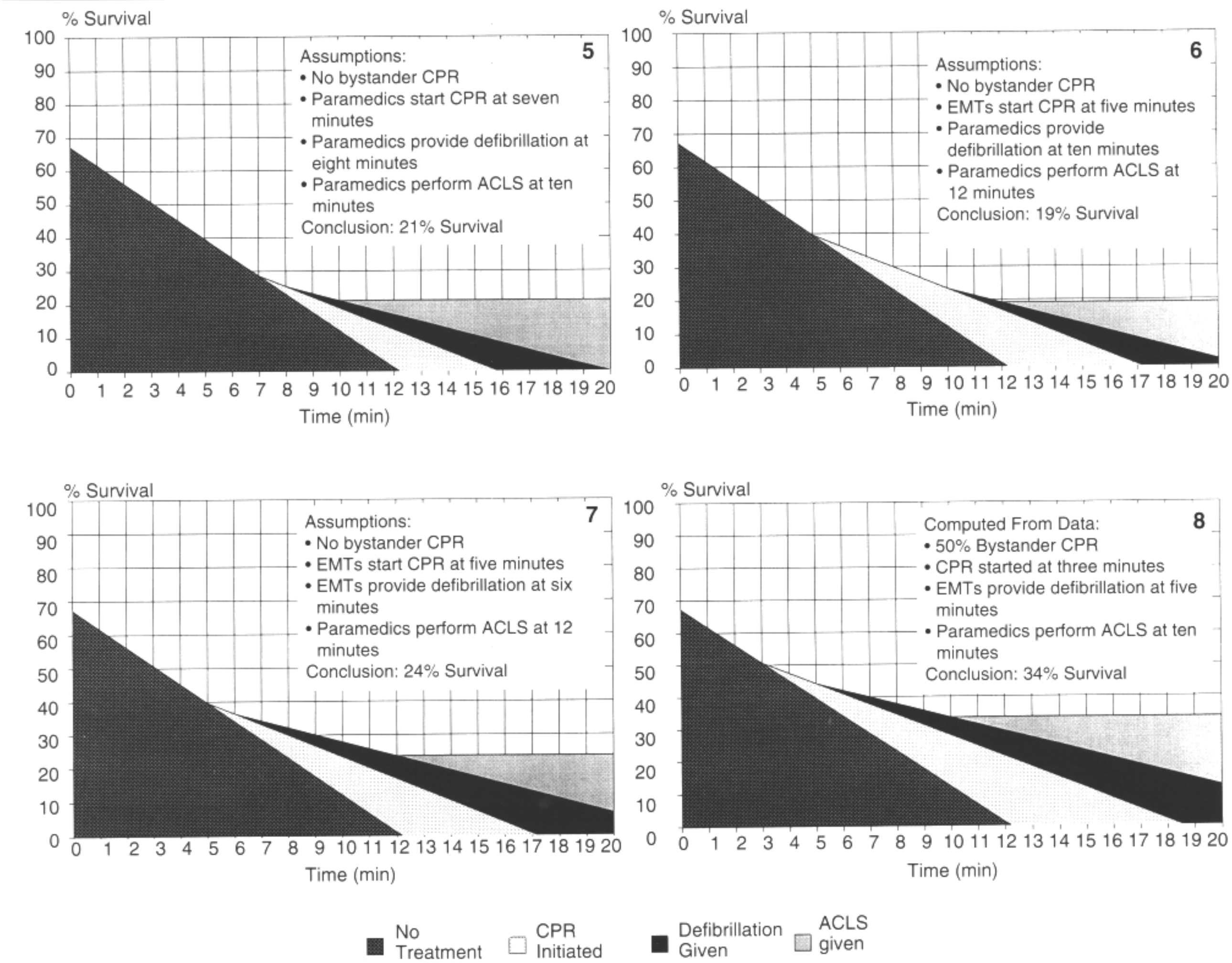


The final step in the development of the model was the elimination of outliers, atypical observations that have undue influence on the fit of the model. We eliminated all observations with residuals (difference between the observed survival rate and the rate predicted by the model) that exceeded the 98th percentile (ie, observations with residuals in the top 2%). After elimination of the outliers, the model was fit again, and the resulting coefficients were used to predict the rate of survival.

To assess the performance of our model, predicted survival rates obtained from the model were compared with rates reported for communities representative of different types of EMS systems: basic EMT, EMT-D (EMTs trained and authorized to defibrillate), paramedic, basic EMT/paramedic, and EMT-D/paramedic. For this comparison, we used data that contained EMS response times and survival rates for cardiac arrest cases in ventricular fibrillation.[4-18] From the EMS response times available from these studies, time intervals to CPR, defibrillation, and ACLS were estimated as described above.

For EMT and EMT-D systems, we assumed that both defibrillation and advanced care occurred on arrival at the hospital 20 minutes after collapse. Although 20 minutes is an estimate, we know this is close to the reported times for systems with EMT-level care.[3]

Figures 5-8.
Survival from cardiac arrest for 5) paramedic system with a response time of six minutes; 6) EMT/paramedic system with response times of four and nine minutes, respectively; 7) EMT-D/paramedic system with response times of four and nine minutes, respectively; 8) King County with an EMT-D/paramedic system with response times of four and nine minutes, respectively, and 50% bystander CPR.



RESULTS

Plotting the rate of survival as the resuscitation process unfolds demonstrates changes in the survival rate with each procedure (Figures 1 through 8). If nothing is done, the survival rate declines to zero rapidly. Any single point on this curve represents the predicted survival for the hypothetical situation in which CPR, defibrillation, intubation, IV medications, and so on occur simultaneously; that is, nothing is done until a particular point in time, and then all interventions occur simultaneously. With the earlier performance of each critical procedure (CPR, defibrillation, ACLS), this decline becomes slower. The regression model gives the following coefficients (standard errors in parentheses) for the three time intervals: time to CPR, −2.3% per minute (0.7%, $P = .001$); time to first shock (DEFIB), − 1.1% per minute (0.7%, $P = .09$); time to paramedic arrival (advanced care [ACLS]), − 2.1% per minute (0.3%, $P < .001$); and a regression constant of 67% (3%, $P < .001$). The F test for the regression model, 45.8 (3,1663 degrees of freedom),[6] was significant at $P < .001$. Substituting these coefficients into the equation gives the following:

$$\text{Survival rate} = 67\% - 2.3\% \times I_{CPR} - 1.1\% \times I_{DEFIB} - 2.1\% \times I_{ACLS} \quad (2)$$

which can be read as the following:

Survival rate =
67% at collapse − 2.3% per minute to CPR − 1.1% per minute to defibrillation − 2.1% per minute to ACLS

The regression constant, 67%, represents the probability of survival in the hypothetical situation in which all treatments are delivered immediately on collapse to patients with prehospital cardiac arrest. This probability is hypothetical because there are no actual patients in our data base for whom time intervals to all three treatments is zero. The shortest time interval to CPR and defibrillation in our model is one minute, and the shortest time interval to ACLS is two minutes. Among 26 patients with prehospital arrest and CPR, defibrillation, and ACLS delivered within three minutes, however, the average survival rate was 50%. With delays in CPR, defibrillatory shock, and definitive care, the magnitude of the decline in survival rate per minute is the sum of the three coefficients (−2.3%, −1.1% , −2.1%), or −5.5%. For each minute to first shock after the start of CPR, survival declines by 3.2% (−5.5% + 2.3%); and for each minute to advanced care once CPR has been started and the first shock has been given, survival declines by 2.1% (−5.5% + 2.3% + 1.1%).

The figure shows a model representation of five types of community EMS services: EMT, EMT-D, paramedic only, EMT/paramedic, and EMT-D/paramedic. These plots demonstrate the change in survival rate as EMS arrival times vary for each system. When comparing survival rates predicted by the model and those observed in the literature (Table), the largest differences between the observed survival rates and those predicted by the model occurred at the lower end of the survival scale. The model predicted no patient survival to 20 minutes when EMTs provide CPR only, whereas observed survival rates for EMT-only systems in three different communities varied from 3% to 12%. For EMT-D systems with an arrival time of four minutes, a 7% survival rate was predicted, and a 26% survival rate was observed. Observed and predicted survival rates agreed more closely for paramedics, EMT/paramedics, and EMT-D/paramedics—systems in which all of these critical procedures were performed before hospital arrival.

Table.
Reported and predicted survival rates for different types of EMS systems

EMS Agency Type	EMT Response Time (min)	Paramedic Response Time (min)	Estimated Time to (min): CPR	Defibrillation	ACLS	Reported Survival Rate (%)	Predicted Survival Rate From Model (%)
EMT only	4		5	20	20	12 [4,5]	0
	7		8	20	20	3-20 [8-10]	0
EMT-D	4		5	6	20	26 [9]	7
	10		11	12	20	12 [11]	0
Paramedic	4		5	6	8	14-30 [12,13]	30
	6		7	8	10	15 [14,15]	21
EMT/paramedic	3	7	4	8	10	25 [16]	28
	4	9	5	10	12	33 [17]	19
EMT-D/paramedic	4	9	5	6	12	34 [18]	24
King County (EMT-D/ paramedic)	4	9	3	5	10	34	34

To verify the stability of the model we split the sample, using patient identification numbers ending in 0 through 4 as the first sample and those ending in 5 through 9 as the second sample. The coefficients of both split models were within two standard deviations of each other. Also, predicted values of both models were within 7% of each other and within 7% of the predicted value for the entire model.

DISCUSSION

The model demonstrates the critical role that time plays in the success of resuscitation from sudden cardiac arrest. The shorter the time to critical interventions, the higher the survival rate. Although this is intuitive, the model demonstrates the quantitative contribution of each intervention to the survival rate. Each intervention used alone slows the rate of dying, and the model clearly shows how placing each treatment earlier in the protocol improves the likelihood of survival. For instance, when a EMT-D/paramedic system is in place with average arrival times of four and nine minutes, respectively, a community bystander CPR program could decrease the average time to CPR by two minutes. Notice in comparing 7 with 8 in the figure that the effect of beginning CPR two minutes earlier enhances the contributions of the other procedures, making the total contribution to survival 10%, much more than the 2.1% per minute, or 4.2%, for the two minutes' earlier CPR. Putting defibrillators in the hands of EMTs makes a difference of 5% in the survival rate given EMT and paramedic arrival times of four and nine minutes, respectively.

Even though the EMS systems of different communities vary in their ability to provide CPR, defibrillatory shocks, and advanced care rapidly, the model can predict expected changes in survival rate for any of these systems given a hypothetical change in protocol. The model does not distinguish effects on survival rate due to factors not under EMS control, such as age, sex, underlying morbidity, and quality of hospital care. Customization of the model by computing coefficients from a community's data may be necessary when demographics, rate of bystander CPR, and hospital care standards differ from those in King County.

Of particular interest is a direct comparison between an EMT/paramedic system and a EMT-D/paramedic system showing the effect of shifting the responsibility for defibrillation from paramedics to EMTs. Fortunately, observed times were available for both systems where the EMTs arrive in four minutes and the paramedics arrive in nine minutes. An EMT/paramedic system that gave an expected survival rate of 19% had an observed rate of 33%. An EMT-D/paramedic system with the same arrival times gave a predicted rate of survival of 24% and an observed rate of 34%, showing a strong improvement in predicted survival rates when both CPR and defibrillation are provided early by EMTs. The current survival rate for King County, which has an EMT-D/paramedic system with an average EMT arrival time of four minutes, an average paramedic arrival time of nine minutes, and a bystander CPR rate of 50%, is 34%, representing the payoff of the aggressive public education campaign on bystander CPR and the policy of training and authorizing EMTs to defibrillate.

In addition, recent research shows that an EMT-D program can improve the probability of survival in ways other than simply providing earlier defibrillation. Because it transfers the task of defibrillation out of the hands of paramedics, it allows paramedics to move more quickly to intubation and IV medication. This means that the specific elements of advanced care occur earlier in such systems.[19] Furthermore, moving defibrillation earlier in an EMT-D system means that personnel will treat an absolutely greater number of persons in ventricular fibrillation because they arrive before the ventricular fibrillation has deteriorated to asystole.[20]

Several assumptions weaken the model. First, we did not have exact times to CPR and defibrillation for all cases. We were forced to estimate these time intervals by adding constants to the EMS response times. These estimates, while consistently applied, are less accurate than measuring exact time intervals. Second, the model assumes that the start of delivery of ACLS is the last procedure that defines the survival rate. We know that this is not true but is merely a representation of the fact that no further information on treatment and response is provided until hospital discharge. Of course, additional interventions occur in the hospital, but the major prehospital interventions end with the performance of ACLS. Third, because the three time intervals are not independent (the same agency often provides at least two procedures), the model best describes situations where CPR, first defibrillatory shock, and advanced care follow each other in the order listed.

As the table shows, the model does not agree with published data for EMT-only and EMT-D communities. One of the following factors may explain this. The published data were from many different sources, making it difficult to assess consistency of reporting among them. Average time intervals to first shock and advanced care were not available for EMT and EMT-D systems. The 20 minutes assumed to be the time interval for advanced care reflects the average hospital arrival time for these systems.[3] The greater-than-expected number of survivors for the actual systems may reflect intervals of less than 20 minutes. Data for these systems tended to be much older and were obtained for communities with smaller populations, which would have allowed faster transport of patients to the hospital. The more advanced lifesaving procedures were not provided, saving time for transport (as the model shows, however, this option does not result in more lives saved). Sample sizes for these studies were smaller, making the effect of random noise greater. A high bystander CPR rate (rates as high as 35% were given[9]) could account for the positive survival times seen for these communities.

CONCLUSION

Knowledge of the relationship between EMS time intervals and survival rate can guide an EMS system to improvements that should increase the survival rate. The model is useful for planning EMS in any community and for comparing the different types of EMS systems. In addition, this model can reflect the variation in survival rates when response times differ within a single system. The model can be customized easily to describe any community. However, a linear least-squares regression on a binary outcome variable may not be valid on small sample sizes. Also, because the predictors (time intervals to CPR, first defibrillatory shock, and advanced care) are highly correlated, the model performs best when applied to systems where all three treatments are given before hospital arrival and the average times to treatment can be computed from the data rather than assumed.

An individual case of cardiac arrest has two possible outcomes: the individual lives or dies. However, this model shows each individual's probability of survival based on a community's ability to deliver CPR, defibrillation, and advanced care.

The model is a graphic representation of the "chain of survival"[21] concept describing the linkage among access, CPR, defibrillation, and ACLS. Between survival and the time intervals by which these interventions are provided, life ebbs rapidly and the slope of death is steep, but the downward fall need not be an inevitable plummet into the jaws of death.

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