The Impending Crisis
Awaiting Cardiac Transplantation
Modeling a Solution Based on Selection

Lynne Warner Stevenson, MD; Stanley L. Warner, PhD; Anthony E. Steimle, MD; Gregg C. Fonarow, MD; Michele A. Hamilton, MD; Jaime D. Moriguchi, MD; Jon A. Kobashigawa, MD; Jan H. Tillisch, MD; Davis C. Drinkwater, MD; Hillel Laks, MD

Background Each month, the number of transplant candidates added to the waiting list exceeds the number of transplantations performed, and many outpatients deteriorate to require transplantation urgently. The current list of 2400 candidates and the average wait of 8 months continue to increase.

Methods and Results To determine the size at which the outpatient and critical candidate pools will stabilize, population models were constructed using current statistics for donor hearts, candidate listing, sudden death, and outpatient decline to urgent status and revised to predict the impact of alterations in policies of candidate listing. If current practices continue, within 48 months the predicted list will stabilize as the sum of an estimated 270 hospitalized candidates, among whom, together with newly listed urgent candidates, all hearts will be distributed and 3700 outpatient candidates with virtually no chance of transplantation unless they deteriorate to an urgent status. Decreasing the upper age limit now to 55 years would reduce the number listed each month by 30% and result within 48 months in a list of only 1490. The list could also be decreased by 30%, however, if it were possible to list only a candidate group with an 80% chance (compared with 52% estimated currently) of sudden death or deterioration during the next year. With this strategy, the waiting list would equilibrate within 48 months to one-third the current size, with 50% of hearts for outpatients, who would then have an 11% chance each month of receiving a heart compared with 0% if recent policies prevail. Total deaths, with and without transplantation, would be minimized by this rigorous selection of outpatient candidates.

Conclusions This study implies that immediate provisions should be made to limit candidate listing and revise expectations to reflect the diminishing likelihood of transplantation for outpatient candidates. Future emphasis should be on improved selection of candidates at highest risk without transplantation. (Circulation. 1994;89:450-457.)

Key Words • transplantation • heart failure

The success of transplantation has stimulated referrals of patients with heart failure. In January 1992, there were 2400 patients listed for cardiac transplantation compared with 1200 in 1989.1,2 Each month, almost twice as many patients are listed for transplantation as actually undergo the procedure.3 By December 1990, 49% of patients awaiting cardiac transplantation who are on the United Network of Organ Sharing (UNOS) waiting list had already been waiting for more than 6 months.1 Physician and patient expectations arise from these analyses of preceding years, which underestimate current waiting times. Many patients have now been waiting for more than 1 year, sometimes 2 years. As the waiting lists grow longer, many outpatients deteriorate to require hospitalization and urgent transplantation.4 The pool of hospitalized candidates, who receive priority for the limited donor hearts, is composed largely of these deteriorating candidates rather than those initially listed with urgent status. The waiting times are increasing for all candidates but particularly for the outpatients, who are receiving a decreasing proportion of the available donor hearts. Outpatients surviving long enough to receive donor hearts may be those who need them the least.5

If current conditions prevail, how many hearts will ultimately be used for urgent transplantation? How often will outpatients candidates receive hearts? Using computer simulations of waiting list progression based on listing practices and waiting list risks, it is possible to predict the sizes of the waiting candidate populations and their expected outcomes. In addition, potential subgroups can be defined to examine the impact of changing criteria for candidate listing. Such information will allow reexamination of current policies and revision of current expectations for newly listed candidates.

Methods

Current conditions were defined (Table 1) according to information available from the Registry of the International Society of Heart and Lung Transplantation,6 UNOS,1-3 the Working Group of Transplant Cardiologists,7 and other published data.5,8,9 In 1990 through 1991, there were approximately 300 patients newly listed each month for transplantation in the United States. National information sources do not report the proportion of patients initially listed as status I ("urgent" or "critical"), which requires hospitalization in an intensive care unit while receiving continuous infusions of
TABLE 1. Current Conditions for Patients Awaiting Transplantation

<table>
<thead>
<tr>
<th>Source of Data*</th>
<th>No. of donor hearts transplanted per month</th>
<th>Priority for donor hearts Status I</th>
<th>No. of patients waiting</th>
<th>No. of patients listed per month</th>
<th>Status I death without transplantation per month</th>
<th>Outpatient sudden death per month</th>
<th>Outpatient deterioration per month</th>
<th>Proportion originally listed as status I</th>
<th>Proportion of status I currently on list</th>
<th>Ratio of urgent transplants to total transplants</th>
<th>Regular status operative mortality (first posttransplantation month)</th>
<th>Urgent status operative mortality</th>
</tr>
</thead>
<tbody>
<tr>
<td>UNOS</td>
<td>167</td>
<td>Status I</td>
<td>2400</td>
<td>300</td>
<td>0.5</td>
<td>0.019</td>
<td>0.047</td>
<td>0.15-0.25</td>
<td>0.05</td>
<td>0.46</td>
<td>0.06</td>
<td>0.14</td>
</tr>
</tbody>
</table>

*ISHLT indicates International Society for Heart and Lung Transplantation; UCLA, University of California, Los Angeles; UNOS, United Network of Organ Sharing; and WGTC, Working Group of Transplant Cardiology.

For simplicity, all patients listed as UNOS status II were considered as outpatients in this analysis, although in reality some hospitalized patients without critical decompensation are also status II. Postoperative survival statistics for the status I and status II recipients were derived from the International Society of Heart Transplant Registry and were used to calculate expected postoperative mortality according to the distribution of donor hearts.

A Markov chain model (see “Appendix”) was constructed to determine the sizes and outcomes of the waiting list populations when an equilibrium is reached such that the number of patients joining the list each month is equal to the number of patients leaving the list as a result of transplantation or death. The overall annual mortality can then be calculated for a waiting outpatient, who may live or die with or without transplantation. The monthly chances of waiting patients to receive hearts were then calculated based on the current supply of donor hearts. To determine the sensitivity of the equilibrium population projection to the estimated values for waiting list sudden death, deterioration, and hospital death, the 6-month event rates were altered by approximately 50% and the equilibrium state was recomputed.

Because the Markov chain model describes conditions when all populations have reached steady sizes, it cannot be used to determine how soon that equilibrium will be reached from current conditions. A month-by-month iterative model was then constructed from present conditions in which candidate listing as either outpatient or critical status, sudden death, deterioration from outpatient to critical status, death in hospital awaiting cardiac transplantation, and transplantation for either outpatients or critical patients were allowed to occur each month, until the equilibrium outpatient and critical status candidate pools reached a size within 5% of those predicted by the Markov chain model. The length of time required to reach equilibrium from current conditions was then defined. With this time, the variation in the predicted waiting list sizes and outcomes was determined as the assumed event rates were altered.

To see how an immediate reduction in the number of patients listed would affect eventual list conditions, the iterative model was redesigned, first by lowering the upper age limit for transplant candidates to 55 years. The impact of age reduction was calculated using the distribution of age among adult recipients for the past 6 years from the International Society of Heart Transplant Registry assuming that recipient age reflects candidate age. From this information, approximately 30% of recipients have been older than 55 years. It was assumed that this candidate population has equal waiting list and postoperative risks as the younger population. Reduction of both outpatient and critical status lists according to age was assumed to be proportional to the relative list sizes.

Reduction of candidate listing was then attempted instead by assuming that selection of outpatient candidates could be improved to identify a population at very high risk of death or deterioration within the next year without transplantation. With current numbers of deaths and deteriorations occurring on the list, the outpatient candidate population size was distilled to smaller sizes with proportionately higher risks. The effects of reducing the outpatient candidate list to populations with 60%, 70%, 80%, 90%, and 99% risks of death or deterioration were analyzed assuming current proportions of sudden death and deterioration. While decreasing the number of outpatients listed according to these changes, the number of candidates initially listed as critical was assumed to remain constant at current rates. These revised conditions of selection restricted to candidates with higher pretransplantation risks were then entered into the Markov chain model to confirm that the results obtained from the iterative model approximated true equilibrium states.

The equilibrium list lengths for outpatient and critical candidates, the proportion of hearts used for critical candi-
dates, the likelihood of transplantation within the next month for outpatient candidates, and expected mortality without transplantation and in the perioperative period were analyzed for these various conditions.

Results

Equilibrium if Current Conditions Prevail

If current conditions prevail, there will eventually be almost 4000 candidates on the list for cardiac transplantation. This equilibrium list size predicted by the Markov chain model will essentially be achieved within 48 months, at which time there will be 3700 outpatients and 270 critical candidates, according to the model-by-month iterative model (Table 2). All hearts available will be used for the hospitalized candidates, 62% of whom can expect hearts within the next month. There will essentially be no hearts available for outpatient candidates (Fig 1).

The number of candidates awaiting urgent transplantation is determined largely by the deterioration rate of patients initially listed for outpatient transplantation, of whom 170 will deteriorate to higher status each month at the equilibrium. This deteriorating population eclipses the proportion of patients initially listed as status I patients. If this proportion were assumed to be 0.25 instead of 0.15, equilibrium conditions would be similar but would be reached sooner, in 36 months, with 285 urgent status candidates and 3300 outpatient candidates. Even with this higher proportion of patients initially listed as urgent status, once equilibrium was reached, there would be twice as many candidates deteriorating to urgent status as being initially listed with urgent status. The subsequent results will be described assuming a proportion of 0.15.

Impact of Varying Estimates of Current Conditions

The sizes of equilibrium populations and monthly chances of receiving a donor heart for outpatient candidates were recalculated after varying the current estimates of outpatient sudden death, deterioration to urgent transplantation, and in-hospital death of critical candidates (Table 3). Changing the expected deterioration rate caused the largest change in the predicted candidate population sizes. The chances for outpatient candidates were not markedly influenced, however, because the decline in critical candidates that results from a decline in deterioration rate maintains a much larger outpatient candidate pool among which to distribute the hearts made available for outpatient transplantation. Increasing the deterioration rate reduces the predicted outpatient candidate pool but expands the pool of critical candidates who then receive all donor hearts. Regardless of these broad estimate ranges, the monthly chance for a given outpatient to receive a donor heart will be no more than 1% if current listing practices continue for the next 48 months.

Impact of Changes in Listing Strategies

Decreasing the size of the candidate pool was examined first by imposing an upper age limit of 55 years. This would be predicted to reduce the current waiting list by 30%, according to the recipient age distribution of transplant recipients in the International Registry, and it was assumed that this reduction would occur equally in the urgent candidate and outpatient candidate populations. Equilibrium would be reached by 3 years, with an urgent candidate population of 110 and an outpatient population of 1380. There would be 95 hearts available for the outpatients, who would then have a 7% chance of receiving a heart each month, which exceeds the chance under current conditions and greatly exceeds the chance if current conditions reach equilibrium (Fig 1). However, the patients between 55 and 65 years old will then demonstrate the natural history of their disease with all of the previously urgent
status candidates and 52% of the outpatients succumbing either to sudden death or to fatal hemodynamic deterioration within 1 year. Then, the yearly mortality, if all potential candidates up to age 65 years are considered, would be no better than with the equilibrium reached under current practices.

A similar degree of reduction of the entire candidate population could also be achieved by continuing to list all the urgent status patients, as currently done, but listing only those outpatients most likely to die or deteriorate without transplantation. To reduce the entire list by 30% would require reducing the outpatient candidates by 35%, which with optimal risk stratification could leave a listed population with an 80% chance of death or deterioration within 1 year if transplantation were not performed, compared with the current outpatient population's combined yearly risk for these events of approximately 52%. This was equal to a mortality risk of 0.038 per month for sudden death and 0.095 per month for deterioration. The outpatient list at 36 months would then be only 780 and, at 48 months, 730 (Table 2). By that time, there would be an 11% monthly chance for each outpatient to undergo transplantation. Selecting an outpatient population with a 90% risk would be associated with an even lower equilibrium population size. Listing a population with 70% yearly risk would give a bigger equilibrium outpatient candidate pool of 1450, but this is still smaller than the current outpatient list and less than half of the 3700 who will be on the list as outpatients at 48 months if the recent listing practices continue (Fig 2).

The waiting list sizes determined at 48 months from the month-by-month iterative model were compared with those obtained at equilibrium in the Markov chain model. The predicted sizes of both the outpatient and critical candidate pools when listing patients at 52%, 60%, 70%, 80%, 90%, and 99% combined risks of sudden death or deterioration were within 5% of the equilibrium populations predicted for the Markov chain model.

**Total Candidate Population Survival**

As the balance between outpatient and urgent status transplantation shifts, posttransplantation survival is also affected. For an individual outpatient candidate, not only is pretransplantation death less likely, but posttransplantation survival is higher if he or she can undergo transplantation before deterioration. The International Registry data demonstrate that 30-day operative mortality is higher for urgent status recipients than for outpatient recipients. After discharge, survival is similar for the two groups. Including the perioperative survival calculation according to strategies of listing showed a further benefit from strategies to reduce waiting list size when total deaths are considered (Table 2).

**TABLE 3. Sensitivity of Outpatient Candidate Expectation to Varying Estimates of Current Conditions**

<table>
<thead>
<tr>
<th></th>
<th>Outpatient Candidates at 48 Months</th>
<th>Critical Candidates at 48 Months</th>
<th>Chance per Month for Outpatient to Receive Heart at 48 Months</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sudden death—model estimates 11% at 6 months</strong></td>
<td>3700</td>
<td>270</td>
<td>0</td>
</tr>
<tr>
<td>6% at 6 months</td>
<td>4450</td>
<td>340</td>
<td>0</td>
</tr>
<tr>
<td>16% at 6 months</td>
<td>3360</td>
<td>240</td>
<td>0.004</td>
</tr>
<tr>
<td><strong>Deterioration rate—model estimates 25% at 6 months</strong></td>
<td>3700</td>
<td>270</td>
<td>0</td>
</tr>
<tr>
<td>10% at 6 months</td>
<td>5300</td>
<td>170</td>
<td>0.01</td>
</tr>
<tr>
<td>35% at 6 months</td>
<td>2860</td>
<td>325</td>
<td>0</td>
</tr>
<tr>
<td><strong>Critical candidate death without transplantation-model estimates 0.5 per month</strong></td>
<td>3700</td>
<td>270</td>
<td>0</td>
</tr>
<tr>
<td>0.25 per month</td>
<td>3820</td>
<td>407</td>
<td>0</td>
</tr>
<tr>
<td>0.75 per month</td>
<td>3820</td>
<td>245</td>
<td>0.003</td>
</tr>
</tbody>
</table>

*These are the estimated rates used in the model.
The National Problem

Cardiac transplantation has been performed in more than 20,000 patients with current 5-year survival rates of 65% to 75%, justifying the initial optimism expressed 25 years ago at the first Bethesda Conference on Transplantation, although at that time there were only 20 cardiac transplant recipients living. The eventual concordance then predicted between the 10,000 to 50,000 potential transplant recipients and the projected donor heart supply, however, has not been realized.

Current conditions of candidate listing and donor harvesting are leading to a waiting list from which all actual recipients of transplantation will have previously deteriorated to become candidates for urgent transplantation, although there will not be enough hearts even for them. In the near future, our waiting list population will be characterized by a high nontransplantation mortality for urgent candidates, threatened transplantation survival statistics as patients undergo transplantation during hemodynamic compromise, and a negligible chance of transplantation for the outpatient regardless of his or her relative risk. Listing of regular status candidates will offer essentially placebo therapy for prevention of sudden death and only a limited chance of rescue even if deterioration necessitates continuous intensive support.

Supply and Demand for Donor Hearts

A dramatic increase in the number of donor hearts would postpone the waiting list crisis. There has, however, been little increase in the past 3 years (1990, 2126 hearts harvested; 1991, 2153 hearts; 1992, 2207 hearts). Public awareness of organ donation and transplantation has increased. Fewer hearts are now rejected for age or minor wall motion abnormalities. At the same time, the number of fatal motor vehicle accidents has decreased, whereas, less fortunately, the number of hearts rejected due to suspected AIDS infection has increased.

The scarcity of donor hearts itself tends to limit listing. Newer centers may accept more patients to build their candidate pool and program statistics. Centers with longer waiting lists that have experienced more waiting list morbidity and mortality may more closely scrutinize new candidates. It is likely that any major increase in immediate donor supply would be answered by an eventual increase in candidates screened and listed. Further efforts to increase donor retrieval must continue to benefit as many needy recipients as possible but are unlikely to obviate the need to restructure the waiting list.

Distillation of the Waiting List

The solution to the impending waiting list crisis requires reduction of the number of candidates listed. As the chances for those actually listed decrease to resemble a lottery, a case could be made for random limitation of listing to reduce at least the costs to the patient and family of uncertainty and occasional relocation in vain. A case could also be made to list only those candidates who have deteriorated to require intravenous or mechanical support until urgent transplantation. This strategy would, however, provide incentive for undertreatment of advanced heart failure and would neglect many patients with severe disability from congestive symptoms, angina, or refractory arrhythmias, which do not mandate continued hospitalization. In addition, the operative risks and mortality are greater for patients with impending multiorgan failure from venous congestion or hypoperfusion.

A specific criterion that could be uniformly imposed to limit candidate acceptance is that of age. Older recipients, even when more carefully selected than younger candidates, have slightly lower long-term survival in the large series, although 1- and 2-year survival is excellent and rejection incidence is lower. Restricting the upper age limit to 55 could reduce the current list by an estimated 30% based on current recipient ages and improve survival for those remaining.
on the list. If the unlisted group of 55 to 65 years is still followed, however, the total effect of imposing a lower standard age limit would be to increase mortality without transplantation above that expected at the equilib-
rium predicted by current conditions, due primarily to the death of those older patients after deterioration.

If the goal is to reduce the list while maximizing survival of the potential candidate population, those not listed should be those at the lowest risk. The estimated risks of the current population indicate that without transplantation, only half of the candidates will have died or deteriorated to status I after 1 year.5,6 Although these risks may vary from program to program, the fact that half of patients currently on the national waiting list have been waiting for more than 1 year indicates that extended survival without transplantation is frequent with current listing policies.

Perfect selection of the candidates who would die or deteriorate within the next year without transplantation is impossible, due in part to the multiple precipitating factors of both sudden death and deterioration.16 If our current selection could be refined, however, such that an outpatient population with an 80% 1-year risk is identified, the total waiting list size could be reduced by the 30%, which was described above for limitation by age instead. The deaths without transplantation would be minimized; fewer patients would have to deteriorate to receive transplantation; and total candidate death, with and without transplantation, would decrease to less than half of that expected per year if the current conditions persist until equilibrium in 48 months.

It should be possible to concentrate the candidate population more closely to those at an 80% risk without transplantation. Previous attempts to stratify risk were limited to the use of prognostic factors identified for a much wider spectrum, including mild to moderate heart failure. More recent information suggests that measure-
ment of peak oxygen consumption, hemodynamic re-
sponse to tailored vasodilator and diuretic therapy, and use of simple criteria for clinical stability will allow identification of outpatients likely to die or deteriorate after apparent stabilization.9,17,18 Improved understanding of the mechanisms of sudden death in heart failure will allow not only better risk stratification but also better prophylactic therapy, which may decrease the risks of sudden death in the clinically stable patient.19,20 The immediate reduction of listed candidates according to risk would likely result in a true overall list reduction rather than a delay followed by a rebound increase the following year because current studies of these populations demonstrate the highest mortality to be in the early months after referral, after which death and deterioration occur at a relatively constant slow rate with no apparent late acceleration at least within the 2 years after initial evaluation.5

Although the rigorous application of revised criteria for listing must await more specific information from ongoing studies of waiting list risk factors and outcomes, information currently available, as described above, does allow for immediate reduction in the number of patients listed. Such reduction is hampered by influence from referring physicians and families more keenly aware of the ravages of heart failure than of the consequences of infection and rejection after transplant-
ation. Even after referral to transplantation, many patients with previous New York Heart Association functional class IV symptoms of heart failure can derive major benefit from optimal medical therapy and enjoy functional capacity similar to that achieved after trans-
plantation.18,21,22 Furthermore, our current practice of listing patients who are relatively stable "to build up time on the list" has increased the long waiting lists on which those outpatients who survive long enough to receive transplantation are paradoxically those who have the best prognosis for survival without transplan-
tation.5 Recognizing that the ability to predict outcome at the time of initial listing remains limited, provision may need to be made to reevaluate patients during their extended time on the waiting list, a process discouraged by patients and families whose lives have revolved around the imminent transplantation. Those candidates demonstrating the capacity to improve peak exercise oxygen consumptions to more than 12 mL·kg⁻¹·min⁻¹ after initial evaluation may have a particularly favorable prognosis.23 The concept of candidacy for transplantation should evolve from one of lifetime membership to one of dynamic movement, which will only be possible if the waiting list is cleared of patients without immediate need. New guidelines for the selection and reevaluation of transplantation candidates according to more objec-
tive criteria of limitation and prognosis have recently been outlined.24 Policies limiting distribution of scarce donor organs, however, will be perceived as threatening by some programs, and public implementation of such policies will require a greater consensus regarding the ultimate goals of transplantation.

Specific Candidate Groups

The models analyze the national donor heart distri-
brution problem as a whole rather than as a sum of smaller problems. Local organ procurement organiza-
tions and individual centers will have longer or shorter lists than the national average. Multiple listing of pa-
tients may lead to occasional duplication, but geo-
ographic and financial constraints limit this option such that only a small overestimation of the national can-
didate pool would result.

Each ABO blood group could also be used to define a pool of candidates with their own waiting list risks. Blood group O patients, who can receive only group O hearts, have a particular disadvantage as approximately 25% of O hearts are currently going to recipients of other blood groups,10 particularly status I recipients. Body size could also be used to define separate groups, with larger patients having a narrower range of poten-
tial donor hearts. The model did include the composite factor of matching inefficiency, which could result from location, blood group, or size, such that not all urgent candidates can be transplanted immediately.

The model was based on the two-status system most widely used. Although the predicted candidate pools could be altered by changing the priority system, the current practice of awarding priority to status I can-
didates clearly maximizes overall candidate survival be-
cause the slightly higher postoperative mortality for these patients is greatly outweighed by their much higher mortality without transplantation, as has been shown in the previous application of the Markov chain to decisions regarding heart transplantation.12 Some regions have an additional status approved by the
UNOS as a "variance," which in general allows certain patients to be awarded intermediate priority for conditions such as preinfarction angina, recurrent cardiac arrest, or need for low-dose inotropic therapy without other intensive intervention. Including this in the model would have the effect of redistributing patients within the current urgent priority group and shifting a very small number of patients from the outpatient pool but would not change the anticipated shortage of transplantation for most outpatients.

Expanded use of assist devices for temporary support could increase survival and the size of the status I candidate pool before transplantation, which would further decrease the hearts available for outpatients.25 A potential favorable impact could result if transplant teams and referring physicians became more confident that patients could be kept alive until transplantation, even after decompensation. Such confidence might decrease the current tendency to list stable outpatients to build up their time on the list before decompensation.

Alternative Therapies

Exploration of new options must continue for patients who cannot achieve reasonable quality of life and prognosis on medical therapy for heart failure. Although transplantation has generally been the procedure of choice for patients with coronary artery disease and very low ejection fraction, increasing attempts to define and revascularize viable myocardium are warranted. The imminent availability of transvenous implantable defibrillators with back-up pacing capability may allow transplantation to be deferred or avoided for many patients with limited symptoms who are transplanted primarily to prevent sudden death. Increasing experience with prolonged and "permanent" use of left ventricular assist devices such as the Heartmate may eventually restore some patients to good functional capacity without transplantation, which would reduce the demand and waiting time for limited human hearts.25

In addition to scientific advances in immunosuppression, the benefits actually realized from transplantation will also reflect trends in listing practices, which should be closely observed. For instance, the number of candidates newly listed each month has increased only slightly from 293 in 1990 to 310 in the first 6 months of 1993 (Timothy Breem, UNOS, personal communication). At the same time, however, the number of candidates removed each month from the list for reasons other than death or transplantation has increased from 32 in 1990 to 45 in 1993, perhaps reflecting an encouraging trend toward reevaluation. It will be important, however, to monitor initial listing changes closely, as current local incentives favor reducing the number of truly compromised candidates rather than those at lower risk.

Study Limitations

The models used in this study assume that monthly chances of transplantation, deterioration, or death remain constant from month to month, whereas the chance of receiving a transplant increases and the chance of dying or deteriorating actually decreases for the outpatient, which would make the prediction of interval risk easier after time.5 This study is limited by the validity of the assumptions about current conditions, which may vary from program to program. However, decrease in sudden death and deterioration rates would only cause the waiting list size to increase faster, as shown in Table 3. Variation in the population of patients listed as urgent would change the rate at which equilibrium will be reached but would not significantly alter the conclusions regarding the imminent waiting list crisis or the approaches to its solution. The model is based on the current calculation that an appropriate donor can be found within 1 month for 64% of urgent candidates. Logistical considerations suggest that as the number of urgent candidates increases, any given donor will be more likely to be appropriate for at least one urgent candidate, so the proportion of hearts used for urgent candidates may increase even faster than predicted.

Implications

Faced with the impending waiting list crisis, we should currently provide more realistic expectations about the waiting time for outpatient candidates and focus on preventing sudden death and deterioration in this growing population. To improve overall survival by distributing the limited number of donor hearts to those who need them most, increasing effort must be devoted to identifying and listing only those patients who remain at highest risk for sudden death and deterioration without transplantation.

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Appendix

The Markov chain model was constructed with eight states defined as outpatient candidate, critical status candidate, outpatient transplant recipient in the first month, critical transplant recipient in each of the first three postoperative months, chronic transplant recipient, and death, as previously described. The model assumes (1) that equilibrium has been reached such that the sizes of the candidate pools are no longer changing and (2) that the likelihood of moving from one given state during the next month does not change from month to month. The model, thus, does not provide for an individual to have a changing likelihood of receiving a transplant according to time on the list unless he or she changes from an outpatient to a critical status candidate. Although this is unlike the real situation for a given patient, it does not change the results significantly for the total national population, within which individual waiting times will vary according to blood type, size, and geographic area.

Death is an absorbing state from which no movement is possible. From all states except death, movement is allowed to some states but not to others. For simplification, it is assumed that critical candidates cannot become outpatient candidates. Outpatient candidates cannot die an in-hospital death without first deteriorating to become a critical candidate. All death in critical candidates is assumed to occur in hospital, whereas death for outpatient candidates is considered sudden. With the available data for outcomes, transition probabilities were calculated from each state to the other possible states.
References

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