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Development of a Hybrid Decision Support Model for Optimal Ventricular Assist Device Weaning

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Background. **Despite the small but promising body of evidence for cardiac recovery in patients that have received ventricular assist device (VAD) support, the criteria for identifying and selecting candidates who might be weaned from a VAD have not been established.**

Methods. **A clinical decision support system was developed based on a Bayesian Belief Network that combined expert knowledge with multivariate statistical analysis. Expert knowledge was derived from interviews of 11 members of the Artificial Heart Program at the University of Pittsburgh Medical Center. This was supplemented by retrospective clinical data from the 19 VAD patients considered for weaning between 1996 and 2004. Artificial Neural Networks and Natural Language Processing were used to mine these data and extract sensitive variables.**

Results. **Three decision support models were compared. The model exclusively based on expert-derived knowledge was the least accurate and most conservative. It underestimated the incidence of heart recovery, incorrectly identifying 4 of the successfully weaned patients as transplant candidates. The model derived exclusively from clinical data performed better but misidentified 2 patients: 1 weaned successfully, and 1 that needed a cardiac transplant ultimately. An expert-data hybrid model performed best, with 94.74% accuracy and 75.37% to 99.07% confidence interval, misidentifying only 1 patient weaned from support.**

Conclusions. **A clinical decision support system may facilitate and improve the identification of VAD patients who are candidates for cardiac recovery and may benefit from VAD removal. It could be potentially used to translate success of active centers to those less established and thereby expand use of VAD therapy.**

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The use of ventricular assist devices (VADs) for treatment of end-stage heart failure has steadily increased during the past 20 years [1, 2]. For a growing number of patients with advanced or refractory cardiac disease, VAD therapy has demonstrated the potential to extend life, improve the quality of remaining life [3–6], and even lead to cardiac recovery [7, 8]. After the first report of VAD weaning in 1995 [9], numerous centers have demonstrated the possibility of cardiac recovery for a subset of VAD patients, including the University of Pittsburgh Medical Center (UPMC), Texas Heart Institute, Berlin Heart Center, Columbia Presbyterian, Toronto General Hospital, and others. Nevertheless, the incidence of VAD weaning remains relatively low compared with the volume of patients treated with VAD therapy [1, 10–13].

Although studies of myocardial function of VAD patients suggest that chronic unloading of the native heart can lead to reverse remodeling [5, 14–16], the underlying cellular, biochemical, and biomechanical mechanisms remain uncertain and are topics of active research. It is therefore not surprising that different sets of criteria have been used for attempting to wean patients from VAD support [4, 17–20]. Lack of a definitive marker in turn limits the confidence to screen patients for recovery and may be partly responsible for the scarcity of VAD weaning.

The decision to wean a patient from VAD support is further complicated by the distributed expertise involved in postoperative management. It also entails competitive objectives, such as survival rate, quality of life, patient preference, and alternative treatment strategies. This complexity confounds efforts to articulate a definitive algorithm for identifying and facilitating cardiac recovery. Consequently, it also hinders the translation of the success of experienced centers to centers that are less established.

The complexity and uncertainty of this decision process makes it an excellent candidate for a clinical decision support system. Motivated by the success of such systems in numerous fields of medicine [21–27], we undertook this study to develop a clinical decision support system specifically customized to the management of VAD patients, with particular emphasis on ventricular

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Abbreviations and Acronyms

ANN	= artificial neural network
APsys	= systolic arterial pressure
AST	= aspartate amino transferase
BBN	= Bayesian belief network
BiVAD	= biventricular assist device
BUN	= blood urea nitrogen
CI	= cardiac index
CREAT	= creatinine clearance
DCM	= dilated cardiomyopathy
ECHO	= echocardiography
EF	= ejection fraction
FAC	= fractional area change
FU	= follow-up
HR	= heart rate
HTx	= heart transplantation
LDH	= lactate dehydrogenase
LV	= left ventricle
LVAD	= left ventricular assist device
LVEF	= left ventricular ejection fraction
MG	= magnesium
METs	= metabolic equivalents
MPAP	= mean pulmonary artery pressure
NLP	= natural language processing
PCWP	= pulmonary capillary wedge pressure
PVR	= pulmonary vascular resistance
PWR	= ventricular power
RER	= respiratory exchange ratio
RET	= reticulocyte count
SA	= stroke area
TPG	= transpulmonary gradient
WU	= wood units
VAD	= ventricular assist device
VO_2%	= peak oxygen consumption

recovery. The clinical experience at UPMC with 19 VAD patients who were considered for weaning between 1996 and 2004 [28, 29] was used as the basis for evaluation of this model.

Material and Methods

The protocol for this study was approved by Institutional Review Board at University of Pittsburgh. Two primary sources of procedural knowledge were collected for the current study: retrospective statistical analysis of patient data and expert knowledge.

Data-Derived Knowledge

In accordance with the Health Insurance Portability and Accountability Act of 1996, de-identified patient data were obtained from the UPMC VAD registry through an honest broker. The study included 19 patients who were supported by a left ventricular assist device (LVAD) or a biventricular assist device (BiVAD) and originally identified as bridge-to-transplant but later considered for recovery between 1996 and 2004. Thoratec (Pleasanton, CA) pneumatic paracorporeal systems were used to support 18 patients and the Thoratec implantable VAD was used in 1. Of the 19 patients who were considered for weaning, 10 were eventually weaned and 9 received a cardiac transplant. Patient details are provided in Table 1.

A total of 250 numeric variables from 6 categories were analyzed using commercially available artificial neural network (ANN) software (Clementine 7.0, SPSS, Chicago, IL) to identify the most predictive variables and their associated thresholds. The variables were decimated using the *prune* algorithm to eliminate those that were weakly correlated with weaning. To avoid overtraining, only 50% of the data sets were analyzed at a time. Additional analysis was performed on the written shift notes recorded by the clinical staff responsible for routine monitoring of these patients. Language patterns within the textual data contained in the shift notes were identified by natural language processing (NLP) using the software program Concordance 3.2 (R. J. C. Watt, Dundee, UK). Word patterns were tabulated in order of frequency and context and compared between weaned and transplanted patients.

Expert Knowledge

Knowledge derived from retrospective experience was elicited through a series of structured interviews and questionnaires of 11 members of the multidisciplinary Artificial Heart Program at UPMC, including surgery, clinical bioengineering, nursing, and psychiatry. The interviews were conducted individually and in small groups to derive a binary decision flowchart for selecting VAD weaning candidates. The flowchart was reviewed and revised in a second interview. The individual flowcharts were combined into a final version and presented to the full panel for approval. The resulting decision flowchart consisted of a five-tier health status screening, followed by a three-tier evaluation of cardiac recovery (Fig 1).

The flowchart defines an optimal weaning candidate as a nonischemic patient who has been supported by the VAD for more than 4 weeks, with normal cardiac rhythm, positive nutritional status, and normal end-organ function. Indices of cardiac recovery, gathered through echocardiographic measurements [29], are considered optimal if the patient is able to maintain an ejection fraction exceeding 40%, ventricular power exceeding 4 (mW/cm^4), and positive change in stroke area with temporary suspension of VAD support. Patients who pass this initial screening are referred for right heart catheterization.

The hemodynamics required to pass the secondary screening include pulmonary capillary wedge pressure less than 20 mm Hg, cardiac index exceeding 2.2 L/min/m^2, and heart rate less than 100 beats/min. Satisfactory results of right heart catheterization allow patients to undergo treadmill ergometry according to a modified Naughton protocol. Patients capable of achieving peak oxygen consumption exceeding 15 mg/kg/min, while maintaining a respiratory exchange ratio that exceeds 1.0 at maximal exercise, are referred to cardiac surgery for removal of the VAD.

Owing to the binary nature of the final decision flow-

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