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ScienceDirect
Journal of Biomedical Informatics 41 (2008) 461–468
Journal of Biomedical Informatics
www.elsevier.com/locate/yjbin

A frame-based representation for a bedside ventilator weaning protocol ☆

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Received 30 April 2007
Available online 21 February 2008

Abstract

We describe the use of a frame-based knowledge representation to construct an adequately-explicit bedside clinical decision support application for ventilator weaning. The application consists of a data entry form, a knowledge base, an inference engine, and a patient database. The knowledge base contains database queries, a data dictionary, and decision frames. A frame consists of a title, a list of findings necessary to make a decision or carry out an action, and a logic or mathematical statement to determine its output. Frames for knowledge representation are advantageous because they can be created, visualized, and conceptualized as self-contained entities that correspond to accepted medical constructs. They facilitate knowledge engineering and provide understandable explanations of protocol outputs for clinicians. Our frames are elements of a hierarchical decision process. In addition to running diagnostic and therapeutic logic, frames can run database queries, make changes to the user interface, and modify computer variables.

Keywords: Decision making; Knowledge management; Decision support system; Knowledge bases; Knowledge representation (computer); Knowledge engineering; Frame-based; Mechanical ventilation; Clinical care

1. Introduction

Computerized protocols provide more assurance of standardization of medical decisions and provide a way to save electronic data on protocol performance and physician compliance for quality improvement activities or research. Adequately explicit computerized protocols (eProtocols) provide treatment instructions defined in precise patient-specific terms after input of patient clinical data (e.g., the fraction of inspired oxygen or mechanical ventilator pressure settings that are required at specific times for an individual patient). The primary proximate purpose of such protocols is to ensure replicable clinician decisions for equivalent patient states. This includes standardization of clinician decisions in clinical trials where blinding is not possible and cointerventions (non-experimental interventions) are unavoidable [1]. Our ultimate purpose is to facilitate the implementation and evaluation of *replicable* adaptive medical patient care protocols that can be applied with equal efficacy in a variety of intensive care units at different centers.

Patients with acute lung injury (ALI) or the acute respiratory distress syndrome (ARDS) typically require days to weeks of mechanical ventilation for respiratory failure. As lung function improves these patients require a program for weaning, or liberation, from the mechanical ventilator. One approach involves daily assessments of respiratory parameters during spontaneous breathing trials. Patients are evaluated for removal of the endotracheal tube when

☆ Funded in part by the NIH (# HHSN268200425210C), the Deseret Foundation, and Intermountain Health Care, Inc.
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1532-0464/$ - see front matter
doi:10.1016/j.jbi.2008.02.002

spontaneous breathing is tolerated within certain parameters for some specified time [2,3]. Another approach to weaning is to gradually reduce the amount of pressure applied by the mechanical ventilator with each breath (pressure support weaning). The clinician weans the patient from mechanical ventilation and the endotracheal tube when specified minimum pressures are reached [4]. Paper protocols for ventilator weaning have been developed, but they differ regarding parameters, thresholds, and the sequence of the decision process. [4–6]. Recently, a randomized trial of a computerized closed-loop weaning application was reported [7] as well as a closed-loop commercial system [8]. An important aspect of our system is the open-loop characteristic which ensures clinician prerogative and oversite. Also, our ventilator protocol is in a form (i.e., a database table) which can be easily exported to other users.

The National Institutes of Health (NIH), National Heart Lung and Blood Institute (NHLBI), acute respiratory distress syndrome (ARDS) network developed a mechanical ventilation protocol that includes pressure support weaning [5,9]. We describe a knowledge engineering process for creating an *adequately-explicit* bedside clinical decision support (CDS) application for the pressure support (PS) weaning portion of this protocol which facilitates the process of liberating a patient from mechanical ventilation support. This weaning protocol is an extension of the computerized ARDS Network ventilation and oxygenation protocols for maintenance of mechanical ventilation for patients with acute lung failure due to ALI and ARDS.

A clinical decision support application contains a knowledge base (KB), an inference engine, a means of communicating results (instructions or actions), a user interface, and an associated patient database (DB) [10–12]. The KB is a collection of encoded knowledge needed to solve problems in some medical area. Inherent in the construction of the KB is an underlying decision model. The inference engine is a computer program that, given a case description (i.e., a patient state), uses the information in the KB to generate new information about the case (i.e., runs the decision logic). The KB used in this application is comprised of database queries, a data dictionary (that maps patient findings to items in frames), and frames (also called decision frames).

The frame as data structure for knowledge representation concept was introduced by Marvin Minsky [13]. Many frame-based CDS applications have been developed over the past 25 years [14–18]. In addition to executing diagnostic and therapeutic logic [10] we also use frames to run DB queries, to make changes to the data entry form, to generate dialogs, and to control global variables (i.e., patient or user interface values maintained in memory when the application runs).

2. Methods

Our frames consist of a title, a list of findings (primary data, results of database queries, and subframes) necessary to make a decision or carry out an action, and a logic or mathematical statement to determine the frame output. An important advantage of using frames for knowledge representation is that they can be created, visualized, and expressed in common medical terms and concepts (e.g., the patient: has an infection, has a need for mechanical ventilation, is ready for a weaning trial, etc.). This is an advantage when interacting with clinicians both for identification of their decision processes and for explanation of protocol outputs. Our frames are elements of a hierarchical decision process. Data elements for higher-level frames can include lower-level frame outputs in combination with primary findings. This means that each frame can *contain* other frames. This is in contradistinction to the more common, but less general, "is_a" relationship of subframes in higher level frames. Frames use a generic structure that can be processed by the inference engine regardless of their content. Frame outputs are saved in the patient's time-stamped database and may be accessed later as other frames are processed. The frame-based hierarchy also allows the interested user to follow the causal reasoning behind the instructions they are being asked to follow.

Our inference engine is computer code with two general algorithms. The "logic processor algorithm" processes the logic of individual frames (i.e., calculates the value of the frames). The "decision tree processor algorithm" passes information between frames (up the decision tree hierarchy) to come to a final conclusion (i.e., generate recommendations or actions). There is no limit on the number of times a frame can be used and there is no required order for the frames to be processed.

Knowledge engineering (KE), in the current context, is the process of creating the KB. This involves extracting information from one or more experts in a clinical domain, and translating that knowledge to a computer representation [10,12]. The knowledge is represented as frames. When the bedside clinician enters patient data, the relevant frames are evaluated, and then linked dynamically in a decision hierarchy that ultimately displays patient-specific recommendations. The bedside clinician may decline any recommendation if they wish, but they are asked to enter a reason for declining.

A number of software tools for KE development are available in the public domain and have been used for various Medical Informatics applications. For example, Clips is an example of an expert system shell [19], Protégé is an application for representing knowledge and ontologies [20,21]; Jess is a rules engine [22]. We developed an application called FrameBuilder [23,24] that specifically generates frame-based knowledge and creates a running application with a user interface and rules engine. FrameBuilder is the culmination of an earlier stream of development that pre-dates the above-mentioned tools [17]. It is an integrated application, with a knowledge engineering environment, a rules engine, and a collection of editors which create a user interface (i.e., a running bedside application). The existing