Prediction of imminent, severe deterioration of children with parallel circulations using real-time processing of physiologic data

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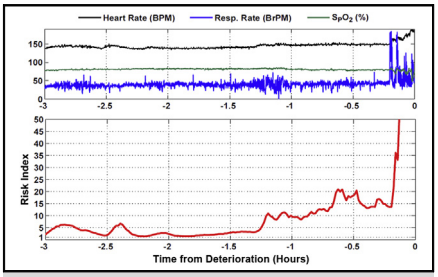
ABSTRACT

Objectives: Sudden death is common in patients with hypoplastic left heart syndrome and comparable lesions with parallel systemic and pulmonary circulation from a common ventricular chamber. It is hypothesized that unforeseen acute deterioration is preceded by subtle changes in physiologic dynamics before overt clinical extremis. Our objective was to develop a computer algorithm to automatically recognize precursors to deterioration in real-time, providing an early warning to care staff.

Methods: Continuous high-resolution physiologic recordings were obtained from 25 children with parallel systemic and pulmonary circulation who were admitted to the cardiovascular intensive care unit of Texas Children's Hospital between their early neonatal palliation and stage 2 surgical palliation. Instances of cardiorespiratory deterioration (defined as the need for cardiopulmonary resuscitation or endotracheal intubation) were found via a chart review. A classification algorithm was applied to both primary and derived parameters that were significantly associated with deterioration. The algorithm was optimized to discriminate predeterioration physiology from stable physiology.

Results: Twenty cardiorespiratory deterioration events were identified in 13 of the 25 infants. The resulting algorithm was both sensitive and specific for detecting impending events, 1 to 2 hours in advance of overt extremis (receiver operating characteristic area = 0.91, 95% confidence interval = 0.88-0.94).

Conclusions: Automated, intelligent analysis of standard physiologic data in real-time can detect signs of clinical deterioration too subtle for the clinician to observe without the aid of a computer. This metric may serve as an early warning indicator of critical deterioration in patients with parallel systemic and pulmonary circulation. (J Thorac Cardiovasc Surg 2016;■:1-7)



Vital signs and risk index as a function of time until deterioration.

Central Message

Critical deterioration events in children with parallel circulation can be predicted 1 to 2 hours before overt decompensation.

Perspective

Acute clinical deterioration is common in patients with a hypoplastic ventricle and parallel circulation. Real-time mathematical transformations of standard physiological data can provide physicians with an early warning of such events allowing the opportunity for early interventions to be performed before the deterioration becomes life-threatening.

CONG

The management of newborns after surgical palliation for congenital heart disease is challenging. Hypoplastic left heart syndrome (HLHS), although accounting for 2% to 3% of all congenital heart disease,[1] is responsible for up to 25% to 40% of all neonatal cardiac deaths.[2-4] The Single Ventricle Reconstruction trial demonstrated that 87% of deaths of subjects undergoing palliation for HLHS occurred before the stage 2 palliative surgery, when the parallel circulation is replaced with a cavopulmonary shunt.[5] As a result, these infants are monitored intensely and continuously. The reason for this is simple: the sooner the care team can detect that a patient is deteriorating, the quicker they can intervene to prevent

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Abbreviations and Acronyms

BCM = Baylor College of Medicine
CPR = cardiopulmonary resuscitation
CVICU = cardiovascular intensive care unit
ECG = electrocardiogram
ECMO = extracorporeal membrane oxygenation
HLHS = hypoplastic left heart syndrome
ICU = intensive care unit
IRB = institutional review board
ROC = receiver operating characteristic
SpO_2 = peripheral capillary oxygen saturation
TCH = Texas Children's Hospital

catastrophic events from occurring. Recent evidence suggests that vigilant monitoring improves survival of patients with a single ventricle after stage 1 palliation.[6,7]

One of the most significant problems encountered while caring for these infants is that detecting impending deterioration can be difficult, even for experienced physicians, because current monitoring technologies are not optimized for this population. For example, in the cardiac intensive care unit (ICU), existing patient monitoring technologies may be confounded by baseline abnormalities of standard vital signs, such as pulse-oximetry, arterial blood pressure, and electrocardiogram. Thus, even when flow to the parallel pulmonary and systemic circulations is optimally balanced, patients are cyanotic. Pulmonary runoff from a systemic to pulmonary shunt can cause low diastolic arterial blood pressure. Cardiac conduction abnormalities can cause the ST segments to be elevated or depressed, so routine electrocardiogram (ECG) monitoring may not be useful to discriminate the status of myocardial perfusion. What is needed is a patient-monitoring system that is specificity optimized to detect problems in the unique physiology of patients with parallel systemic and pulmonary circulation, rather than for the general patient population.

The purpose of this study was to develop a new metric (a risk index) that is derived from continuous physiologic measurements, and predictive of imminent deterioration for subjects with parallel systemic and pulmonary circulations, before stage 2 palliation. Although the present study design is similar to that used in a traditional observational, multivariate regression analysis of factors related to deterioration, the process of predictive model development is fundamentally different. Rather than test for physiologic differences between subjects who experience a deterioration and those who do not, we assert that physiology immediately before deterioration is abnormal, and that physiology not in close proximity to deterioration events is stable. From this assertion, a classification model is constructed to maximize the recognition of predeterioration physiology from stable physiology based on recorded data. Our risk index is, therefore, a measure of how similar a patient's current physiology is to physiology that occurs just before critical deterioration. Real-time utilization of this index may provide the opportunity for clinicians to perform early interventions before deterioration becomes life-threatening, potentially affecting patient morbidity and mortality.

METHODS

Patient Cohort and Data Collection

A 1-year prospective observational study was conducted of infants who underwent surgical palliation at Texas Children's Hospital (TCH) in 2013. Approval was obtained from the institutional review board (IRB) at the Baylor College of Medicine (BCM) with a waiver of consent before the start of the study. Eligible subjects had any anatomic diagnosis of either a morphologic left or right ventricle, provided their early neonatal palliative surgery resulted in a mixing lesion with ventricular outflow to both pulmonary and systemic circulations. Subjects were enrolled on admission to the cardiovascular ICU (CVICU) immediately following early neonatal palliation, and enrollment continued until stage 2 palliation was performed (ie, the interstage period). All eligible subjects were enrolled and included in the analysis. Instances of critical deterioration were defined as the need for cardiopulmonary resuscitation (CPR) or endotracheal intubation, and were found via a chart review. Events were verified using physiologic recordings from patients.

Physiologic data were captured continuously from every monitored bed in the CVICU and the cardiology inpatient units using the Sickbay Platform (Medical Informatics Corp, Houston, Tex) for the duration of the study. Recorded data included high-resolution waveforms (eg, 4 ECG leads [240 Hz], chest impedance [120 Hz], vascular pressures [60 Hz]), and low-resolution vital signs measured intermittently or calculated by the bedside monitor at 0.5 Hz (eg, heart rate, respiration rate, arterial oxygen saturation [SpO_2], ST segments, arterial pressures). The data were stored on site for analysis, and automatically de-identified and coded by the Sickbay system to prevent the release of protected health information. Data analysis and model development were conducted using the Matlab (The MathWorks, Natick, Mass) programming environment. Data captured while a patient was on extracorporeal membrane oxygenation (ECMO) were excluded from the analysis.

Selecting Input Variables to the Algorithm

Candidate input variables to the algorithm were selected by a team of clinical experts based on physiologic rationale. This was done by delineating the etiologies of deterioration in these patients and then identifying measurable physiologic parameters that may be perturbed by these etiologies. Etiologies theorized to cause the observed events included cardiac ischemia, acute heart failure, shunt thrombosis, and changes in the systemic to pulmonary flow ratio due to changes in resistance of the respective vascular circuits. For each of these etiologies, a list of measurable candidate physiologic variables was generated. The initial candidate physiologic variables included heart rate, heart rate variability, arterial blood pressure (systolic, diastolic, and mean), common atrial pressure (systolic, diastolic, and mean), ST segment elevation, ST segment variability, respiratory rate, respiratory rate variability, SpO_2, central venous pressure, core temperature, toe temperature, and core-toe temperature difference. This comprehensive list was then reduced by excluding measurements that were unlikely to be consistently present during a deterioration event, given the time frame of when most of the events were observed. For each remaining variable, a correlation coefficient was calculated between the values observed in the predeterioration and control data. The total number of input variables was limited to 6 so as to minimize model overfitting. The 6 variables with the largest magnitude correlation coefficients were included in the model. The final list of inputs included variables directly sampled from the monitor and those that are derived from the primary monitored