Seminars in Perinatology ▮ (2017) ▮▮▮–▮▮▮

Available online at www.sciencedirect.com

Seminars in Perinatology

www.seminperinat.com

Special equipment considerations for neonatal ECMO

James Connelly[a], *and Thane Blinman, MD*[a,b,*]

[a]*ECMO Program, Children's Hospital of Philadelphia, Philadelphia, PA*
[b]*Division of General, Thoracic, and Fetal Surgery, Perelman School of Medicine, University of Pennsylvania, Philadelphia, PA*

ARTICLE INFO

Keywords:
Neonatal ECMO
Allometric scaling
ECMO equipment

ABSTRACT

Extracorporeal membrane oxygenation (ECMO) for neonates is applied routinely at major children's hospitals around the world. While the practice seems routine, the peculiar physiology of the small human imposes particular constraints on selection of equipment, performance of the circuit, and risks to the child. The physiology of small patients and physics of circuit elements leave many areas opaque and far from optimal, but still allow assembly of a set of useful heuristics for good practice. Here, we examine individual mechanical components of the ECMO circuit with attention to selection, pitfalls, and peculiarities of each when applied to the neonate.

Introduction

Neonatal respiratory failure is the most common indication for extracorporeal life support, with over 30,000 neonatal "runs" listed in the extracorporeal life support organization (ELSO) database.[1] The first neonatal survivor of what became known as neonatal extracorporeal membranous oxygenation (ECMO) suffered from meconium aspiration syndrome, and was named Esperanza by her caretakers in 1975. The technology that was used to support Esperanza quickly became standard for babies that followed, and remained essentially unchanged for years. Dr. Bartlett's team used a roller pump, a bladder box device, a simple oxygenator, and a heat exchanger. Gravity drove passive drainage from the right atrium, and portable pressure transducers were placed strategically to monitor the condition of the oxygenator. The compliance chamber (bladder) in the bladder box device enabled a microswitch to control electricity to power the pump. The net result was the first type of servoregulation to handle a decreased venous return state, the "chirping" of the alarm indicators alerted the specialist to attend to the conditions presented via various techniques.

While the essence of the "circuit" is the same, modern neonatal ECMO equipment is substantially improved, incorporating new materials and more advantageous designs. For example, rolled silicone membrane oxygenators have been replaced by polymethylpentene diffusive oxygenators. Similarly, the simple bladder box has been updated by a compliance chamber integrated into the tubing system. Rarely seen are cannulas lacking wire-reinforcement. Finally, in recent years some centers have shifted from occlusive roller pumps to centrifugal technology thought to offer better blood

Abbreviations: ECLS, extracorporeal life support; ECMO, extracorporeal membrane oxygenation; ELSO, extracorporeal life support organization; ICU, intensive care unit; NICU, neonatal intensive care unit; VO_2, oxygen consumption; DO_2, oxygen delivery; VA, veno-arterial; VV, veno-venous; PVC, polyvinylchloride

*Corresponding author at: Thane Blinman, MD, Children's Hospital of Philadelphia, 3401 Civic Center Blvd, Philadelphia, PA 19104.
E-mail address: blinman@email.chop.edu (T. Blinman).

https://doi.org/10.1053/j.semperi.2017.12.004
0146-0005/

handling characteristics. The design and physics of each of these components determines perfusion performance of the circuit in specific ways.

Here, we review the individual components that make up the modern ECMO circuit in application to neonatal support. In each case, specific features that impose particular constraints, convey advantages, or inform clinical practice for neonatal ECMO are explored. Beneath all of these considerations lie the peculiarities of infant physiology, chief among these being the limitations and demands imposed by size-based physiology.

Names

ECMO and ECLS are used interchangeably in casual use, but they are not the same. As one of the "fathers" of extracorporeal support puts it: "extracorporeal life support" (ECLS) denotes the use of prolonged extracorporeal cardiopulmonary bypass usually via extra-thoracic cannulation in patients with acute, reversible cardiac or respiratory failure unresponsive to conventional medical or pharmacologic management."[2] ECLS is the more general term, typically used to describe temporary support of cardiac or pulmonary function using mechanical devices. In this way, "ECLS" seems to encompass ventricular assist devices, artificial hearts, and the classical ECMO circuit as well. When using the "heart–lung machine" to completely bypass the cardiopulmonary circulation, it is referred to as "cardiopulmonary bypass". In contrast, when ECLS is used in the intensive care unit (ICU) or emergency department (ED) to augment oxygenation, ventilation, or cardiac output it is generally referred to as "ECMO." It is this version, as used in neonates, typically with pulmonary hypertension (e.g., as in diaphragmatic hernia), meconium aspiration, sepsis, and other neonatal shock states that provides the scope for this discussion.

Flows

ECMO is not bypass. The entire cardiac output and oxygen delivery (DO_2) of the infant is not replaced by circuit flow perfusion, even on veno-arterial (VA) ECMO. Instead, a fraction of cardiac output is supported. This fraction is large enough to overcome shock, but generally not so large as to extinguish pulsatile flow contributed by the baby's native circulation. In order to determine how much flow (and to allow choosing equipment with capacities that will support that flow) to supply, one must know the native cardiac output (CO), and the typical fraction of support needed. But in order to project expected CO, one must understand how oxygen consumption (VO_2) varies in different sized humans. These size-dependent, nonlinear changes in physiology over a wide range of body size fall under the idea called "allometric scaling."

Allometric scaling holds that body mass is the chief determinant of changes in physiology across a range of body mass (as opposed to height, body surface area, or other indexes). In general, physiological scaling relationships all can be understood with a single general scaling equation:

$$Y(m) \cong Am^b\varepsilon$$

This equation says that any physiological parameter "Y" that varies as a function of mass "m" follows a power law, with the constant "A" and the scaling exponent "b" determined empirically. The error factor "ε" accounts for external forcings or errors (e.g., the driving effect of fever on metabolic rate). Of particular interest is the scaling exponent "b," which can take on values of 0, 1, or positive or negative fractions. For example, heart rate varies over body size according to an inverse power law, with a negative fractional exponent, around –0.28.[3] Normal heart rate for an infant lies on a inverse power-law curve around 130 bpm, but an 80 kg adult's heart rate is found on the same curve at around 60 bpm. Most physiological parameters (heart rate, respiratory rate, VO_2, DO_2, lung surface area, gut length, etc.) vary nonlinearly this way, and power laws model this variability well. Occasionally, parameters vary linearly with mass, where $b = 1$ (e.g., tidal volume, gastric volume, bladder capacity, and total blood volume). Finally, if the exponent is 0, it means that the parameter does not vary with mass, for example, erythrocyte size, myocyte cross sectional tensile strength, axonal transmission speed, bladder evacuation time, etc. (Fig. 1).

Oxygen consumption (i.e., energy expenditure) in humans follows power-law scaling over a wide range of body size.

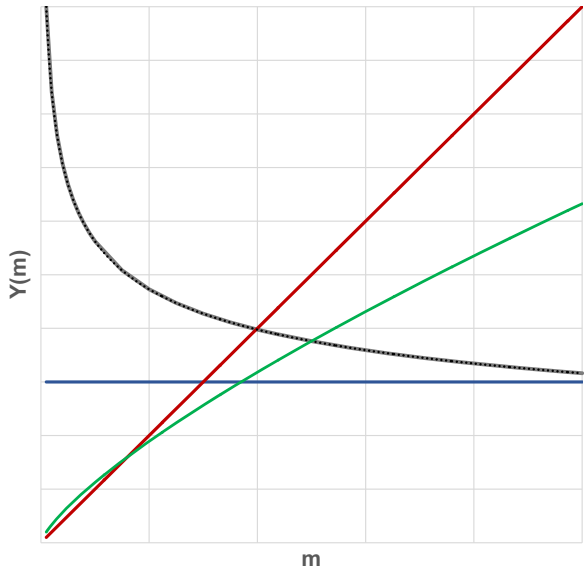

Fig. 1 – Allometric scaling curves. Scaling in organisms of different body masses can be invaraiant ($b = 0$, blue line), linear or isometric ($b = 1$, red line), or allometric following a power law ($0 < b < 1$, green line) or an inverse power law ($-1 < b < 0$, black line). The error term E moves the relationship up and down the Y axis and represents an external forcing (e.g., the effect of fever on metabolic rate). These relationships reveal how physiological parameters such as VO_2 or cardiac output are very large on a per-kilo basis (black line) even if absolute rates (green line) are still very small in the infant. The highly nonlinear relationship at smaller masses also reveals how there are larger than realized physiological variations between, say, a 2.8 kg and a 5.0 kg infant. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)