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How Fast Is Too Fast?:

A Practice Change in Umbilical Arterial Catheter Blood Sampling Using the Iowa Model for Evidence-Based Practice

Myrna Gordon, RN, BSN, Lisa Bartruff, RN, MSN, ARNP, Sara Gordon, RN, MSN, ARNP, Maria Lofgren, RN, MSN, ARNP, and John A. Widness, MD

University of Iowa Children's Hospital, University of Iowa Hospitals and Clinics, Iowa

Abstract

A multidisciplinary team at the University of Iowa Children's Hospital utilized the Iowa Model of Evidence-Based Practice to Promote Quality Care as a basis for changing practice related to the rate of drawing and flushing umbilical artery catheters in very low birth-weight infants. Research indicates that rapid withdrawal of blood or flushing of catheters that are placed in the aorta can affect cerebral blood flow velocity, volume, and oxygenation. Alteration of cerebral blood flow in premature infants has been correlated with the incidence of intraventricular hemorrhage and periventricular leukomalacia, which can be a significant cause of morbidity and mortality in this population. Using this research as a guide, along with expert opinion, scientific principles, and theories, a new standard of practice was written, and the staff educated.

Keywords

blood sampling; cerebral blood flow; evidence-based practice; intraventricular hemorrhage; research utilization; umbilical artery catheter

As technology has made possible the survival of extremely premature infants, medical researchers have tried to discover new and better treatments that will prevent or limit conditions that can lead to impaired outcomes such as chronic lung disease, blindness, deafness, mental retardation, and cerebral palsy. Nursing has also attempted to improve outcomes through research and quality management (QM) initiatives.

A nurse on the QM Committee in the neonatal intensive care unit (NICU) at the University of Iowa Children's Hospital began to examine nursing practice in accessing central catheters from an epidemiological perspective, suspecting that there was wide variation in practice, and that aseptic technique was not always maintained. The technique used to access and draw blood samples from umbilical arterial catheters (UACs) was scrutinized informally. During these observations a new potential problem was noted: nurses might unknowingly be putting their patients at risk by drawing and flushing the catheters too rapidly. This led to a formal QM project that utilized the Iowa Model of Evidence Based Practice to Promote Quality Care¹ in the development of a new Standard of Practice (SOP) guiding blood sampling from UACs.

The Iowa Model (Figure 1) is a guide, which assists nurses in improving care through the use of research utilization, expert opinion, scientific principles, theories, and case studies.

This model was chosen because there was very little conclusive or specific research on which to base a practice change. It provides a framework to assist nurses in utilizing other evidence that might support a practice change or a best practice.

This article will present the development of a new SOP for blood sampling from UACs, generally following the process of the Iowa Model¹ and provide some background information regarding cerebral blood flow (CBF) in very low birth-weight (VLBW) infants, methods of measurement, and the implications of alterations in cerebral blood flow velocity (CBFV).

Triggers

The Iowa Model¹ begins with critical thinking by nurses, which can be based on a problem or knowledge. In this case, there was a combination of problem- and knowledge-focused triggers that complemented each other. An assessment of variations in aseptic technique raised concern that there was also variation in the actual process of drawing blood and flushing the UACs, and that the rate at which this was done should be specified in the SOP with attention to the effect it might have on VLBW infants. At the time this question arose, it was unknown whether the velocity of blood withdrawal or flushing of UACs could alter CBF in VLBW infants. The staff QM team was sensitized to this potential problem because of a change in the philosophy of care that had evolved in the NICU over the last 10 years. More emphasis was being placed on increases or decreases in arterial blood pressure and the corresponding changes in CBFV and volume in very low birth-weight infants. Clinicians were aware that these changes may lead to intraventricular hemorrhage (IVH) or ischemia.² This issue was addressed by implementing an SOP that emphasized minimal handling including no bath, limiting or abolishing routine suctioning of endotracheal tubes, new taping strategies to prevent unplanned extubations, and providing sedation and analgesia for painful procedures. Medical treatments have also changed, essentially following most of the guidelines recommended by the Vermont-Oxford Network, which list strategies to prevent brain hemorrhage and ischemic injury.³ Key elements include avoiding the following: rapid volume expansion, hypercarbia, hypocarbia, anemia, hypoglycemia, and pneumothorax.

IVH and periventricular leukomalacia (PVL) continue to be highly relevant problems for NICUs. The incidence of IVH had decreased in the early 1990s, but then remained static from 1995 to 1999.⁴ Incidence has an inverse relationship to gestational age: the lower the age, the higher the incidence. This fact, combined with the realization that survival rates for extremely premature infants at the limits of viability are increasing,⁵ indicate that IVH will be an ongoing problem. In the interim, PVL has become the leading cause of neurological problem in VLBW infants, implicating ischemic injury from decreased blood flow, followed by reperfusion and oxidative injury from free radicals.⁶

Decision Point: Priority to the Organization

The University of Iowa Children's Hospital NICU is a level III nursery that provides care to newborns that require subspecialty care not available at other hospitals in the state. Many high-risk obstetrical patients are referred for care and delivery. These factors contribute to a high population of extremely premature newborns either admitted by birth or transported in. Good outcomes in all infants are a high priority for the Division of Neonatology, but because infants on the edge of viability are at very high risk for neurological impairment, evidence-based care that can impact on this population is valued and put into practice. The Division of Neonatology has demonstrated its commitment to improving outcomes by their membership in the Vermont Oxford Network, an international collaborative dedicated to improving the quality and safety of medical care for newborns and their families.⁷ When the

potential problem was brought to the members of the division, they provided support and collaboration.

The Department of Nursing emphasizes quality of care in their mission statement that is evidenced by achieving Magnet Status in January 2004. The UIHC is in the process of redesignating Magnet status in 2008. The Magnet initiative was one step that the department took as a way to retain veteran nurses by encouraging them to contribute to quality, educational, and research projects.⁸ Many nursing units have QM committees that focus on problem areas that are amenable to evidence-based interventions. Initiating a change in practice research and other evidence that could impact outcomes of extremely premature infants is in concert with the organizations goals and mission statement.

Forming a Team

To develop and implement specific strategies to improve process, a core team of stakeholders was formed. This multidisciplinary team included representatives from the following departments: medicine, nursing, phlebotomy, and epidemiology; ad hoc members came in as needed. Each team member had specific responsibilities and contributed data and knowledge from their area of expertise. For example, the neonatologist was a liaison with the Division of Neonatology, assisted in critiquing the research, and provided expert opinion. Other neonatologists and a cardiologist provided valuable knowledge about physiologic principles. Epidemiology became involved in the initial stages of investigation, before the aim of the project was completely defined. The QM committee is primarily a nursing unit endeavor; therefore, the majority of the work was done by nurses. Phlebotomy was primarily concerned in the implementation phase, as they are usually at the bedside to receive blood samples from the nurses accessing the UAC.

Relevant and Related Research

Information from the Agency for Healthcare Research and Quality web site⁹ assisted with the evaluation of the quality of evidence from the articles reviewed (Box 1). This system classifies evidence into a hierarchy by evaluating the quality and types of study. Table 1 summarizes the literature and levels of evidence pertinent to measurements of cerebral blood flow and tissue oxygenation during UAC blood sampling.

Umbilical artery catheters (UACs) are used frequently in the neonatal intensive care population for monitoring blood pressure and to give fluids and draw blood, thereby avoiding painful procedures, and providing more accurate results. The relevant procedures were written when 500-g infants did not survive. There were several questions that guided our literature search. First, does withdrawal of blood from a UAC decrease CBF and oxygenation; conversely, does reinstallation of blood and flushing of a UAC increase CBF? Next, research related to specific volumes and rates that are safe were needed to base our new practice on. Ultimately, studies that established a safe volume per kilogram over a specific unit of time were sought. A Medline search was done using the keywords: umbilical arterial catheter, cerebral blood flow, very low birth-weight, and premature infant. Four research articles were found that were relevant to the question of the effect of velocity and volume in accessing UACs in neonates, although none of them provided a clear guideline about safe volumes and rates (Table 1).

Critique and Synthesis of the Research

One large multicenter study found no evidence that there was any difference in UAC placement, high versus low, in relation to IVH or death.¹⁰ High placement refers to the area in the aorta corresponding to thoracic vertebrae 6 through 9; low placement is usually

referred to as lumbar 2 through 5. A Cochrane review of 5 randomized controlled trials and 1 alternate assignment study found that there is a lower incidence of vascular complications with high catheters, without any difference in other adverse effects.¹¹ The specific study that we examined was chosen because of the dependent variable of IVH. No protocol was set that established a consistent rate of draw and flush, or that addressed the amount of blood drawn. It should be noted that there has been an increase in survival of smaller infants since this study was published.

Three other studies were designed to evaluate CBF, although they did not measure the incidence of IVH. They all used experimental designs. These studies specifically examined CBFV, changes in cerebral blood volume (CBV) and oxygenation, and tissue oxygenation. Definitions of these terms and others used in the medical research studies to follow are listed in Table 2.

Changes in the velocity of blood flow in the anterior cerebral artery during the sampling cycle in both high and low UACs was first described in 1996.¹² This study used Doppler ultrasonography while flushing the UAC and demonstrated increased systolic and diastolic blood pressure, turbulence and microbubbles in the aorta. Turbulence was decreased with a slower rate of flush infusion. This study demonstrates a direct, positive relationship between the rate of flush and the change in blood flow velocity that occurs. The same volume was used in this study; however, the effect of volume in relation to infant weight and its effect on CBF were not investigated.

Although Doppler ultrasonography measures CBF velocities in the larger cerebral arteries, it cannot assess oxygenation to the brain. The next step that advanced knowledge about the effects of UAC sampling on VLBW infants examined changes in CBV and oxygenation.¹³ This study demonstrated a significant decrease in oxygenated hemoglobin (O₂Hb) that persisted beyond the time of the blood draw. Decreased levels of O₂Hb indicate that there is less oxygen available for tissue delivery. Cerebral blood flow was decreased in addition to a persistent decrease in cerebral oxygenation. This combination of physiologic events may indicate the potential for ischemia to vulnerable areas of the premature infant brain. Ischemia in watershed areas of the white matter can cause PVL,¹⁴ whereas ischemia to the germinal matrix could lead to ischemia/reperfusion injury, resulting in hemorrhage and damage to oligodendroglial precursors. Table 3 lists the unique characteristics of premature infant's brains that make them especially susceptible to conditions and events that are better tolerated in mature neonates. This study did not control for the rate of aspiration, flushing, or the volume withdrawn and flushed. The description of this sample included VLBW infants. It would be useful to consider the differences in results when UAC sampling is performed on babies of different weights, controlling for rate and volume. This would provide information on the effects the same sampling procedure has on infants with different circulating blood volumes and different vessel size. Considering the percentage of cardiac output to a specific volume and rate of aspiration or flushing and the effect on CBF measures could be one approach to obtain better information about infant weights and safe methods of sampling. Careful consideration would have to be given to the ethical aspects of such a study because of the potential sequelae that could be associated with decreased CBV and cerebral oxygenation. Follow-up of the sample might be useful in linking these results to later IVH or PVL, although many other events might affect those outcomes.

A later study did control for the variables of volume and rate, although not for infant weight.¹⁵ In addition to measuring O₂Hb, and deoxygenated hemoglobin, a tissue oxygenation index (TOI) was calculated. These investigators chose 20 seconds and 40 seconds as comparative speeds of withdrawing fluid and flushing the catheter to evaluate any differences these rates might impact on cerebral oxygenation. The authors found that

drawing 2.3 mL of blood in 20 seconds from a UAC significantly decreased the O₂Hb and TOI while a draw time of 40 seconds had no effect. They recognized that the volume represents a different percentage of total circulating volume in infants of different sizes and that gestational age may have an effect.

Although this article addresses effects from sampling with UACs, a more recent article¹⁶ demonstrates a similar decrease in cerebral oxygenation and CBV when sampling from an umbilical venous catheter.

Decision Point: Sufficient Research?

The research studies suggested that blood sampling from UACs could have a significant effect on CBF and oxygenation. It is important to note that these studies had very small samples, and that replication with larger, randomized trials is needed to support their findings. There are still questions as to how these numbers translate to adverse effects such as ischemia and hemorrhage, but the basic thesis that preventing any change in these parameters is the desired outcome is supported by previous research.² Stable premature infants maintain cerebrovascular autoregulation to a limited extent; however, sick premature infants, who are typically the patients requiring UAC access, have pressure-passive cerebral circulation, making them susceptible to hemorrhage and ischemia.^{2,17,18} The team consensus was that sufficient research existed indicating that blood sampling from UACs could alter cerebral hemodynamics, although this research did not provide enough information about specific volumes and rates of flow that should be implemented.

Other Evidence

At this point in the Iowa Model,¹ it is appropriate to gather evidence from case reports, expert opinion, and scientific principles and theories, or to conduct research. A search of the National Guideline Clearinghouse was performed using the key words: cerebral blood flow, IVH, umbilical artery, umbilical catheters, and neonates with no pertinent results. The Cochrane Database of Systematic Reviews included several articles that addressed IVH or ischemia as outcomes relating to UAC position¹¹ and the use of heparin,¹⁹ but not sampling procedures. An attempt to benchmark with other institutions was also unsuccessful. Ultimately, scientific principle and expert opinion, in combination with the limited research described previously, were used to develop a protocol.

Scientific Principle: Poiseuille's Law

Poiseuille's Law states that blood flow increases as pressure increases from one end of a vessel to another, and that blood flow increases as the radius of the vessel increases (Table 4).²⁰ This principle is directly related to the effects of blood sampling from UACs and the effect it has on CBF. The average diameter of the descending aorta in a 24-week gestation neonate is approximately 4 mm. When the aorta bifurcates, the resulting diameters are 2 mm.²¹

As the diameter of the vessel decreases, the resistance to flow increases by the radius to the fourth power. Thus, a 50% decrease in the radius from 2 mm to 1 mm results in a 16-fold increase in resistance to flow (Figure 2). The pressure gradient must increase by 16-fold to maintain the same flow. Based on Poiseuille's Law, flushing at a high flow rate will greatly increase the pressure in small caliber blood vessels possibly damaging these fragile vessels, leading to an increased risk of IVH. Therefore, to decrease the pressure that a fragile vessel is subjected to, one must decrease the flow rate. Similarly, drawing blood too rapidly from the aorta could cause ischemia in these smaller blood vessels by dramatically reducing blood flow from a large decrease in the pressure gradient.

Expert Opinion

A QM report that included the literature review was presented to the Division of Neonatology in March 2003. Opinions on a safe volume and rate of aspiration and instillation in UACs were sought. Based on one of the studies,¹⁵ in which 1 mL/40 seconds appeared to be safe and 1 mL/20 seconds affected CBF, the rate of 1 mL/30 seconds was the consensus result and thought to be safe by all neonatologists present. Although this rate has not yet been proven by research, this rate may be safer than the previous standard of 1 mL/5 seconds, which was utilized.

Piloting the Change in Practice

According to the Iowa Model,¹ there are 6 steps in this phase of the process: select outcomes to be achieved, collect baseline data, design evidence-based practice guidelines, implement on a pilot unit, evaluate the process and outcomes, and modify the practice guidelines. These 6 steps were followed with one exception. Because of the small size of the unit where UACs are utilized, there was no pilot. The protocol was simply implemented in the Bay 1 NICU. The guidelines will be modified pending further research.

Outcomes

The overall goal of the practice change project was to attain consistency in the accessing of and the withdrawal of blood samples from UACs in the NICU. The reason for this primary goal was simply prevention of fluctuations in CBF.

Baseline Data

A nursing-care practice survey was done to evaluate the current practice in the NICU for umbilical catheter blood draws. Wide variation in practice was noted in almost all aspects of the procedure, especially in amounts drawn to clear the line, and the rate of aspirations, reinstallation, and flushing. These data were used to educate the staff about the problem with variations in practice, and as data to measure improvement after implementation of a new policy. In reviewing the current policy, it was clear that the procedure was vague and outdated, although it was rarely used as a reference, as nurses are taught to do this procedure one-on-one with a preceptor. One challenge would be to keep a new policy in the fore-front of the minds of the staff.

Protocol Design

The inspiration for a possible practice change developed as the principal investigator (PI) became concerned with her own observations of staff nurse colleagues accessing UACs for blood sampling without regard to rate. A questionnaire survey related to UAC blood sampling was written by the PI and distributed to all NICU registered nurses (RNs) in the spring of 2000. Those who received the survey were staff RNs with a variety of nursing and NICU experience, a mixture of educational level and age, and were all female. As expected, this showed variations in practice regarding UAC line sampling. Although the focus of the survey was on accessing the UAC, the variations in practice led to further investigation by the PI. A blind audit of the rate at which staff nurses drew blood from a UAC and instilled a flush solution was completed by the PI, while working alongside them. This revealed an additional important clinical question. If the site prepping varied so much in the unit, did the rate of blood drawing and instillation of a flush solution really differ as much among staff members as seemingly observed? These findings and questions were presented at the Division of Neonatology's monthly meeting. This group included representatives from medicine, nursing, pharmacy, phlebotomy, social work, nutrition, and respiratory therapy. In

July 2000, after the information was presented, a literature review was initiated. This was a lengthy process. Because of difficulty finding research on the rate of blood aspiration and instillation from the umbilical catheters, the literature review was not completed until February 2003 and data were presented to the Division of Neonatology.

Implementation

The new SOP included these key elements:

- Aspirate from the UAC at the *rate of 1 mL/30 seconds* to clear the line (mixture of fluid and blood)
- Draw sample in new syringe at the *rate of 1 mL/30 seconds*
- Reinstill the mixture of fluid and blood at the *rate of 1 mL/30 seconds*
- Instill a clean syringe of flush solution at the *rate of 1 mL/30 seconds*

The time-frame (1 mL/30 seconds) was introduced to the staff as the new practice for withdrawal and return of blood as well as instillation of flush solution into the UAC. This was implemented in NICU Bay 1, because it has only 11 beds, and the patients are the most acutely ill, thus being more likely to have a UAC. Education of staff was a major part of implementing this guideline. The rationale for the change was an important part of this process. Individual in-services were given to all nurses involved in the drawing of blood samples from arterial lines. One proven method to improve the process of change is the use of reminders. Three interventions used for this were a pocket reference card, the SOP online at each bedside computer, and routine reminders posted by nursing management.

Evaluation and Modification of Outcomes

In July 2003, 1 month after implementation of the revised SOP, a spot check of current practice was done. Five NICU staff nurses including the PI observed their nursing peers during UAC blood draws. The staff demographics did not change from the time of the original survey and subsequent clinical questions regarding UAC line preparation and rate of flush being raised. The 5 nurses completing the spot check worked a variety of shifts allowing for all RNs involved in UAC line draws to be included. The PI was utilized as an observer as this is where the idea for the practice change originated. The staff were observed by their peers for correct technique (drawing/instilling blood no faster than 1 mL/30 seconds) and reeducated immediately as needed. Forty nurses were observed for technique without their knowledge of being watched. Eighty-eight percent had correct technique and required no reeducation. The observers were neither conducting research nor truly monitoring outcomes, but rather auditing compliance and knowledge of a recent change in practice. Nurses, physicians, and phlebotomists are all aware of the study and consequent practice change and are responsible for ensuring follow-through with reminders and education of their peers if needed. Ongoing observational audits to evaluate application of a new practice as well as on-the-spot reeducation and rationale as needed are important in ensuring compliance and safety in the NICU.

Decision Point: Change Appropriate for Practice?

The completion of the 6 steps for piloting a change in practice led to an important decision. The information from the literature review, expert opinion, staff questionnaire and education, and unit observations provided enough evidence for a change in practice. This change was not only a serious step that addressed a problem, it also heightened awareness of the fragility of these tiny infants, and how nursing care can impact their future neurodevelopment.

Institute the Change in Practice

Revisions to the current standard for UAC blood draws were proposed to the SOP committee. Changes were approved and the SOP was updated accordingly. All of our SOPs are reviewed and revised every 3 years in accordance with Joint Commission on the Accreditation of Healthcare Organizations guidelines. The new standard was distributed for adaptation into practice in June 2003 and last reviewed in June 2006.

Evaluate Structure, Process, and Outcomes

The new SOP was approved rapidly and integrated into the online documentation system to provide ready access. A key element that would ingrain the new practice into the culture of the NICU is in the education of new staff. Orientation to the unit requires several weeks of didactic classes where this protocol and the principles that inspired it are introduced. A period of preceptorship follows, when these ideas should be reinforced. Indications are that improvement needs to be made in this area.

The process itself appears to remain prudent until further research indicates the need for a practice change. One exciting idea is the possible use of near-infrared spectroscopy at the bedside for continuous data about cerebral hemodynamics and oxygen delivery and consumption. Currently, it is used in research, but important information about baseline values and new imaging technologies using the data are being developed.

The initial evaluation of the education effort indicated that the implementation of the new SOP had been successful. Subsequent, informal observations indicate that staff needed reinforcement about this important aspect of nursing care. When they understand the rationale behind the slow aspiration and flushing of UACs, they were more than willing to comply. Plans are in progress to improve education efforts by designing a presentation for the didactic portion of new staff's orientation, and for the annual preceptor workshop. Another potential intervention is to require a yearly competency review and quiz. Continued monitoring of staff knowledge of the SOP is necessary.

Conclusion

Prevention of IVH in the VLBW infant is an important aspect of NICU nursing practice. Better overall outcomes for the babies are directly related to the expert care given. This high level of nursing care is based on evidenced-based practice, expert opinion, and well-designed SOPs.

The Iowa Model of Evidence-Based Practice to Promote Quality Care¹ was a useful tool to guide the process of changing an outdated SOP. The triggers were both problem focused and knowledge based. Although improving processes and procedures that might affect outcomes are high on the organization's priority list, this project did not require a significant financial investment or any other difficulty for the hospital. This is why the focus was on the Division of Neonatology and their commitment to improving outcomes of VLBW infants. The Department of Nursing also has a significant interest in nurses conducting QM projects. The difficulty of this project was the lack of relevant research of this specific practice. It was necessary to decide on a practice that would seem to be safe, although not proven with large, randomized, controlled trials. Combining the knowledge gained from the research, along with Poiseuille's Law, and expert opinion the rate of 1 mL/30 seconds was chosen as the appropriate rate. Ideally, the rate would be based on the infant's weight; 1 mL/30 seconds is much more significant to a 500-g infant with an estimated blood volume of 40 mL, than to a 1500-g infant with a volume of 120 mL. Recently, another study has published results, although only the abstract was available at the time of publication.²² It will be necessary to

continue to review the literature and change the policy as indicated. The most arduous part of the process was one-on-one education and follow-up after observation for compliance. Integrating the procedure into the SOP online promotes easy access for staff. In addition, if all new staff are educated correctly from the start, this nursing task will become a nonissue. The QM committee will continue to occasionally monitor staff to ensure that standardized procedures are being carried out. The NICU nurses are committed to caring for their special babies and ensuring that the best in nursing care is always given.

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Box 1. Hierarchy of Study Types⁹

- I.** Systematic reviews and meta-analyses of randomized controlled trials
- II.** Randomized controlled trials
- III.** Nonrandomized intervention studies
- IV.** Observational studies
- V.** Nonexperimental studies
- VI.** Expert opinion

FIGURE 1.
The Iowa Model of evidence-based practice to promote quality care.

FIGURE 2.

Schematic representation of the inverse relationship of the diameter of a vessel to the resistance of flow. This is an example of a 50% reduction in the diameter of the aorta in a 24-week infant, resulting in a 16-fold increase in the resistance to flow. r = radius; d = diameter; mm = millimeter.

TABLE 1

Literature Review (Umbilical Artery Catheters)

Author/year	Study type/design	Methodology	Population/Sample size	Outcome variables	Level of evidence (see Box 1)	Findings with statistical significance
Umbilical artery catheter trial study group ¹⁰ (1992)	Prospective, multicenter randomized group trial	Randomization scheme for equal numbers of high UACs or low UACs placed within the first 6 h of life	970 neonates birthweights: 500–1499 g; 481: high 489: low	Stratified by weight groups IVH grades: 0–I, II–IV, in survivors and those who died Complications	Level II ^a	Increased risk of vascular complications with low placement in general. No difference in IVH/death
Lott et al ¹² (1996)	Prospective, single center, nonrandomized, pre/posttest measurements	Measurement of cerebral blood flow velocity in the anterior cerebral artery using Doppler ultrasound, in VLBW infants during sampling with UACs in high and low position (20 seconds/2ml)	30 infants, < 1501 g at 24 h of life (within 6 h)	Cerebral blood flow velocity as calculated with AUVc (area under the velocity curve) and PI (pulsatility index)	Level IV ^b	Decreased cerebral blood flow velocity both high and low during sampling—greater in high; increased CBFV in high during instillation.
Roll et al ¹³ (2000)	Prospective, single center, nonrandomized, descriptive	NIRS (near infrared spectroscopy) changes in cerebral blood volume and oxygenation during sampling from UACs. (no specified rate of sampling)	20 infants, < 1501 g, DOLO-2 with a UAC	Concentrations of oxygenated Hgb (O ₂ Hb), deoxygenated Hgb (HHb), and cytochrome oxidase. to measure cerebral blood volume	Level IV ^b	O ₂ Hb decreased significantly from baseline. HHb did not change significantly.
Schultz et al ¹⁵ (2003)	Prospective, single-center, nonrandomized, descriptive	Measures of O ₂ Hb, HHb, tissue oxygenation index (TOI), with 2 blood samplings at 2 speeds, 20 and 40 s	20 infants, preterm with high UACs (median gestational age 30.14 wk, median wt 1170 g)	O ₂ Hb, HHb, TOI	Level IV ^b	O ₂ Hb and TOI decreased with 20 s sampling. No change with 40-s sampling.
Roll et al (2006) ²²	Prospective, single-center, nonrandomized, descriptive	NIRS, measure O ₂ Hb, HHb during sampling with specified volumes (mL) and velocities: 1.6 to clear over 80 or 40 s, 1.7 asp over 40 or 80 s, or 0.2 over 30 s, and 1.6 to re instill over 30 s, and 0.6 to flush over 6 s	48 infants, mean wt 965 g, mean age 27 wk	Cerebral blood volume and cerebral oxygenation	Level IV ^b	With all 3 methods of sampling O ₂ Hb decreased significantly, HHb did not change

^aAt least 1 well-designed experimental study.

^bNonexperimental, observational studies.

TABLE 2**Terminology**

Autoregulation	Ability to maintain constant blood flow with variations in blood pressure: vessels contract with increased pressure and dilate with decreased pressure
Cerebral blood flow velocity (CBFV)	Measure (by Doppler) that is determined by cerebral blood flow and cerebrovascular resistance: Velocity increases as volume increases and area decreases
Cerebral blood volume (CBV)	Sum of O ₂ Hb + HHb = total hemoglobin = CBV
Deoxygenated hemoglobin (HHb)	Hemoglobin without bound oxygen: consumed
Near-infrared spectroscopy (NIRS)	Noninvasive monitoring using scalp optodes: Measures variables to determine perfusion and oxygenation
Oxidized cytochrome	Measures that can indicate intracellular oxygen availability or utilization Decrease indicates critical decrease in oxygen to cell
Oxygenated hemoglobin (O ₂ Hb)	Oxygen available in cerebral blood
Tissue oxygenation index (TOI)	Measure of cerebral oxygen consumption using NIRS Ratio of O ₂ Hb to total Hb; might reflect cerebral venous saturation
Turbulence	Related to velocity and diameter, causes loss of energy Diameter decrease → velocity increase = turbulent flow

TABLE 3Comparative Characteristics Predisposing the Preterm Infant Brain to IVH and PVL²

Intraventricular Hemorrhage	Periventricular Leukomalacia
Germinal matrix	Extremely low blood flow
Fragile capillaries	
Lack of support structure	Watershed areas
Fibrinolytic activity	End zones: long arteries Focal, severe ischemia (cysts)
Border zones	End zones: short arteries
Avascular	Oligodendroglial precursors (OLs)
High oxidative metabolism	Vulnerable to free radicals
Prone to hypoxic/ischemic injury	Mature OLs form myelin
	Decrease in white matter volume
Loss of autoregulation	Ventriculomegaly
	Border zones: between long arteries
Possible pressure gradient with decrease in extracellular volume	Diffuse, moderate ischemia Loss of autoregulation

TABLE 4

Formulas Based on Poiseuille's Law²⁰

(Resistance to flow)		(Volume flow rate)	
$R = \frac{8\eta L}{\pi r^4}$		$F = \frac{P_1 - P_2}{R}$	
η = Viscosity	r = Radius	L = Length	