Prone Position Ventilation in Neurologically Ill Patients: A Systematic Review and Proposed Protocol

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OBJECTIVES: Prone positioning has been shown to be a beneficial adjunctive supportive measure for patients who develop acute respiratory distress syndrome. Studies have excluded patients with reduced intracranial compliance, whereby patients with concomitant neurologic diagnoses and acute respiratory distress syndrome have no defined treatment algorithm or recommendations for management. In this study, we aim to determine the safety and feasibility of prone positioning in the neurologically ill patients.

DESIGN AND SETTING: A systematic review of the literature, performed in accordance with the Preferred Reporting Items for Systematic Review and Meta-Analyses 2009 guidelines, yielded 10 articles for analysis. Using consensus from these articles, in combination with review of multi-institutional proning protocols for patients with nonneurologic conditions, a proning protocol for patients with intracranial pathology and concomitant acute respiratory distress syndrome was developed.

MEASUREMENTS AND MAIN RESULTS: Among 10 studies included in the final analysis, we found that prone positioning is safe and feasible in the neurologically ill patients with acute respiratory distress syndrome. Increased intracranial pressure and compromised cerebral perfusion pressure may occur with prone positioning. We propose a prone positioning protocol for the neurologically ill patients who require frequent neurologic examinations and intracranial monitoring.

CONCLUSIONS: Although elevations in intracranial pressure and reductions in cerebral perfusion pressure do occur during proning, they may not occur to a degree that would warrant exclusion of prone ventilation as a treatment modality for patients with acute respiratory distress syndrome and concomitant neurologic diagnoses. In cases where intracranial pressure, cerebral perfusion pressure, and brain tissue oxygenation can be monitored, prone position ventilation should be considered a safe and viable therapy.

KEY WORDS: acute respiratory distress syndrome; cerebral perfusion pressure; intracranial pressure; management protocol; neurologic condition; prone position

First defined in 1998 and later reclassified in 2011, acute respiratory distress syndrome (ARDS) is a lung injury that occurs secondary to an exaggerated inflammatory response, either from direct injury to lung parenchyma or indirectly through systemic precipitating factors (1, 2). Among the primary tenets of management of patients with ARDS are lung-protective ventilation strategies. When standard ventilation strategies fail, additional

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measures, such as pharmacologic paralysis, extracorporeal membrane oxygenation (ECMO), or prone position ventilation, should be considered. Prone positioning has become a targeted therapy through improving lung recruitment and ventilation-perfusion mismatch (3).

Data from the Prone Positioning in Severe ARDS (4) trial supported that early application of a prone position ventilation strategy significantly reduced 28-day and 90-day mortality for patients with severe ARDS. This study and most ARDS trials, however, have excluded patients with primary neurologic diagnoses, and results of these trials may not be applicable to the neurologically ill population. Concerns of positional increases in intracranial pressure in patients with already reduced intracranial compliance informed these exclusions. However, this has resulted in a unique predicament, whereby patients with concomitant neurologic diagnoses and ARDS have no defined treatment algorithm or recommendations for prone positioning.

In this systematic literature review, we aim to determine the safety and feasibility of prone positioning in neurologically ill patients. Additionally, we aim to report the intracranial alterations during prone positioning, including intracranial pressure (ICP), cerebral perfusion pressure (CPP), and brain tissue oxygenation ($Pbto_2$). Finally, we developed a prone position protocol for neurologically ill patients.

METHODS

Systematic Literature Review

This study was a systematic review and was, therefore, exempt from institutional review board approval. No external funding sources were used. A systematic review of the literature was performed in accordance with the Preferred Reporting Items for Systematic Review and Meta-Analyses 2009 guidelines (**Fig. 1**). The search was performed on April 17, 2020. The following electronic databases were queried: MEDLINE via PubMed, (1946–), the Cochrane Library (Wiley interface, current issue), CINAHL plus with full text via EBSCO, Web of Science/Knowledge via Clarivate Analytics, and ClinicalTrials.gov. Search terms are available in **Supplementary Table 1** (Supplementary Digital Content 1, http://links.lww.com/CCM/G85). The search was performed by a health-science librarian at University Hospitals Cleveland Medical Center.

The initial title and abstract query identified a total of 173 articles, after the removal of duplicates. Title and abstract screening were completed by two independent reviewers (C.M.L., E.Z.H.), and any inclusion conflicts were decided by a third arbiter (J.M.W.). Inclusion and exclusion criteria were defined a priori. The inclusion criteria were as follows: 1) articles published in English language OR English translation available; 2) all study design types, including case reports, series, editorial articles; 3) report on a subset of patients with neurologic conditions who required/underwent prone ventilation; and 4) must include the protocol used for prone ventilation. For the purposes of this search and presumed dearth of literature, the only defined exclusion criteria were as follows: 1) nonhuman studies, 2) basic science research, and 3) pediatric patients (< 18 yr old).

Following application of inclusion and exclusion criteria, 18 studies were included for full text screening. Full text screening and application of inclusion and exclusion criteria were performed by two independent reviewers (C.M.L., E.Z.H.), and a third arbiter (J.M.W.) was used for resolution of inclusion conflicts. The reference lists of articles selected for full text review were screened for additional articles for inclusion. Of these articles, 10 met inclusion and exclusion criteria and were included in the final analysis. Quality of Evidence scores for included articles was assessed using the appropriate Joanna Briggs Institute critical appraisal tool for the study design (**Supplementary Table 2**, Supplementary Digital Content 1, http://links.lww.com/CCM/G85) (5). This tool is a systematic, quantitative means of assessing the quality of a manuscript. Unique appraisal tools exist for different study designs.

Generation of Proning Protocol

Through consensus among authors and in combination with review of multi-institutional proning protocols for patients with non-neurologic conditions, a proning protocol for neurologically ill patients and concomitant ARDS was developed. In the absence of scientific consensus or high-quality evidence, consensus opinion for the purposes of this work was determined by simple majority author opinion. There were very few points where dissenting opinions were raised; however, in these instances, the stance was ultimately agreed upon following further in-depth topic-relevant literature review and discussion.

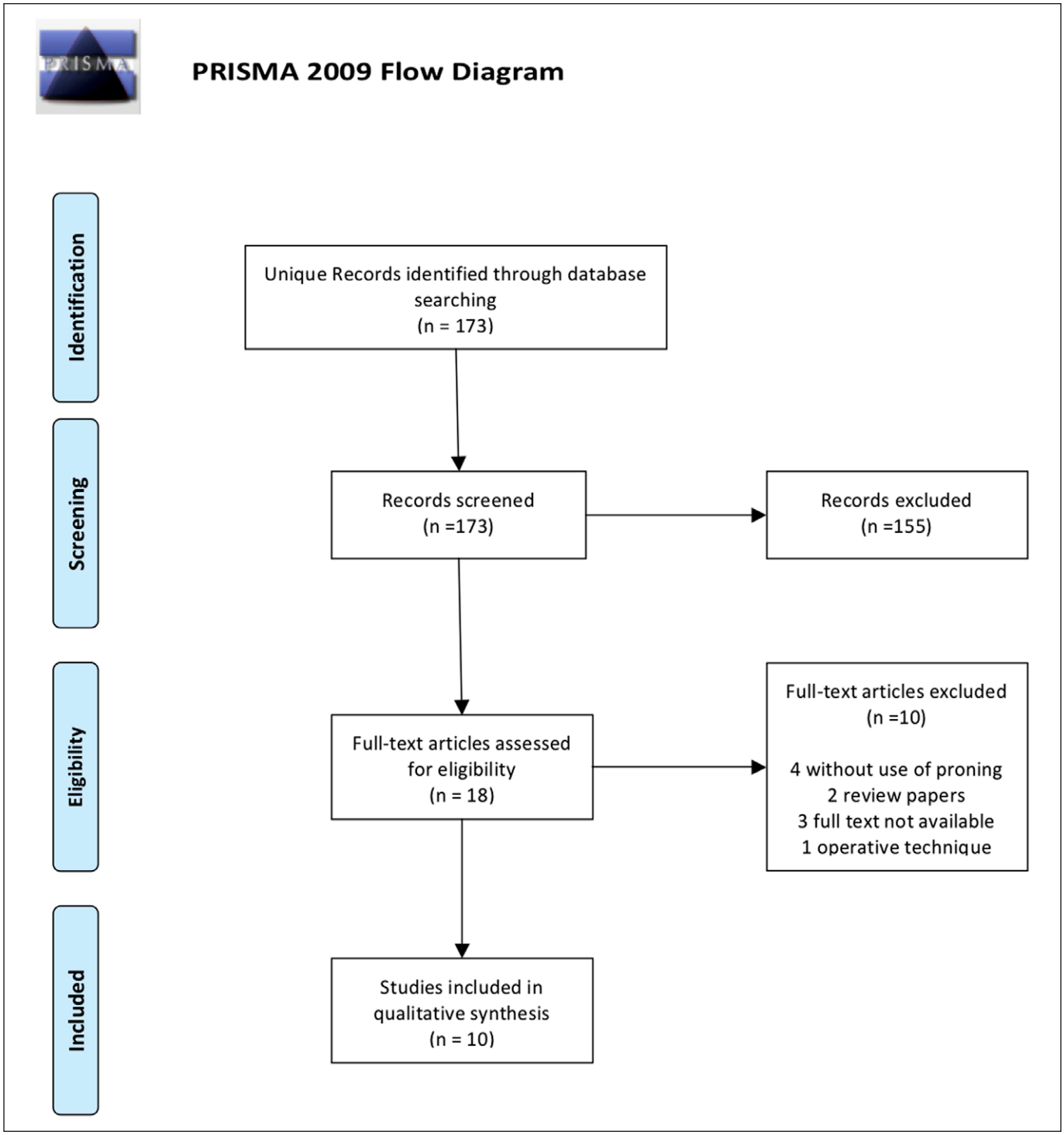

Figure 1. Preferred Reporting Items for Systematic Review and Meta-Analyses (PRISMA) flow diagram representing article screening and inclusion.

RESULTS

Systematic Literature Review

A total of 10 articles were included in final analysis and are outlined in **Table 1**. Study design of those included were one randomized clinical trial, four cohort studies (two retrospective, two prospective), four case reports, and one case series. These studies reported methodology/protocols for prone positioning, as well as changes in secondary measures during prone positioning, such as ICP, CPP, mean arterial pressure (MAP), $Pbto_2$, and Pao_2 (**Table 2**).

TABLE 1.
Summary of Studies Included in This Systematic Literature Review

References	Neurologic Injury	Proning Duration[a]	Proning Modifications	Adjuvant Therapy	Quality of Evidence
Randomized control trial					
Beuret et al (10)	Glasgow Coma Scale score ≦ 9 ($n = 25/51$ proned)	4 hr	Head elevated 20°	None reported	9/13
Cohort studies					
Reinprecht et al (6)	SAH ($n = 19$)	14 hr	Head midline or turned laterally and elevated 15–20°	None reported	8/11
Thelandersson et al (9)	TBI ($n = 6$) ICH ($n = 2$) SAH ($n = 3$)	3 hr	None reported	None reported	8/11
Nekludov et al (7)	TBI ($n = 5$) SAH ($n = 2$) ICH ($n = 1$)	1 hr	Head elevated 10°	Continuous norepinephrine infusion	8/11
Roth et al (8)	SAH ($n = 15$) TBI ($n = 8$) Cardiovascular accident ($n = 6$)	8 hr	Proning angle of 135° used	None reported	8/11
Case series					
Dominguez-Berrot (13)	TBI ($n = 3$)	Case 1: 16 hr Case 2: 6 hr Case 3: 12 hr	None reported	Mannitol for elevated ICP	7/10
Case reports					
Beuret et al (15)	ICH ($n = 1$)	4 hr	None reported	None reported	8/8
Bein et al (10)	Diffuse axonal injury ($n = 1$)	8 hr	Head turned laterally and pillow under right side of thorax	Extracorporeal membrane oxygenation and mannitol for elevated ICP	7/8
Gritti et al (14)	Epidural hematoma and SAH ($n = 1$)	4 hr	Head elevated 15–20°	Inhaled nitric oxide	8/8
Kayani et al (16)	Epidural hematoma and ICH ($n = 1$)	2 d	Helmet worn during proning	None reported	8/8

ICH = intracerebral hemorrhage, ICP = intracranial pressure, SAH = subarachnoid hemorrhage, TBI = traumatic brain injury.
[a]Reported time is consecutive.

TABLE 2.
Baseline Physiologic Data and Changes During Proning

References		Neurologic Injury	Intracranial Pressure (mm Hg)		Cerebral Perfusion Pressure (mm Hg)		Other Reported Data[a]	
			Baseline	Proned	Baseline	Proned	Baseline	Proned
Beuret et al (10)		Glasgow Coma Scale score ≦ 9	11 ± 8.8	23.7 ± 9.6 20.2 ± 5.4	NR	NR	NR	NR
Reinprecht et al (6)		SAH	9.6 ± 3.5	15.8 ± 3.5[b]	74.4 ± 8.4	67.0 ± 7.1[b]	MAP: 82.6 ± 7.6 Pa_{O_2} (torr): 92.9 ± 11.9 Brain tissue oxygenation (torr): 27.2 ± 4.19	83.0 ± 7.0 129.2 ± 24.4[b] 33.5 ± 5.26[b]
Thelandersson et al (9)		TBI, ICH, or SAH	16 ± 6	15 ± 4	78 ± 12	78 ± 13	MAP: 94 ± 15 Heart rate: 67 ± 15	93 ± 13 73 ± 15[b]
Nekludov et al (7)		TBI, ICH, or SAH	12 ± 6	15 ± 4[b]	66 ± 7	73 ± 8[b]	MAP: 78 ± 8	88 ± 8[b]
Roth et al (8)		TBI, SAH, or cardiovascular accident	9.5 ± 5.9	15.4 ± 6.2[b]	82 ± 14.5	80.1 ± 14.1	MAP: 72.6 ± 17.5 PEEP (mbar): 11[c] Pco_2: 43.1[c] P/F: 135.4 ± 43	64.7 ± 17.5[b] 11.1[c] 38.1[b,c] 339.8 ± 93.6[b]
Domínguez-Berrot (13)	Case 1	TBI	15[c]	28[c]	67[c]	66[c]	Pa_{O_2}: 60[c] MAP:82[c] P/F: 60[c]	92[c] 94[c] 115[c]
	Case 2	TBI	19[c]	25[c]	65[c]	62[c]	Pa_{O_2}: 66[c] MAP: 84[c] P/F: 66[c]	66[c] 87[c] 66[c]
	Case 3	TBI	17–18[c]	18–20[c]	70–73[c]	72–80[c]	Pa_{O_2}:57–57.7[c] MAP: 85–90[c] P/F: 57.7–87[c]	61.4–92[c] 88–100[c] 61.4–295[c]
Beuret et al (15)		ICH	27[c]	38[c]	62[c]	55[c]	Pa_{O_2}: 108[c] $Paco_2$: 54[c]	124[c] 53[c]
Bein et al (12)		Diffuse axonal injury	17[c]	18[c]	NR	NR	PEEP (mbar): 16[c] Po_2: 74[c] Pco_2: 32[c]	14[c] 125[c] Pco_2: 35[c]
Gritti et al (14)		Epidural hematoma and SAH	14[c]	14–26[c]	70[c]	60–111[c]	Pa_{O_2}: 123[c] P/F:145[c]	124–303[c] 137–378[c]
Kayani et al (16)		Epidural hematoma and ICH	NR	NR	NR	NR	NR	NR

ICH = intracerebral hemorrhage, MAP = mean arterial pressure, NR = not reported, PEEP = positive end-expiratory pressure, P/F = P_{AO_2}/F_{IO_2} ratio, SAH = subarachnoid hemorrhage, TBI = traumatic brain injury.

[a]Units of mm Hg, unless otherwise stated.

[b]Statistical significance from baseline.

[c]Data for which SDs were not reported.

Data reported for randomized controlled trial and cohort studies are reported as means with SDs (mean ± SD), when possible.

Reinprecht et al (6) performed a retrospective analysis of 19 patients with subarachnoid hemorrhage (SAH) and ARDS who were treated with prone position ventilation. Patients underwent prone ventilation for 16 consecutive hours. During this time period, ICP, CPP, MAP, $Pbto_2$, and Pao_2 were measured. Prone position ventilation resulted in decreased CPP (73–68 mm Hg) and increased ICP (9–15 mm Hg), relative to those measurements in the supine position. ICP measurements exceeded 20 mm Hg more frequently in the prone than in the supine position (18% and 2%, respectively). The authors also reported a significant increase in $Pbto_2$ in the prone position (27–32 mm Hg), which mirrored an increase in Pao_2 (98–127 mm Hg). $Pbto_2$ fell below 20 mm Hg less frequently in the prone position (33% prone, 10% supine).

Nekludov et al (7) performed a prospective analysis of prone positioning in eight patients with SAH ($n = 2$), intracerebral hemorrhage (ICH) ($n = 1$), or traumatic brain injury (TBI) ($n = 5$) and acute lung injury. The authors also reported elevations in ICP in the prone position (15 mm Hg compared with 12 in supine). However, CPP (66 mm Hg supine, 73 mm Hg prone) and MAP (78 mm Hg supine, 88 mm Hg prone) due to their use of continuous norepinephrine infusion to maintain CPP of at least 60 mm Hg.

Roth et al (8) performed a retrospective analysis of 29 patients with acute brain injury and acute lung injury that were treated with a modified prone positioning, where patients were placed at an angle 135 degrees instead of the standard 180-degree prone position. This decrease in rotation was used for easier assessment of neurologic status and yet still resulted in significant improvements in oxygenation (Pao_2/Fio_2 [P/F] ratio increased from 135 to 345). The authors reported a consistent finding of increased ICP in the prone position (9.5–15.4 mm Hg), an increase in frequency of ICP greater than 20 mm Hg (4% vs 17.9%) in the prone position, and a decrease in MAP (72–64 mm Hg). In this subset of patients, no difference was seen in CPP between prone and supine positions; however, patients in the prone position had an increased frequency of CPP less than 70 mm Hg (24.4% vs 17.9%).

Thelandersson et al (9) performed a prospective pilot study of 11 patients with TBI or ICH and acute lung injury. ICP, MAP, CPP, Pao_2, and arterial oxygen saturation were measured before, during, and after patients were placed into the prone position. The authors did not observe significant changes in ICP, CPP, or MAP in this patient subset. Similar to other reports, Pao_2 and arterial oxygen saturation were increased in the prone position.

In a prospective randomized controlled trial performed by Beuret et al (10) prone position ventilation was used for 25 of 51 patients presenting with Glasgow Coma Scale (GCS) score of 9 or lower and a requirement for mechanical ventilation. The other 26 patients included in the study were randomized to supine positioning. Of note, patients with severe hypoxemia, defined as P/F less than or equal to 150, or ICP greater than or equal to 20 were excluded from inclusion in this study which limits the applicability of these findings to the population of patients with severe ARDS. Patients underwent prone position ventilation for 4 hours daily, and the primary study outcome was prevention of a worsened lung injury, as measured by the Lung Injury Score (11). The duration of proning was markedly shorter than what has been considered therapeutic in previous studies (4). ICP monitors were used in 24% of cases ($n = 6$). Frequency of worsened lung injury was significantly reduced in the prone position group compared with the supine position patients (12% vs 50%; relative risk = 4.17; $p = 0.003$). Although ICP was not reliably measured, it was reported to be routinely elevated when patients were placed into the prone position. The authors did note, however, ICP appeared to downtrend over the duration of the 4-hour period of prone positioning.

The remaining five studies consisted of four case reports and one case series, which reported data for a cumulative total of seven patients. Bein et al (12) reported on a patient with SAH and subsequent ARDS who underwent ECMO, followed by intermittent prone positioning. Dominguez-Berrot (13) reported data for three patients with TBI and acute lung injury. Patients in this study received intermittent mannitol for treatment of ICP elevations while in the prone position. Gritti et al (14) described a patient with an epidural hematoma, SAH, and ARDS who received nitrous oxide during prone positioning. Gritti et al (14), Beuret et al (15), Bein et al (12), and Dominguez-Berrot (13) all reported increases in ICP after prone positioning. Beuret et al (15), Gritti et al (14), and Domínguez-Berrot (13) reported inconsistent changes in CPP after prone positioning, whereas CPP measurements were not reported by Bein et al (12). Neither ICP nor CPP measurements were reported by Kayani et al (16).

Proning Protocol for Patients With Neurologic Injury

The interpretation of the cumulative results of the above data indicated is that for patients with neurologic conditions who have failed standard oxygen therapy in a barotrauma protection protocol, prone position ventilation should be considered when indicated in acute lung injury or ARDS. This is defined as acute onset of diffuse, bilateral infiltrates on chest radiograph, or P/F less than or equal to 300 mm Hg, in the absence of evidence of left ventricular failure (clinical evidence or pulmonary artery occlusion pressure ≤ 18 mm Hg) (17, 18). Invasive ICP monitoring mitigates risk of unchecked elevated ICP for patients with reduced intracranial compliance. Specific indications for ICP monitoring are discussed in *Special Considerations for Proning Patients with Neurologic Injury.*

Safety considerations for proning patients can be found in **Supplementary Materials: Safety Considerations for Prone Positioning** (Supplementary Digital Content 2, http://links.lww.com/CCM/G86). Patients may be proned manually on a standard bed, as described in **Supplementary Materials: Procedure for Manual Proning** (Supplementary Digital Content 2, http://links.lww.com/CCM/G86) or with a specialty bed (19), such as the rotoprone therapy system (20). In accordance with published literature supporting improved outcomes in patients who are treated with prone position ventilation, patients receiving this therapy should be placed in the prone position for at least 12 hours consecutively, or as long as tolerated, with data suggesting benefit to proning for as long as 17 hours (4). After this, patients may be returned to the supine position for up to 4 hours prior to reinitiation of proning. Indications for urgent interruption of proning include refractory intracranial hypertension, refractory decrease in $Pbto_2$ to a value less than 20 mm Hg, an inability to maintain CPP greater than 60 mm Hg, a decrease in P/F by 20% when compared with supine position, or any other clinically relevant complications attributable to prone positioning occurring during a prone session. Refractory intracranial hypertension is defined as sustained elevation of ICP to 20 mm Hg or higher for 10–15 minutes that is unresponsive to tiered escalation of ICP-lowering medical management (21). Weaning from mechanical ventilation should be done in the typical fashion.

Contraindications for Proning Patients

Absolute contraindications to prone positioning include spinal instability, an open chest, defined as being within 24 hours of cardiac surgery or having significant chest trauma, and central cannulation for venoarterial ECMO or biventricular assist device support. Relative contraindications include pregnancy, unstable fractures, open abdomen, and hemodynamic instability. Previous guidelines included intracranial hypertension as a relative contraindication for proning; however, these will be addressed in *Special Considerations for Proning Patients with Neurologic Injury.*

Special Considerations for Proning Patients With Neurologic Injury

Data support the ability to perform brainstem reflexes testing when the patient is turned 135°, as opposed to the conventional 180° (8). However, since patients should be at minimum heavily sedated during proning (4), the ability to perform a full neurologic examination is limited. In lieu of frequent neurologic exams, consider liberal criteria for placement of ICP and/or $Pbto_2$ monitors. Continuous monitoring of these variables may serve as an alternative to frequent neurologic examinations; in turn, $Pbto_2$ monitoring may serve as a surrogate marker for lung function (22). Monitor placement is recommended for patients not following commands but with GCS score of greater than 8 prior to initiation of proning and at risk of neurodeterioration.

In the setting of focal mass lesion (i.e., intracranial hemorrhage), prone positioning is recommended only after confirmation of radiographic stability of the hemorrhage. For management of patients with risk of seizure, continuous electroencephalogram in conjunction with sedation/paralytics should be used. Seizure may be treated using aggressive management. All patients in the prone position will be heavily sedated, and benzodiazepines may be used liberally as an adjunct for seizure prevention or treatment.

In cases of elevated ICP, elevations in head of bed, sedation management, avoidance of hypercarbia, blood pressure augmentation, intermittent osmotic diuretics, and cerebrospinal fluid diversion all remain as viable treatment options in the prone position. Early decompressive hemicraniectomy is, in and of itself, not a contraindication for prone positioning.

A report of the clinical course of a patient with concomitant neurologic injury and ARDS is detailed in the **Supplementary Materials: Case Report** (Supplementary Digital Content 2, http://links.lww.com/CCM/G86).

DISCUSSION

There is a paucity of literature from which to create an evidence-based approach to determine acceptable candidates for prone position ventilation for those admitted with neurologic conditions. The majority of published reports that examined treatment-related outcomes and variations in treatment protocols excluded patients with neurologic diagnoses (4, 23, 24). Exclusion of patients with neurologic diagnoses is rooted in literature that supports elevations in ICP and changes in CPP when patients are placed in the prone position (25, 26). Historical exclusion of these patients has resulted in a dearth of neurologic literature to support a proven treatment strategy for prone position ventilation in patients with neurologic injury and ARDS, which has been shown to be an underdiagnosed condition in patients admitted to ICUs (27).

The results of the systematic literature review performed here support the conclusions mentioned above with respect to ICP and CPP. However, although these physiologic changes do often occur, standard medical management of alterations in these physiologic factors may allow for maintenance within the normal range of values. Granted, if the primary medical issue is refractory elevation in ICP in patients who cannot safely undergo surgery, those patients may not be viable candidates for prone ventilation strategies. With regard to the changes in CPP that may be observed, the literature is inconclusive. However, no reports were identified that suggested a decrease in CPP below acceptable thresholds that was not amenable to improvement by medical therapy.

The utilization of ICP monitoring in conjunction with other multimodality monitoring tools (i.e., $Pbto_2$ and cerebral blood flow monitoring) is particularly important in the setting of limited ability to perform neurologic examination. Data from the literature review supported an improvement in systemic oxygenation in the prone position and also an improvement in $Pbto_2$, when measured. Although the clinical relevance of these findings remains uncertain, the implications for this finding could prove useful, pending the results of ongoing clinical trials examining the utility of $Pbto_2$-targeted therapy in TBI (28). If the primary etiology of the patient's poor $Pbto_2$ is poor lung function, then improving ventilation may ultimately prove beneficial by improving the $Pbto_2$.

One significant compromise with placement into the prone position is the loss of frequent and accurate neurologic assessments due to need for heavy sedation and/or paralytic administration. For patients with neurologic conditions who are to undergo prone position ventilation, ICP, CPP, and MAP should be consistently monitored.

Finally, the decision for a patient's eligibility to be proned safely is dynamic. The management of patients with acute brain injury is often complex and rapidly changing. Refractory ICP elevations may be seen early or in a delayed fashion in the course of neurologic injury. These changes must be taken into account and will guide feasibility of safely placing a patient into the prone position. Ultimately, the use of multimodality monitoring should be used in conjunction with other measures of systemic hemodynamic function and oxygenation. Some consideration should be given to utilization of invasive cardiopulmonary monitoring, when applicable, to aid in decision-making with respect to goal-directed therapy.

CONCLUSIONS

Prone position ventilation results in elevations in ICP and may result in compromised CPPs. Clinical trials that examined prone position ventilation for the treatment of ARDS excluded neurologic patients on the basis of these physiologic concerns. The results of this systematic literature review indicate that although these physiologic changes do occur, they may not occur to the degree that would warrant exclusion of prone ventilation as a treatment modality in cases of severe ARDS. A protocol for prone position ventilation and considerations for management of neurologic examinations and multimodality monitoring are outlined herein. The quality or patient-oriented evidence is limited and based off of evidence primarily from cohort studies and case reports. In cases where ICP, CPP, and potentially $Pbto_2$ can be monitored, prone position ventilation should be considered a safe and viable therapy for patients with moderate-to-severe ARDS and concomitant neurologic diagnoses.

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REFERENCES

1. Artigas A, Bernard GR, Carlet J, et al: The American-European Consensus Conference on ARDS, part 2: Ventilatory, pharmacologic, supportive therapy, study design strategies, and issues related to recovery and remodeling. Acute respiratory distress syndrome. *Am J Respir Crit Care Med* 1998; 157(4 Pt 1):1332–1347
2. Ranieri VM, Rubenfeld GD, Thompson BT, et al; ARDS Definition Task Force: Acute respiratory distress syndrome: The Berlin definition. *JAMA* 2012; 307:2526–2533
3. Stevens RD, Lazaridis C, Chalela JA: The role of mechanical ventilation in acute brain injury. *Neurol Clin* 2008; 26:543–563
4. Guérin C, Reignier J, Richard JC, et al; PROSEVA Study Group: Prone positioning in severe acute respiratory distress syndrome. *N Engl J Med* 2013; 368:2159–2168
5. Tufanaru C, Munn Z, Aromataris E, et al: Chapter 3: Systematic reviews of effectiveness *In*: Joanna Briggs Institute Reviewer's Manual. Aromataris E, Munn Z (Eds). The Joanna Briggs Institute, 2017
6. Reinprecht A, Greher M, Wolfsberger S, et al: Prone position in subarachnoid hemorrhage patients with acute respiratory distress syndrome: Effects on cerebral tissue oxygenation and intracranial pressure. *Crit Care Med* 2003; 31:1831–1838
7. Nekludov M, Bellander BM, Mure M: Oxygenation and cerebral perfusion pressure improved in the prone position. *Acta Anaesthesiol Scand* 2006; 50:932–936
8. Roth C, Ferbert A, Deinsberger W, et al: Does prone positioning increase intracranial pressure? A retrospective analysis of patients with acute brain injury and acute respiratory failure. *Neurocrit Care* 2014; 21:186–191
9. Thelandersson A, Cider A, Nellgård B: Prone position in mechanically ventilated patients with reduced intracranial compliance. *Acta Anaesthesiol Scand* 2006; 50:937–941
10. Beuret P, Carton MJ, Nourdine K, et al: Prone position as prevention of lung injury in comatose patients: A prospective, randomized, controlled study. *Intensive Care Med* 2002; 28:564–569
11. Murray JF, Matthay MA, Luce JM, et al: An expanded definition of the adult respiratory distress syndrome [published correction appears in Am Rev Respir Dis 1989 Apr;139(4):1065]. *Am Rev Respir Dis* 1988; 138:720–723
12. Bein T, Kuhr LP, Metz C, et al: ARDS und schweres Schädelhirntrauma. Therapiestrategien im Konflikt [ARDS and severe brain injury. Therapeutic strategies in conflict]. *Anaesthesist* 2002; 51:552–556
13. Dominguez-Berrot AM: Decúbito prono en pacientes con hipertensión endocraneal e insuficiencia respiratoria aguda grave [prone positioning in patients with intracranial hypertension and severe acute respiratory failure]. *Med Intensiva* 2009; 33:403–406
14. Gritti P, Lanterna LA, Re M, et al: The use of inhaled nitric oxide and prone position in an ARDS patient with severe traumatic brain injury during spine stabilization. *J Anesth* 2013; 27:293–297
15. Beuret P, Ghesquieres H, Fol S, et al: Décubitus ventral et pneumopathie sévère chez un patient traumatisé crânien avec hypertension intracrânienne [prone position and severe pneumopathy in a patient with head injuries and intracranial hypertension]. *Ann Fr Anesth Reanim* 2000; 19:617–619

16. Kayani AS, Feldman JP. Prone ventilation in a patient with traumatic brain injury, bifrontal craniectomy and intracranial hypertension. *Trauma* 2015; 17:224–228
17. Ranieri VM, Rubenfeld GD, Thompson BT, et al; ARDS Definition Task Force: Acute respiratory distress syndrome: The Berlin definition. *JAMA* 2012; 307:2526–2533
18. Costa EL, Amato MB: The new definition for acute lung injury and acute respiratory distress syndrome: Is there room for improvement? *Curr Opin Crit Care* 2013; 19:16–23
19. Morata L, Sole M, Guido-Sanz F, et al: Manual versus automatic prone therapy: Impact on patient outcomes. *Crit Care Med* 2018; 46:494
20. Baacke MG, Neubert T, Spies M, et al: Rotoprone®: A new and promising way to prone positioning. *Crit Care* 2002; 6(Suppl 1):P19
21. Matthews L, Barwise J: Refractory intracranial hypertension. *In*: Advanced Perioperative Crisis Management. McEvoy MD, Fuese CM (Eds). Oxford Univeristy Press, 2017
22. Ngwenya LB, Burke JF, Manley GT: Brain tissue oxygen monitoring and the intersection of brain and lung: A comprehensive review. *Respir Care* 2016; 61:1232–1244
23. Blanch L, Mancebo J, Perez M, et al: Short-term effects of prone position in critically ill patients with acute respiratory distress syndrome. *Intensive Care Med* 1997; 23:1033–1039
24. Johannigman JA, Davis K Jr, Miller SL, et al: Prone positioning for acute respiratory distress syndrome in the surgical intensive care unit: Who, when, and how long? *Surgery* 2000; 128:708–716
25. Stocchetti N, Rossi S, Buzzi F, et al: Intracranial hypertension in head injury: Management and results. *Intensive Care Med* 1999; 25:371–376
26. Ng I, Lim J, Wong HB: Effects of head posture on cerebral hemodynamics: Its influences on intracranial pressure, cerebral perfusion pressure, and cerebral oxygenation. *Neurosurgery* 2004; 54:593–597
27. Bellani G, Laffey JG, Pham T, et al: Epidemiology, patterns of care, and mortality for patients with acute respiratory distress syndrome in intensive care units in 50 countries [published correction appears in JAMA. 2016 Jul 19;316(3):350] [published correction appears in JAMA. 2016 Jul 19;316(3):350]. *JAMA* 2016; 315:788–800
28. Okonkwo DO, Shutter LA, Moore C, et al: Brain oxygen optimization in severe traumatic brain injury phase-II: A phase II randomized trial. *Crit Care Med* 2017; 45:1907–1914