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EDITOR'S CHOICE

Neonatal Magnetic Resonance Imaging Without Sedation Correlates With Injury Severity in Brachial Plexus Birth Palsy

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Jennifer Moriatis Wolf, MD, has no relevant conflicts of interest to disclose.

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Learning Objectives

Upon completion of this CME activity, the learner should achieve an understanding of:

- The evaluation of injury using magnetic resonance imaging (MRI) in neonates with brachial plexus palsy
- The need for predictive imaging for decision making in observation versus surgery for treatment
- What the severity of injury portends for future treatment in neonatal brachial plexus palsy

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Purpose Which infants with brachial plexus birth palsy (BPBP) should undergo microsurgical plexus reconstruction remains controversial. The current gold standard for the decision for plexus reconstruction is serial clinical examinations, but this approach obviates the possibility of early surgical treatment. We hypothesize that a new technique using 3-dimensional volumetric proton density magnetic resonance imaging (MRI) without sedation can evaluate the severity of BPBP injury earlier than serial clinical examinations.

Methods Infants were prospectively enrolled prior to 12 weeks of age and imaged using 3 Tesla MRI without sedation. Clinical scores were collected at all visits. The imaging findings were graded based on the number of injured levels and the severity of each injury, and a radiological score was calculated. All infants were followed at least until the decision for surgery was made based on clinical examination.

Results Nine infants completed the MRI scan and clinical follow-up. The average Toronto score at presentation was 4.4 out of 10 (range, 0–8.2); the average Active Movement Scale score was 50 out of 105 (range, 0–86). Four infants required surgery: 2 because of a flail limb and Horner syndrome and 2 owing to failure to recover antigravity elbow flexion by age 6 months. Radiological scores ranged from 0 to 18 out of a maximum score of 25. The average radiological score for those infants who required surgery was 12 (range, 6.5–18), whereas the average score for infants who did not require surgery was 3.5 (range, 0–8).

Conclusions Three-dimensional proton density MRI can evaluate spinal nerve roots in infants without the need for radiation, contrast agents, or sedation. These data suggest that MRI can help determine the severity of injury earlier than clinical examination in infants with BPBP, although further study of a larger sample of infants with varying severity of disease is necessary. *(J Hand Surg Am. 2017;42(5):335–343. Copyright © 2017 by the American Society for Surgery of the Hand. All rights reserved.)*

Type of study/level of evidence Diagnostic II.

Key words Brachial plexus birth palsy, MRI, neonatal brachial plexus palsy, obstetric brachial plexus palsy.

Which newborns with brachial plexus birth palsy (BPBP) would best be served by microsurgical exploration and plexus reconstruction has been a difficult question to answer without reliable objective tests to guide decision making. The surgeon must balance the fact that 70% to 90% of infants with BPBP will recover spontaneously, with the knowledge that earlier nerve repair is likely to lead to improved outcomes for those infants who do require surgery.[1–3] The benefit of early stratification of these groups would be 2-fold: first, those injuries that do require surgery could be repaired as soon as possible, and second, families of the majority of infants who will make a good recovery could have that information early on and be spared months of worry.

For adults with traumatic brachial plexus injuries, a fairly clear algorithm has been developed to guide treatment.[4–6] Adults can participate in clinical examinations of strength and sensation, and ancillary tests such as magnetic resonance imaging (MRI), electromyography, and myelography have been shown to have good predictive capacity.[7–11] Infants with BPBP, however, cannot participate well in clinical examinations, and the tests used in adults are fraught with difficulty. Electromyography and nerve conduction studies have been called "overly optimistic" in infants.[12] Various explanations have been given for this, including different innervation patterns of the infants' musculature.[13,14] Computed tomography (CT) myelography, which involves general anesthesia, a lumbar puncture, and radiation, has been shown to have high specificity for nerve root avulsion when pseudomeningoceles are seen.[15] A recent evaluation of magnetic resonance myelography found that it had a similar specificity for avulsed nerve roots as for CT myelography.[16] However, the sensitivity of both techniques remains low, and neither can evaluate infants with postganglionic neurotmesis due to poor soft tissue contrast. Furthermore, both magnetic resonance and CT myelography in infants require general anesthesia owing to the long examination times.

The current reference standard for evaluating severity in BPBP is the clinical examination repeated

ACTIVE MOVEMENT SCALE
EVALUATION FORM

Involved side: L R		Date:							
		Therapist Initials:							
Shoulder	Flexion C5-6								
	Abduction C5-6								
	Adduction C5-7								
	Internal Rot. C5-T1								
	External Rot. C5-6								
Elbow	Flexion C5-6								
	Extension C7								
Forearm	Pronation C6-T1								
	Supination C5-6								
Wrist	Flexion C7								
	Extension C6								
Finger	Flexion C8								
	Extension C7								
Thumb	Flexion C8								
	Extension C7								

Observation		Muscle Grade
Gravity Eliminated	No Contraction	0
	Contraction, no motion	1
	Motion 0-50%	2
	Motion 51%-full	3
	Full Motion	4
Against Gravity	Motion 0-50%	5
	Motion 51%-full	6
	Full Motion	7

GUIDELINES:

- A score of 4 *must* be achieved before a higher score can be given.
- Movement is assessed *within* available passive and age-appropriate range.
- Digit extension is assessed at the MP joints.
- Finger flexion is assessed by fingertips to DPC with a single grade for the best digit.

A

Toronto Score	Clinical Grade	Numerical Score
Elbow flexion:	___	___.___
Elbow extension:	___	___.___
Wrist extension:	___	___.___
Finger extension:	___	___.___
Thumb extension:	___	___.___
Total score:		___ ___.___

Toronto Score Grading System

Observation	Clinical Grade	Numerical Score
No joint movement	0	**0**
- Flicker of movement	0+	**0.3**
- Less than 50% range	1−	**0.6**
50% range of movement	1	**1.0**
- More than 50% range	1+	**1.3**
- Good but not full range	2−	**1.6**
Full range of movement	2	**2.0**

B

FIGURE 1: Worksheets used to document the **A** AMS and **B** Toronto test scores.

over several months. At our institution, the Active Movement Scale (AMS) and the Toronto Test Score are used for this evaluation[17,18] (Fig. 1). It is generally accepted that infants with global injuries and nerve root avulsions should undergo surgery by 3 months of age.[3,19] However, there is controversy regarding which infants with upper trunk injuries would benefit from surgery, with recommendations for considering biceps recovery to have failed ranging between 3 and 6 months.[2,3] Ultimately, this controversy stems from the fact that the infant's recovery pattern over time is used to differentiate between

TABLE 1. Narakas Classification of Brachial Plexus Birth Injury

Grade	Description
I	C5−6 injury
II	C5−7 injury
III	Global plexus injury
IV	Global plexus injury with Horner syndrome

types of nerve injuries. Earlier diagnosis of the specific pattern of injury might make this clearer.

We have developed an imaging protocol of 3-dimensional volumetric proton density (PD) MRI that can be performed without sedation in infants. This technique involves no radiation, no contrast, and no anesthetic risk. The hypothesis of this study was that this new MRI sequence can evaluate the severity of BPBP injury earlier than serial clinical examinations.

MATERIALS AND METHODS

Subjects

Infants who presented to our BPBP clinic prior to 12 weeks of age were eligible for enrollment once the diagnosis of BPBP was confirmed through history and physical examination. Infants older than 12 weeks of age were excluded. By limiting the study to infants 12 weeks and younger, we hoped to capture those who would be easiest to swaddle (and thus comply with the MRI protocol), as well as those who would benefit most from the information given by early MRI. Informed consent and HIPAA consent was obtained from the legal guardians of all participants. This research was approved by the Institutional Review Board of the University of California Davis Medical Center and the study protocol conformed to the 1975 Declaration of Helsinki. Subjects were excluded after enrollment if they were unable to complete the MRI scan owing to excessive movement. All subjects were followed at least until the decision on whether to proceed with microsurgery was made.

Demographic data, birth history, and Narakas type[20] (Table 1) were collected during the enrollment visit. Toronto and AMS score data were collected prospectively at the enrollment visit and all subsequent routine clinic visits. It is our practice to follow infants monthly until 6 months of age or until a decision for surgery is made, then every 2 to 3 months until 1 year of age depending on the infant's recovery. After 1 year of age, the progression of clinic visits varies based on the severity of the child's injury. Toronto and AMS scores are routinely collected at

FIGURE 2: Infant mannequin positioned in the MedVac Immobilizer.

each visit. The decision for surgery in this study was made by the same surgeon (A.S.B.) who also performed all of the surgeries. Surgery was considered indicated for subjects with a flail arm and Horner syndrome at 3 months and for subjects with an upper trunk injury if they failed to demonstrate antigravity elbow flexion (AMS $\geq$ 5) by 6 months. For those infants in the study who underwent microsurgical plexus exploration, the status of each nerve root was recorded as intact, postganglionic rupture, or preganglionic avulsion by the operating surgeon (A.S.B.). This status was determined based on the intraoperative appearance of the nerve root as well as intraoperative somatosensory evoked potential (SSEP) testing as follows: avulsed (no repeatable response with maximal stimulation), ruptured (repeatable response to SSEPs but without distal motor function), or intact (repeatable response to SSEPs with distal motor function). If there was disagreement between the surgeon's clinical judgment and the SSEP readings, the surgeon's overall judgment took precedence.

MRI protocol

Families were given instructions prior to their MRI appointment to keep their child awake prior to the

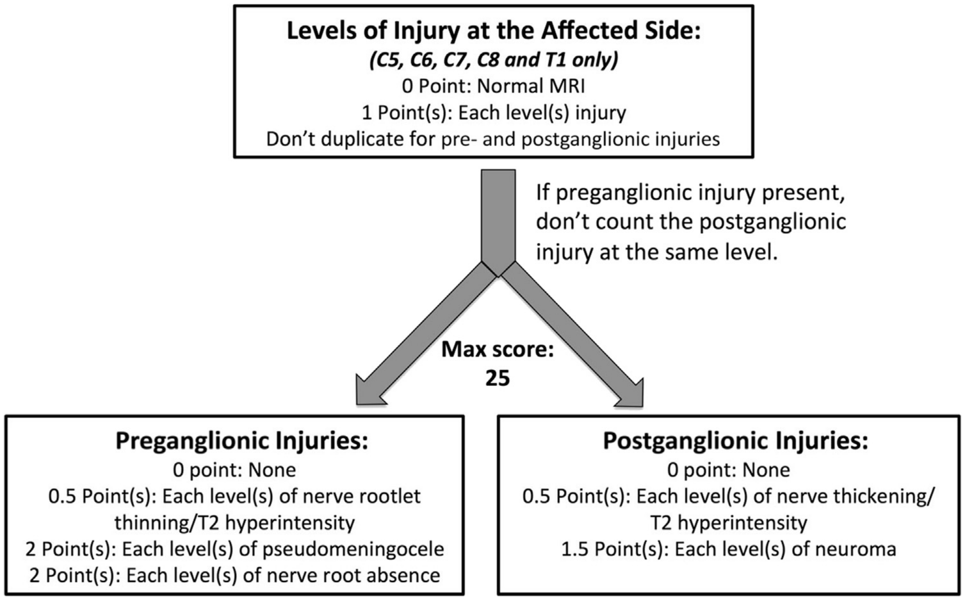

FIGURE 3: Flowsheet used to assign the radiological score.

examination and to feed them within 30 minutes of the examination to increase the chance of the baby sleeping during the examination time. Each infant was positioned in the 3 Tesla MRI scanner (GE Healthcare, Waukesha, WI) using a vacuum suction−controlled infant positioner, the MedVac Immobilizer (CFI Medical, Fenton, MI)[21] (Fig. 2). The MRI scanning protocol was composed of a localizer sequence followed by standard sagittal T2 sequence and 3-dimensional PD coronal sequences oriented in the plane of the cervical spine and extended outward to include the involved brachial plexus. The total scanning was approximately 8 minutes excluding setup time with the MedVac Immobilizer, of which the localizer, sagittal T2, and coronal 3-dimensional PD sequences were each 1 minute, 3.4 minutes, and 3.5 minutes, respectively. Each subject's MRI scan was reviewed independently by 3 attending neuroradiologists (P.Y.S., A.E.N., and P.S.L.) using a custom radiological scoring system, the Shriners Radiologic Score (SRS) (Fig. 3).[22] Using this system, each injured level was first assigned 1 point. Additional points were then assigned based on the location (pre- vs postganglionic) and severity of the injury. If the zone of injury included both the pre- and the postganglionic regions, only the preganglionic injury was scored. The total possible radiological score ranges from 0 points (no MRI findings) to a maximum of 25 points (all 5 levels with preganglionic pseudomeningoceles and absent nerve rootlets). The operating surgeon (A.S.B.) was not aware of the radiological scores until after completion of the study.

Statistical methods

Two-sample Wilcoxon tests were used to compare the SRS scores for the surgical versus nonsurgical groups as well as the AMS and Toronto scores of the same groups. Spearman correlations were used to compare the radiological and clinical scores to each other.

RESULTS

Sixteen subjects with initial appointments at our BPBP clinic prior to 12 weeks of age were eligible for enrollment, and 13 of these families agreed to participate. Four infants were not able to complete the MRI scan owing to excessive motion. These infants were aged 5, 8, 11, and 12 weeks at the time of the examination. The first infant, age 5 weeks, was enrolled prior to availability of the MedVac Immobilizer and was unable to complete the MRI protocol owing to motion. The other infants who failed testing were positioned in the MedVac Immobilizer but were still able to move too much to capture usable images. This left 9 subjects with usable data.

Clinical results

Study subjects were 4 boys and 5 girls, with an average age of 5 weeks at enrollment (range, 3−9 weeks). The left arm was injured in 5 subjects. There were 3 Narakas type 1, 4 Narakas type 2, and 2 Narakas type 4 injuries. The average Toronto score at presentation was 4.4 out of 10 (range, 0−8.2); the average total AMS score at presentation was 50 out of 105 (range,

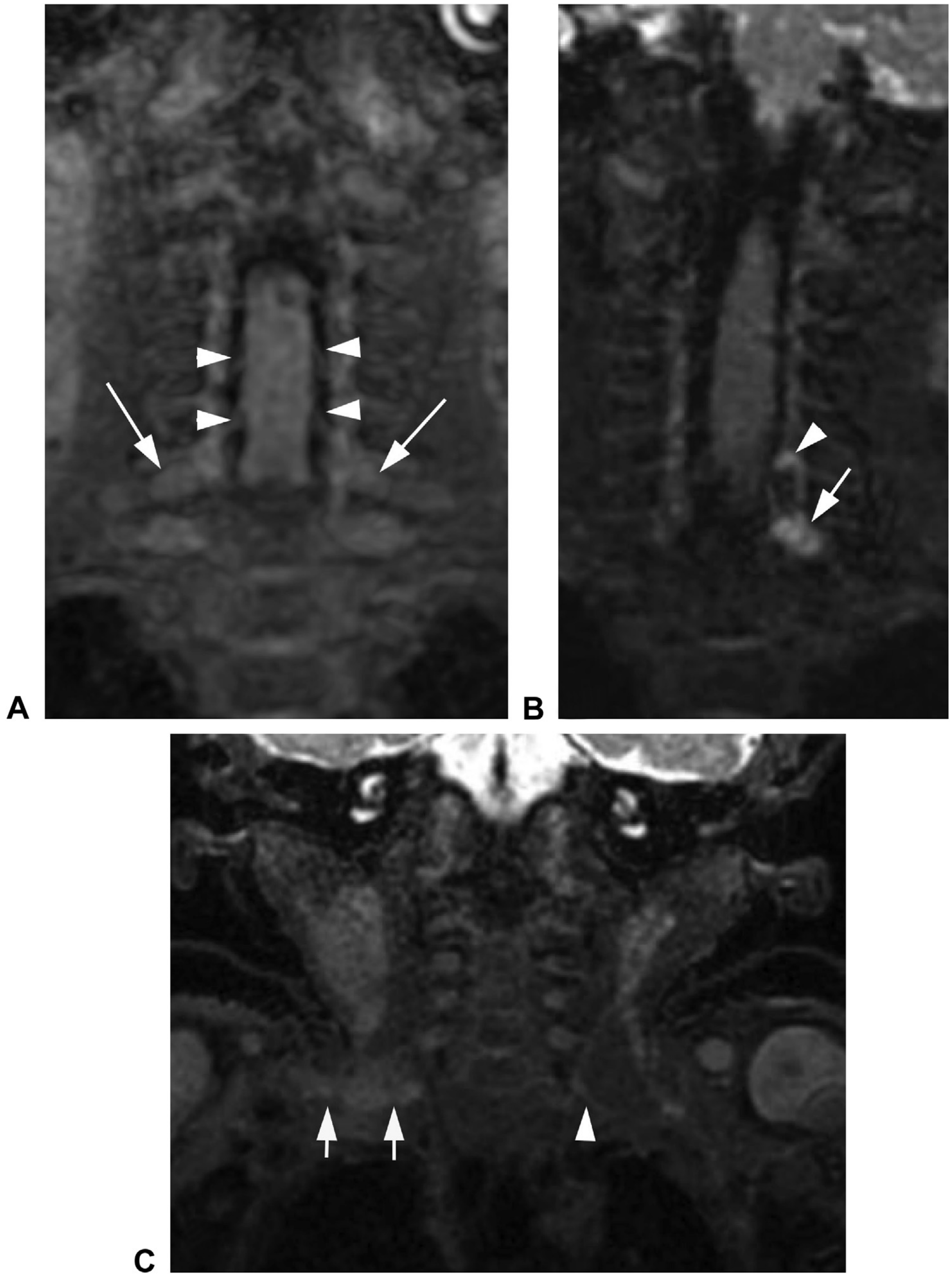

FIGURE 4: Representative examples of typical MRI finding using the coronal 3-dimensional PD MRI sequence. **A** Normal preganglionic nerve roots (arrowheads) and a normal dorsal root ganglion (arrows). **B** Left C7 (arrowhead) and C8 (arrow) pseudomeningoceles and avulsed nerve roots. **C** Right C5 and C6 nerve postganglionic ruptures with neuromas at the trunk level (arrows), with normal left C6 postganglionic nerve appearance (arrowhead).

0–86). All subjects were scheduled for follow-up every 4 weeks from the date of enrollment until 6 months of age or until the decision for or against surgery could be made. Two subjects were lost to follow-up between 2 and 5 months of age and then returned; all others kept their monthly appointments. Four of 9 infants in this study ultimately required microsurgery based on the indications of a flail limb and Horner syndrome in 2 infants and failure to recover antigravity elbow flexion by 6 months of age with an upper trunk injury in 2 infants. The other 5 infants did not meet these indications.

Surgical decisions were made solely based on the results of serial clinical examinations. The surgeon (A.S.B.) did not know the radiological score for each infant at the time of surgical decision making.

Imaging results

The MRI sequence allowed visualization of preganglionic pseudomeningoceles with and without nerve

TABLE 2. Clinical Versus MRI Findings for Patients Indicated for Surgery

Subject*	Narakas	Age at Enrollment (wk)	Enrollment AMS EF	Enrollment Toronto	MRI SRS	3-Mo AMS EF	3-Mo Toronto	Preoperative AMS EF	Preoperative Toronto	Surgical Findings
2	2	5	2	6.4	6.5	2	6.4	2	7.5	C5 and C6 avulsions
3	1	4	2	6.3	9.5	2	4.9	2	6.6	C5 and C6 rupture
4	4	6	0	0	18	1	0.3	1	0.3	C5, C7, C8, T1 avulsion; C6 rupture
7	4	3	0	0	14	2	0.6	2	0.6	C5, C6 rupture; C7, C8 avulsion

AMS EF, 0−7 scale; SRS, 0−25 scale.

*Subject numbers 1, 8, 11, and 12 were unable to complete the MRI due to motion and so were excluded from the study.

TABLE 3. Clinical Versus MRI Findings for Patients not Indicated for Surgery

Subject*	Narakas	Age at Enrollment (wk)	Enrollment AMS EF	Enrollment Toronto	MRI SRS	3-Mo AMS EF	3-Mo Toronto	5-Mo AMS EF	5-Mo Toronto
5	2	5	2	1.2	3	1	3.8	3	6.5
6	2	4	7	5.9	0	7	9.6	7	10
9	1	3	2	8.2	0	6	9.6	6	9.6
10	1	4	2	6.9	6.5	2	8.6	5	9.3
13	2	9	1	4.9	8	5	8.6	5	9.3

AMS EF, 0−7 scale; SRS, 0−25 scale.

*Subject numbers 1, 8, 11, and 12 were unable to complete the MRI due to motion and so were excluded from the study.

rootlet avulsion, postganglionic neuromas, and nerve root thickening (Fig. 4). For the infants who required surgery, the average radiological score was 12 (range, 6.5−18), whereas the average score for infants who did not require surgery was 3.5 (range, 0−8). The mean SRS scores for the surgery versus no surgery groups were significantly different ($P < .05$), although there was some overlap in scores between the 2 groups. Active Movement Scale for elbow flexion (EF) and Toronto scores at enrollment were similar between the 2 groups. At 3 months of age, neither the Toronto score nor the AMS EF differentiated between the surgical and the nonsurgical groups ($P = .064$ and 0.248, respectively), although it is possible the Toronto score would have reached significance with a larger study group. The imaging scores as well as clinical scores at various time points are listed in Tables 2 and 3.

Spearman correlations demonstrated that the SRS was correlated with the AMS EF score at enrollment (−0.83; $P < .05$) but not at 3 months of age (−0.56; $P = .12$). Conversely, the SRS was correlated with Toronto scores at 3 months of age (−0.79; $P < .05$) but not at enrollment (−0.61; $P = .083$).

DISCUSSION

We present here the results of a pilot study using a new 3-dimensional PD MRI protocol to delineate the severity of BPBP early in infancy without the need for radiation or sedation. Early MRI may prove to be an improvement on the Toronto score (used at 3 months of age) or the AMS EF score (used at 5−6 months of age) for 2 reasons. First, the early MRI has the potential to differentiate severely affected infants in the first weeks of life, before either score can be applied. Second, the Toronto score at 3 months of age cannot identify the infant with a severe C5 and C6 injury but normal lower roots who will go on to require surgery based on the failure of antigravity biceps function at 6 months of age.

This study has several limitations. First, this is a pilot study with few subjects. Further prospective study is required to validate the radiological score on a larger scale as well as determine whether this scoring system can assist surgeons in decision making when determining the indications for microsurgery in an infant with BPBP. A larger study sample may be able to establish a threshold radiological score that would help determine the need for surgery as well as establish the sensitivity and specificity of the imaging findings. Second, because only 4 of our 9 subjects went on to surgery, our numbers were too small to evaluate the correlation between MRI findings and intraoperative findings; future study is needed on this topic. Finally, in this study, we used the surgeon's decision, using available clinical data, to determine the indication for surgery. Bias was minimized because decisions for surgery were made using commonly accepted clinical standards, without knowledge of the radiological score. Further study is needed to determine the generalizability of this approach.

The decisions surrounding surgery for infants with BPBP are complex because clinical examination is used to infer which levels of the plexus are injured and what is their likelihood of spontaneous recovery. Early 3-dimensional PD MRI of the rootlets and plexus enables visualization of the actual injury without sedation, contrast, or radiation, potentially enabling an earlier determination of which injuries are not likely to recover spontaneously. The benefits of early stratification include the potential for earlier surgery for those who need it as well as fewer clinic visits and less worry for families whose children are likely to recover spontaneously.

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JOURNAL CME QUESTIONS

Neonatal Magnetic Resonance Imaging Without Sedation Correlates With Injury Severity in Brachial Plexus Birth Palsy

1. Neonates with brachial plexus birth palsy (BPBP) with nerve root avulsions are generally recommended to undergo surgical exploration at which age?

   a. 2 weeks old
   b. 1 month old
   c. 2 months old
   d. 3 months old
   e. 6 months old

2. The difference in Narakas classificatiions I and II is based on:

   a. C7 function
   b. C6 function
   c. C5 function
   d. Presence or absence of Horner’s sign
   e. Presence or absence of pneumothorax

3. Imaging the brachial plexus and neck with magnetic resonance imaging (MRI) in infants took approximately:

   a. 2 minutes
   b. 8 minutes
   c. 15 minutes
   d. 30 minutes
   e. 1 hour

4. This study demonstrated that MRI:

   a. Can accurately predict time to recovery from BPBP
   b. Correlated well with Toronto and Active Movement Scale (AMS) scores
   c. Improves ability to identify muscle weakness
   d. Provides advanced imaging
   e. Improves pain due to direct opioid receptor binding after surgery

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