The relationship between Chiari 1.5 malformation and sleep-related breathing disorders on polysomnography

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OBJECTIVE Chiari 1.5 malformation is a subgroup of the Chiari malformation in which tonsillar descent into the foramen magnum is accompanied by brainstem descent. No data exist on whether operative decompression in patients with Chiari 1.5 improves sleep-related breathing disorders (SRBDs) and whether there are radiological parameters predicting improvement.

METHODS The authors performed a retrospective cohort study of consecutive pediatric patients with Chiari 1.5 malformation and SRBDs at the Alberta Children's Hospital. An SRBD was characterized using nocturnal polysomnography (PSG), specifically with the apnea-hypopnea index (AHI), the obstructive apnea index, and the central apnea index. Preoperative values for each of these indices were compared to those following surgical decompression. The authors also compared preoperative radiographic factors as predictors to both preoperative AHI and the change in AHI with surgery. Radiological factors included tonsillar and obex descent beneath the basion–opisthion line, the presence of syringomyelia, the frontooccipital horn ratio, the pB–C2 line, and the clivoaxial angle.

RESULTS Seven patients (5 males, 2 females) met inclusion criteria. One patient had two surgical decompressions, each with pre- and postoperative PSG studies ($n = 8$). The median age was 9 years. Before surgical decompression, 75% underwent tonsillectomy/adenoidectomy. The majority (87.5%) experienced snoring/witnessed apnea preoperatively. The median tonsillar and obex descent values were 21.3 mm and 11.2 mm, respectively. The median values for the pB–C2 line and clivoaxial angle were 5.4 mm (interquartile range [IQR] 4.5 mm, 6.8 mm) and 144° (IQR 139° , 167°), respectively. There was a statistically significant change from preoperative to postoperative AHI (19.7 vs 5.1 , $p = 0.015$) and obstructive apnea index (4.5 vs 1.0 , $p = 0.01$). There was no significant change in the central apnea index with surgery (0.9 vs 0.3 , $p = 0.12$). No radiological factors were statistically significant in predicting preoperative AHI and change in AHI.

CONCLUSIONS This is the first series of pediatric patients with Chiari 1.5 with SRBDs who demonstrated a marked improvement in their PSG results postdecompression. Sleep apnea has a significant impact on learning and development in children, highlighting the urgency to recognize Chiari 1.5 as a more severe form of the Chiari I malformation.

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KEYWORDS Chiari 1.5 malformation; pediatric; sleep-related breathing disorders; surgical decompression

SLEEP-RELATED breathing disorders (SRBDs) are a spectrum of disorders that are obstructive, central, and mixed in etiology.¹ SRBDs in the pediatric population have several deleterious sequelae, such as delayed growth and development, as well as adverse cognitive and behavioral effects.² It has been suggested that childhood sleep apnea is associated with a 10-point decline in IQ

relative to healthy children.³ These drastic effects can be prevented with early diagnosis and treatment in children.⁴

One of the more recently recognized and less common etiologies of SRBDs is the Chiari malformation. Chiari malformations encompass a series of hindbrain malformations that vary in their clinical severity.⁵ The most common is the Chiari I malformation, which is defined

ABBREVIATIONS ACH = Alberta Children's Hospital; AHI = apnea-hypopnea index; Δ AHI = change in AHI; CAI = central apnea index; CN = cranial nerve; CSA = central sleep apnea; CXA = clivoaxial angle; FOHR = frontooccipital horn ratio; IQR = interquartile range; OAI = obstructive apnea index; OSA = obstructive sleep apnea; PSG = polysomnography; SRBD = sleep-related breathing disorder.

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as descent of the cerebellar tonsils into the foramen magnum and requires a cerebellar tonsil descent of 5 mm or greater.⁶ Chiari 1.5 malformation is a more recently defined subgroup, in which the descent of the tonsils into the foramen magnum is accompanied by descent of the medulla structure.⁷ Chiari 1.5 has been shown to have a more progressive disease course compared with its Chiari I counterpart.⁷ Specifically, these children more frequently present with bulbar symptoms and are at an increased risk of needing an occipitocervical fusion.⁸ There have been no studies examining pediatric patients with Chiari 1.5 malformation who have SRBDs, and whether surgical decompression improves their polysomnography (PSG) results or clinical manifestations of sleep apnea.

Previous studies have described the association of Chiari malformations and SRBDs, but with a focus on the Chiari I malformation.^{9–16} In patients with Chiari I malformations, there have been case reports and small retrospective studies showing the success of surgical decompression in improving SRBDs.^{12–14,17–19} The exact etiology of obstructive sleep apnea (OSA) and central sleep apnea (CSA) in Chiari malformations has not been clearly elucidated. It has been suggested that OSA may be caused by compression of cranial nerves (CNs) IX and X by the cerebellar tonsils. In terms of CSA, multiple theories have been proposed, including compression of the medulla respiratory centers and the reticular activating system, as well as an effect on afferent input from the carotid bodies.⁶ We hypothesized that surgical decompression would relieve pressure on the lower CNs and brainstem, improving OSA and CSA.

At this time, there are no specific guidelines as to when children with Chiari malformations should undergo PSG.⁶ Conversely, there are no guidelines specifying when a child with SRBD symptoms should receive MRI to assess for a Chiari malformation.^{12,18}

The objectives of this study were to determine if operative decompression of Chiari 1.5 malformations in pediatric patients quantitatively improved SRBDs and to determine if there may be radiological factors that may predict this response as well as the SRBD symptomatology itself.

Methods

Patient Selection

The design was a retrospective cohort study of consecutive pediatric patients presenting with a Chiari 1.5 malformation and SRBDs at Alberta Children's Hospital (ACH). The ACH operative database was examined for cases treated between January 2011 and February 2016. The inclusion criteria were age younger than 18 years, a diagnosis of a Chiari 1.5 malformation, both pre- and postoperative sleep studies with an SRBD diagnosis, and patients having undergone a posterior fossa decompression. The operative technique was a suboccipital craniectomy with C1 arch removal, tonsillectomy, and expansile duraplasty. However, with the patient who had two decompressions, the second surgery included removal of scar tissue, removal of regrowth of C1 and part of C2, and no duraplasty. Demographic and clinical data were abstracted and analyzed. These included age at presentation in years,

sex, race (separated into White and other), date of surgery, prior adenotonsillectomy surgery, presenting complaints and symptomatology (including headache, developmental delay, snoring, gasping, mouth breathing, and witnessed apnea), and neurological deficits such as cranial neuropathies and focal weakness.

Overnight Sleep Study Parameters

PSG studies were recorded either as having been requested by neurosurgery or as a precursor to neurosurgery consultation. Patients received nocturnal PSG studies before and after surgery, following the guidelines set by the American Academy of Sleep Medicine. The baseline preoperative sleep studies were completed after the adenotonsillectomy in each patient. Following the American Academy of Sleep Medicine guidelines, the apnea-hypopnea index (AHI) is defined as the number of apneas and hypopneas per hour of sleep time.²⁰ An AHI of 1.5 or more events per hour is considered abnormal in children.²¹ Although there are no clear guidelines on OSA severity in children, an AHI of greater than 1 to 5 events per hour is suggestive of mild OSA, an AHI of greater than 5 to 10 events per hour is suggestive of moderate OSA, and an AHI greater than 10 is suggestive of severe OSA.^{22,23}

The obstructive apnea index (OAI) is the number of obstructive apneas per hour of sleep time. Finally, the central apnea index (CAI) is the number of central apneas per hour of sleep time.²⁰ Sleep efficiency refers to the percentage of time spent in sleep. It is calculated by the total time spent in stage N1, stage N2, stage N3, and REM sleep divided by the total time spent in bed multiplied by 100. Minimum oxygen saturations were recorded from continuous monitoring of arterial oxyhemoglobin saturation. Finally, peak transcutaneous CO₂ measurements were also acquired, and these represent the skin-surface partial pressure of CO₂. This is a noninvasive estimate of the partial pressure of arterial CO₂.²⁰

Radiographic Factors

All children underwent the same MRI protocol at ACH. T1-weighted and T2-weighted axial and sagittal images of the brain and spinal cord were examined. The Chiari 1.5 malformation was defined as brainstem herniation (obex below the foramen magnum) in concert with tonsillar herniation greater than 5 mm (Fig. 1A and B).⁷ The presence of a syrinx was noted for each patient. The frontooccipital horn ratio (FOHR) was calculated for each patient and is the maximum frontal horn diameter plus the maximum occipital horn diameter divided by two times the biparietal diameter.²⁴

The pB–C2 line developed by Grabb et al.²⁵ is a radiographic factor used to evaluate ventral brainstem compression indirectly. The pB–C2 was treated as a continuous variable, using a line drawn from the basion to the inferior-posterior aspect of the vertebral body of C2 (B–C2), and another line is drawn perpendicular through the tip of the odontoid to the ventral dura mater (pB–C2). A distance between these two lines greater than or equal to 9 mm is suggestive of ventral brainstem compression (Fig. 1C).

The clivoaxial angle (CXA) is formed by a line drawn

FIG. 1. Midsagittal T1-weighted MR images obtained in a patient with a Chiari 1.5 malformation. Tonsillar (A) and obex (B) herniation can be seen through the foramen magnum. Ventral brainstem compression was evaluated using the pB–C2 line (C) and CXA (D).

along the posterior surface of the body of the axis and odontoid process intersecting with the clival basilar line (Fig. 1D). An angle of less than 150° is suggestive of possible ventral brainstem compression.²⁶ For the analysis, the CXA was treated as a continuous variable.

Statistical Analyses

Continuous variables were reported as medians with interquartile ranges (IQRs) due to the small sample size. Categorical variables were reported as frequencies and percentages. In the primary analysis, preoperative PSG parameters (AHI, OAI, and CAI) were compared to their postoperative counterparts by using the Mann-Whitney U-test, assuming nonparametric distributions with our small sample sizes. In the secondary analysis, preoperative radiological parameters were compared to both the preoperative AHI and the change in AHI (Δ AHI) between pre- and postoperative testing—each using Spearman's rank correlation coefficient test. Due to the small sample size, these secondary analyses were a priori considered as hypothesis generating only. A p value < 0.05 was considered statistically significant. All analyses were conducted using SAS (version 9.4, SAS Institute). This study had eth-

ics approval from the Conjoint Health Research Ethics Board at the University of Calgary.

Results

Patient Group

Seven patients who met inclusion criteria were identified. All patients with Chiari 1.5 malformations identified at our institution had pre- and postoperative PSG sessions during this time period and were included in this study. One patient had two surgical decompressions with preoperative and postoperative PSG ($n = 8$ procedures). All patients had a posterior fossa decompression with a C1 laminectomy, tonsillopexy, and duraplasty, and the patient who had the two decompressions had removal of scar tissue and removal of regrowth of C1 and part of C2 with no duraplasty for his second surgery.

Clinical and Demographic Characteristics

Table 1 outlines the demographic and clinical characteristics of the patient group. Four patients were referred to neurosurgery with existing sleep studies in which SRBD had already been diagnosed. In the other 3 patients, sleep studies were ordered by neurosurgery due to high clinical

TABLE 1. Clinical and demographic characteristics prior to surgical decompression in 8 cases of Chiari 1.5 malformation

Variable	Value
Age at presentation in yrs, median (IQR)*	9 (4, 13)
Male sex*	5 (71.4%)
Race*	
White	6 (85.7%)
Other	1 (14.3%)
Presenting symptoms	
Headache	5 (62.5%)
Duration of headache in mos, median (IQR)	18 (0, 24)
CN palsy	1 (12.5%)
Motor weakness	0 (0%)
Previous tonsillectomy/adenoidectomy	6 (75%)
Developmental delay	4 (50%)
Preop sleep-disordered breathing symptoms	
Snoring	7 (87.5%)
Gasping	4 (50%)
Witnessed apnea	7 (87.5%)
Mouth breathing	5 (62.5%)

Unless otherwise indicated, values are expressed as the number of patients (%).

* Based on 7 individual patients; i.e., 1 patient had 2 decompressions. Percentages for symptoms are based on 8 cases.

suspicion of SRBD. The median age was 9 years (IQR 4, 13 years), with 5 male and 2 female patients identified. The majority of the patients (63%) presented with headache prior to their procedure, with a median duration of 18 months. In 6 of the 8 presentations (75%), patients underwent a tonsillectomy and adenoidectomy prior to surgical decompression and baseline PSG. Regarding SRBD symptoms, the majority (87.5%) experienced snoring and witnessed apnea preoperatively. Postoperatively, all patients who had experienced headache prior to surgery improved. Also, the patient who had a CN VI palsy improved completely after surgical decompression.

Preoperative Radiographic Measurements

Table 2 summarizes the radiographic measurements for the patient group before surgical decompression. The median tonsillar and obex descent values below the foramen magnum were 21.3 and 11.2 mm, respectively. The minimum tonsillar and obex descent values were 9 and 6.4 mm, respectively, confirming that all patients had Chiari 1.5 malformations. One-third of the patients had syringes prior to surgery. No syringes resolved after surgery. None of our patient population had syringobulbia. The median FOHR was within 0.33, indicative of no associated hydrocephalus. The median pB–C2 and CXA values were 5.4 mm and 144°, respectively.

Preoperative Baseline Sleep Study Results

The patient group baseline and postoperative nocturnal PSG results are displayed in Table 3. Each patient had 1 preoperative PSG and 1 postoperative PSG on average 182 days (range 75–503 days) before surgery and 284 days

TABLE 2. Preoperative radiographic measurements in 8 procedures

Variable	Value
Tonsillar descent in mm	21.3 (13.8, 28.2)
Obex descent in mm	11.2 (8.3, 18.3)
No. w/ syrinx present	3 (37.5%)
FOHR	0.33 (0.31, 0.38)
pB–C2 line in mm	5.4 (4.5, 6.8)
CXA in degrees	144 (139, 167)

Unless otherwise indicated, values are expressed as the median (IQR).

(range 167–690 days) after surgery. The median sleep efficiency preoperatively was 88% versus 93% postoperatively. There was a statistically significant improvement from preoperative to postoperative sleep apnea severity, with a median AHI of 19.7 (IQR 11.7, 37.6) versus 5.1 (IQR 2.3, 9.5) ($p = 0.015$). OSA specifically improved, with a preoperative OAI of 4.5 (IQR 3.5, 7.4) to 1.0 (IQR 0.1, 1.9) ($p = 0.01$). There was no significant change in CAI (from 0.9 to 0.3) from predecompression to postdecompression ($p = 0.12$).

Predictors of AHI

Table 4 displays the various radiographic parameters that were investigated in a hypothesis-generating manner to see if they predicted either preoperative sleep apnea severity (based on AHI value) or an improvement thereof (Δ AHI). No radiological factors were found to be statistically predictive.

Discussion

Our study evaluated whether operative decompression in pediatric patients with Chiari 1.5 malformations improved SRBD and, secondarily, if there were any radiological factors that predicted such improvement in sleep-disordered breathing. This is the first series of pediatric patients with Chiari 1.5 SRBD who demonstrated a significant improvement in their PSG results postdecompression. Specifically, there was a substantial decrease seen after surgery in severity (AHI, from 19.7 to 5.1) but, specifically with an OSA pattern (OAI, from 4.5 to 1.0), no significant change seen regarding the CAI. No radiological factors were found to have a statistically significant impact in predicting preoperative AHI and Δ AHI with surgery.

Sleep-Disordered Breathing in Patients With Chiari Malformations

OSA and CSA have been associated with Chiari malformations, although the exact prevalence of SRBD in patients with Chiari malformations remains unknown.⁶ However, there is growing evidence of SRBD in patients with Chiari malformations. Dauvilliers and colleagues prospectively assessed 46 patients of all ages with Chiari I and II malformations for SRBD. They discovered a prevalence of 70%.¹⁰ These findings were supported by another large study of 103 patients with Chiari malformations reported by Henriques-Filho and Pratesi, who demonstrated

TABLE 3. Comparison of preoperative to postoperative PSG parameters in 8 cases

PSG Parameter	Median Value (IQR)		p Value
	Preop	Postop	
AHI	19.7 (11.7, 37.6)	5.1 (2.3, 9.5)	0.015
OAI	4.5 (3.5, 7.4)	1.0 (0.1, 1.9)	0.01
CAI	0.9 (0.5, 5.8)	0.3 (0, 1.3)	0.12
Sleep efficiency	88% (84%, 94%)	93% (88%, 97%)	NA
Minimum O ₂ saturation	87% (84%, 90%)	89% (88%, 90%)	NA
Peak transcutaneous CO ₂ in mm Hg	50 (44, 53)	47 (41, 49)	NA

NA = not applicable.

an SRBD prevalence of 63%.²⁷ However, regarding pediatric patients the literature is more variable. Two studies that only assessed pediatric patients with Chiari I malformation had an SRBD prevalence range of 24%–41%.^{9,12} The previously mentioned study by Dauvilliers et al. reported a prevalence of SRBD in children of 60%; however, this included 5 patients with Chiari II malformation, which is a much different population.¹⁰

The Chiari 1.5 malformation is a relatively new category, with a significant lack of literature investigating the prevalence and effects of SRBD. A recent study by Ferré et al. prospectively evaluated 20 adult patients with Chiari 1.5 and 70 with Chiari I malformations. Fifty percent were found to have SRBD, with no statistically significant difference between the two Chiari categories.¹¹ Compared with their Chiari 1.5 malformation PSG data, the median values in our study were higher for OAI (4.5 vs 0.9) and CAI (0.9 vs 0.1). However, our patients were children, and the aforementioned study did not report AHI for comparison. This further emphasizes the paucity that exists in the literature regarding SRBD in pediatric patients with Chiari 1.5 malformations.

Surgical Decompression and Sleep-Disordered Breathing in Patients With Chiari Malformations

There is currently no literature that assesses whether surgical decompression improves SRBD in pediatric patients specifically with Chiari 1.5 malformations. In terms of pediatric patients with Chiari I, there have been case reports and small retrospective studies showing success in improving SRBD.^{12–14,17–19} Haji and colleagues¹³ reviewed 109 children with a diagnosis of Chiari I in whom PSG had been performed. Fifty-four percent had an asymptomatic Chiari I malformation, whereas 46% of children required surgical decompression. The AHI in the surgical group was significantly higher than in the nonsurgical group (9.9 vs 3.6, $p = 0.041$). The authors also found a trend toward significance in the improvement of AHI ($p = 0.053$), as well as in the proportion of children with more severe sleep apnea with an AHI greater than 2.5 (47.4% vs 15.8%, $p = 0.07$) postdecompression.¹³ Also, Moore et al. identified children with Chiari I who underwent PSG before and after surgical decompression. Of 86 children, 16 (19%) underwent a posterior fossa decompression for

TABLE 4. Analysis exploring whether any radiological parameters predict sleep apnea severity

Preop Radiological Parameter	p Value for Association w/ Preop AHI	p Value for Association w/ Δ AHI
Tonsillar descent	0.82	0.91
Obex descent	0.69	0.91
Presence of a syrinx	0.89	0.69
FOHR	0.60	0.29
pB–C2 line	0.23	0.57
CXA	0.27	0.69

SRBD. Thirty-eight of these children showed improvement in their SRBD (50% reduction in AHI after surgery).¹⁴ Finally, Gagnadoux et al.²⁸ prospectively enrolled 16 patients (3 pediatric) with Chiari I (not Chiari 1.5), syringomyelia, and PSG. The mean AHI was severe at 36.6, with the AHI being 10 or higher in 12 of the 16 patients (75%). Eight patients underwent surgical decompression, with the postoperative PSG studies showing a significant decrease in the CAI (from 14.9 to 1.3, $p = 0.03$). There was no significant decrease found for AHI (from 56.5 to 37.2, $p = 0.10$).²⁸ In our study, we saw a significant decrease in AHI with decompression (from 19.7 to 5.1, $p = 0.015$) and specifically with OAI (from 4.5 to 1.0, $p = 0.01$).²⁸ Patients with Chiari 1.5 have been known to have a more progressive disease course, and this could help explain the significant difference identified.^{5,8} Khatwa and colleagues reported on 3 patients with Chiari I malformations with exclusively CSA who underwent surgical decompression—all showed improvement postoperatively. We did not find a significant change in the central apnea parameters. This could be related to the severity of CAI, the fact that both studies had a small sample size, and the different types of Chiari malformation examined.¹²

The paradox of OAI/AHI improvement with surgical decompression versus CAI is interesting, especially given that 75% had a previous tonsillectomy/adenoidectomy. However, we hypothesized that surgical decompression relieved compression of the lower CNs, leading to OAI/AHI improvement. Regarding CAI, potentially there could be permanent damage from compression preventing improvement with surgery. In addition, we had a small sample size, and this could limit detection of a significant difference after surgical decompression.

Radiographic Measurements and Sleep-Disordered Breathing in Patients With Chiari Malformations

Amin et al. determined in 68 pediatric patients with Chiari I malformations that hydrocephalus was the only radiographic difference on MRI between those who had SRBD and those who did not.²⁹ In addition, Ferré and colleagues did find hydrocephalus to be significantly associated with SRBD in 20 adult patients with Chiari 1.5 and 70 with Chiari I ($p = 0.010$). The presence of syringomyelia, retroflexed odontoid, or basilar invagination was not found to be associated with SRBD.¹¹ However, Khatwa and colleagues did find that syringomyelia, angu-

lation of the odontoid, degree of tonsillar herniation, and CSF attenuation were greater in patients with Chiari I with SRBD.¹² Also, Dhamija et al.³⁰ did a retrospective review of 24 pediatric patients with Chiari I malformations who underwent PSG. Interestingly, these authors found that greater tonsillar and obex descent was significantly associated with a higher AHI and CAI. Regarding the pB–C2 line, 54% had a measurement greater than 9 mm, but neither the pB–C2 line nor the CXA correlated with any PSG parameters.³⁰ Thus, it is evident that the literature regarding radiographic differences for patients with Chiari malformations is discordant for patients with SRBD. In the present study, we did not find any radiological variables to be associated with preoperative sleep apnea severity (i.e., AHI) or Δ AHI after surgical decompression for pediatric patients with Chiari 1.5 malformations.

The Role of PSG and MRI in Patients With Chiari Malformations

Currently, there are no definitive guidelines regarding when a child with a Chiari malformation should undergo PSG.^{6,12} Clinical assessment made through obtaining a child's history and performing a physical examination is a poor predictor of SRBD diagnosis and severity.^{6,31} Untreated SRBD in children has been associated with delayed growth and development, as well as adverse cognitive and behavioral effects.² Sleep apnea in children has been associated with a 10-point decline in IQ relative to healthy children.³ Losurdo and colleagues assessed 53 children with Chiari I and found that 24% had SRBD, but that only 4 patients had symptoms of SRBD.⁹ Four of our 7 patients underwent a PSG study prior to MRI and neurosurgical assessment. This may demonstrate that, in some cases, severity of sleep-disordered breathing symptoms may predate typical Chiari symptoms.

Also, there are no guidelines specifying when a child with SRBD symptoms should receive an MRI study to assess for a Chiari malformation. In many centers, including our institution, the PSG finding that generates the order for an MRI study is almost always an elevated CAI. We now know that a high OAI should also be an indication for MRI unless there is a known alternative rationale for a high OAI (i.e., patients with tonsillar hypertrophy or another explanation for OSA by ear, nose, and throat [ENT] evaluation). We strongly urge readers to reconsider what their current practice is regarding MRI and PSG findings. Finally, although PSG parameters can be used as a potential objective measure for Chiari surgical success, patient-reported outcomes should be the ultimate measure of success.

Limitations

Limitations of this work include a retrospective design and a single-center population that may not be representative of other centers and populations. Each patient only had one postoperative PSG study on average 284 days after surgery. We cannot ensure the sustainability of the changes observed in the SRBD postoperatively, and further follow-up would be needed. PSG studies were not performed on all patients with Chiari malformations, and therefore the exact incidence of SRBD at our center is unknown. Another limitation includes not having a Chiari I

malformation comparison group, because this could help determine whether tonsillar or brainstem herniation might be driving the SRBD. The final limitation is the small sample size and, specifically, our secondary analyses surrounding radiological predictors can only be interpreted as hypothesis generating. A prospective study with a larger sample size is a crucial next step to support the significance of our results.

Conclusions

We report the first study of pediatric patients with Chiari 1.5 malformations who show significant improvement in their SRBD after surgical decompression. We were unable to demonstrate any radiographic factors that can predict improvement—larger prospective studies are needed to provide a definitive answer. A high index of suspicion for SRBDs in patients with a Chiari 1.5 malformation is recommended, primarily focusing on the AHI and OAI results.

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Disclosures

The authors report no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper.

Author Contributions

Conception and design: all authors. Acquisition of data: all authors. Analysis and interpretation of data: all authors. Drafting the article: Riva-Cambrin, Sader. Critically revising the article: all authors. Reviewed submitted version of manuscript: all authors. Approved the final version of the manuscript on behalf of all authors: Riva-Cambrin. Statistical analysis: Riva-Cambrin, Sader. Administrative/technical/material support: Riva-Cambrin, Sader, Hader, Hockley. Study supervision: Riva-Cambrin, Hader, Kirk, Adeleye.

Supplemental Information

Previous Presentations

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