

C1 Lateral Mass Displacement and Transverse Atlantal Ligament Failure in Jefferson's Fracture: A Biomechanical Study of the "Rule of Spence"

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BACKGROUND: Jefferson's fracture, first described in 1927, represents a bursting fracture of the C1 ring with lateral displacement of the lateral masses. It has been determined that if the total lateral mass displacement (LMD) exceeds 6.9 mm, there is high likelihood of transverse atlantal ligament (TAL) rupture, and if LMD is less than 5.7 mm TAL injury is unlikely. Several recent radiographic studies have questioned the accuracy and validity of the "rule of Spence" and it lacks biomechanical support.

OBJECTIVE: To determine the amount of LMD necessary for TAL failure using modern biomechanical techniques.

METHODS: Using a universal material testing machine, cadaveric TALs were stretched laterally until failure. A high-resolution, high-speed camera was utilized to measure the displacement of the lateral masses upon TAL failure.

RESULTS: Eleven cadaveric specimens were tested ($n = 11$). The average LMD upon TAL failure was 3.2 mm (± 1.2 mm). The average force required to cause failure of the TAL was 242 N (± 82 N). From our data analysis, if LMD exceeds 3.8 mm, there is high probability of TAL failure.

CONCLUSION: Our findings suggest that although the rule of Spence is a conceptually valid measure of TAL integrity, TAL failure occurs at a significantly lower value than previously reported ($P < .001$). Based on our literature review and findings, LMD is not a reliable independent indicator for TAL failure and should be used as an adjunctive tool to magnetic resonance imaging rather than an absolute rule.

KEY WORDS: Atlantoaxial instability, Atlas fracture, C1 fracture, Jefferson's fracture, Lateral mass overhang, Rule of Spence, Transverse atlantal ligament

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The incidence of atlas fractures has doubled in the past few decades according to a recent epidemiological study, accounting for approximately 11% of all cervical fractures and 25% of craniocervical injuries.^{1,2} Jefferson's fracture, a type of atlas fracture, was first described in 1927 and represents a burst fracture of the atlas with disconnection of the anterior and posterior arches resulting in lateral spreading of the lateral masses (Figure 1).³ In 1970, Spence et al⁴ simulated Jefferson's fractures in 10 cadavers and determined that if the total lateral

mass displacement (LMD) exceeds 6.9 mm, there is high likelihood of transverse atlantal ligament (TAL) rupture. Heller et al⁵ subsequently studied open-mouth (odontoid) view X-rays and redefined the value to 8.1 mm based on an inherent magnification of 18% on odontoid films.

The TAL is considered as the strongest ligament in the spine and its integrity is key in establishing the stability of atlas fractures.^{6–8} Two very recent studies using computed tomography (CT) scan measurements and magnetic resonance imaging (MRI) to assess TAL integrity concluded that lateral mass overhang (LMO) on coronal imaging was not a reliable indicator of TAL injury.^{9,10} The "rule of Spence," which has significant clinical value in ascertaining the need for further imaging and surgical intervention, is

ABBREVIATIONS: CT, computed tomography; LMD, lateral mass displacement; LMO, lateral mass overhang; MRI, magnetic resonance imaging; TAL, transverse atlantal ligament

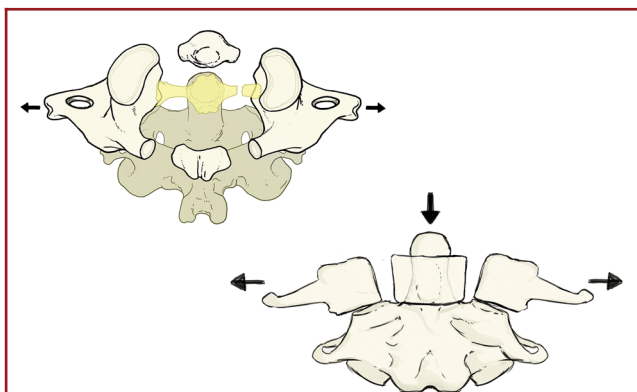


FIGURE 1. In a Jefferson's fracture, axial force causes fractures of the anterior and posterior arches of the atlas and spreading of the lateral masses. The total overhang of the C1 on C2 lateral masses on imaging is referred to as LMO.

now being questioned. Additionally, from our literature review there is a paucity of biomechanical evidence to support the rule of Spence.

The goal of this study was to test the amount of LMD necessary for TAL failure using modern biomechanical techniques.

METHODS

Eleven fresh-frozen C1-2 specimens were harvested from 6 male and 5 female cadavers ($n = 11$). The mean age at death was 67 yr (range 24-100 yr). All soft tissue was removed, preserving only the TAL. The specimens were kept moist in a sealed airtight bag stored at -20° until ready for testing. The specimens were carefully inspected for pre-existing abnormalities such as prior fractures, congenital malformations, tumors, or other pathology.

Prior to testing, the specimens were thawed overnight. The lateral masses were embedded in a low-melting point alloy (Cerrobend, Chicago, Illinois). A custom 3-D-printed mold was fitted to the lateral masses and used in the embedding process. Reference marks were placed on the lateral masses, which were later used to measure displacement.

Six of the 11 specimens were then secured into a universal testing machine (Instron E10000, Canton, Massachusetts) and baseline LMD measurements were made (Figure 2). Next, the anterior and posterior arches were cut with an oscillating saw to allow disconnection of the lateral masses. Care was taken to avoid disrupting the fixation apparatus or camera distance.

In the other 5 specimens, Jefferson's fractures were replicated by making 4 cuts in the C1 ring using an oscillating saw, before securing them into the universal testing machine. Two anterior cuts were placed at the junction of the anterior arch and the lateral mass, and 2 posterior cuts were placed at the *sulcus arteriae vertebralis*, which is the thinnest bone in the posterior arch. This allowed for removal of the anterior and posterior arches and disarticulation of the odontoid process from the C1 vertebrae. These specimens were then loaded into the universal testing machine (Figure 3). Prior to the start of the TAL failure test, the specimens were preloaded up to 5 N to remove the gaps in the fixturing and slack in the ligament. Baseline lateral mass distance measurements



FIGURE 2. Baseline lateral mass distance was measured prior to disconnecting the anterior arch of C1 (red arrow) with the TAL (yellow arrow) maintained in its neutral zone.

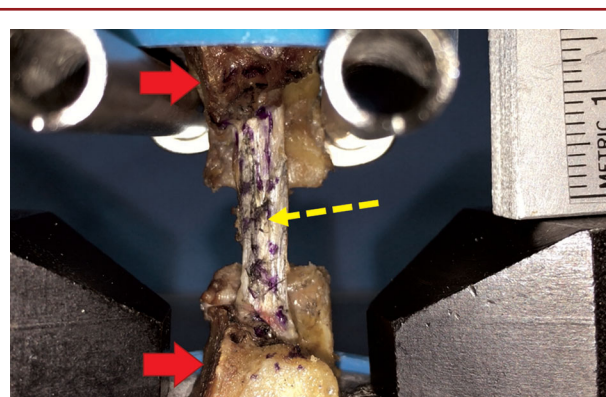


FIGURE 3. The lateral masses (red arrows) were embedded in a metal alloy, keeping the TAL (dashed-yellow arrow) clean of any embedding material. After embedding the lateral masses were secured into the universal testing machine.

were then made with 5 N pretension applied, which closely estimates normal physiological baseline (see Limitations).

Next, the TAL failure test was performed in all 11 specimens. The lateral masses were stretched laterally until TAL failure, at a rate of 5 mm/min. A high-resolution, high-speed camera (iPhone 6, recording at 240 frames per second, Apple Inc, Cupertino, California) was utilized to capture the experiment. An image processing software (ImageJ; NIH Image, National Institutes of Health) was used to identify the exact frame TAL failure occurred and measure the displacement. The total displacement that yielded ligament failure was calculated as the distance between the reference points at failure compared to the baseline measurements. The TAL failure was defined as the complete rupture of the ligament, which was confirmed by the reduction in the tensile load despite increasing displacement and by gross examination of the specimens after testing.

TABLE. C1 LMD upon Transverse Atlantal Ligament Failure

Experiment	Age	Gender	LMD (mm)	Failure load (N)
1	68	M	2.4	264.4
2	61	F	3.8	72.3
3	61	M	2.3	254.4
4	61	F	3.1	180.0
5 ^a	64	F	1.7	403.1
6	79	M	4.1	259.0
7	68	M	2.8	263.3
8	100	F	2.7	155.0
9	24	M	2.3	365.6
10 ^a	68	M	5.6	258.4
11	87	F	4.6	143.0

LMD: lateral mass displacement

^aTAL avulsion occurred in these specimens

In the shaded specimens, baseline lateral mass distance was measured with an intact C1 ring.

LMD measurements were summarized using mean, standard deviation, and gamma cumulative density function. Pearson correlation was used to assess the relationship between LMD and the maximum force needed for TAL failure. In addition, a sample t-test was used to compare our findings with those previously reported. All tests were conducted at a significance level of $P < .05$ using a statistical software (SAS 9.4, Cary, North Carolina).

Institutional Review Board approval was not obtained because this was a cadaveric study and did not include any protected health information.

RESULTS

TAL rupture occurred in 9 specimens and TAL avulsion occurred in 2 specimens. TAL avulsion resulted in detachment of the TAL with a small piece of cortical bone; of note, the ligament remained grossly intact in these specimens. One of the specimens with TAL avulsion had known osteopenia (T-score -2); however, there was no available bone density data on the other avulsion specimen.

The average displacement upon TAL failure was 3.2 mm (± 1.2 mm; Table). The average force required to rupture the TAL was 241 N (± 82 N). After data analysis, it was determined that at LMD beyond 3.8 mm, there is greater than 75% probability of TAL failure (Figure 4).

There was an inverse relationship between the strength of the ligaments (determined by the failure load) and the failure displacement; ie, stronger ligaments failed at smaller displacements (correlation coefficient -0.48 ; Figure 5).

The mean LMD in the current study of 3.2 (1.7-5.7) mm was significantly lower compared to findings reported by Spence et al⁴ 6.39 (5.6-7.6) mm, $P < .001$, Radcliff et al⁹ 5.4 (3.5-6.8) mm, $P < .001$ and Heller et al⁵ 7.5 (6.6-8.9) mm, $P < .001$. In contrast, there was borderline significant difference between our findings and those reported by Perez-Orribo et al¹⁰ 2.4 (0.6-8.7) mm, $P = .05$ (Figure 6).

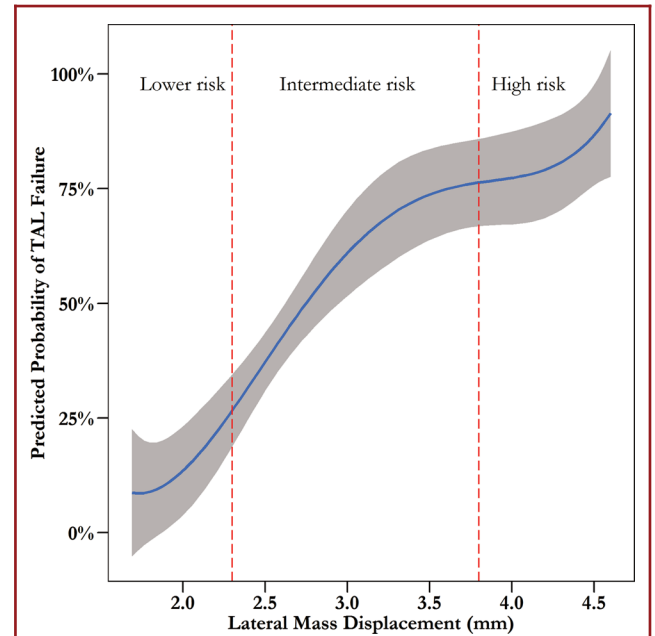


FIGURE 4. Probability of TAL failure based on LMD. Cut off points were set at 25% and 75% probability with 2.3 and 3.8 mm LMD, respectively.

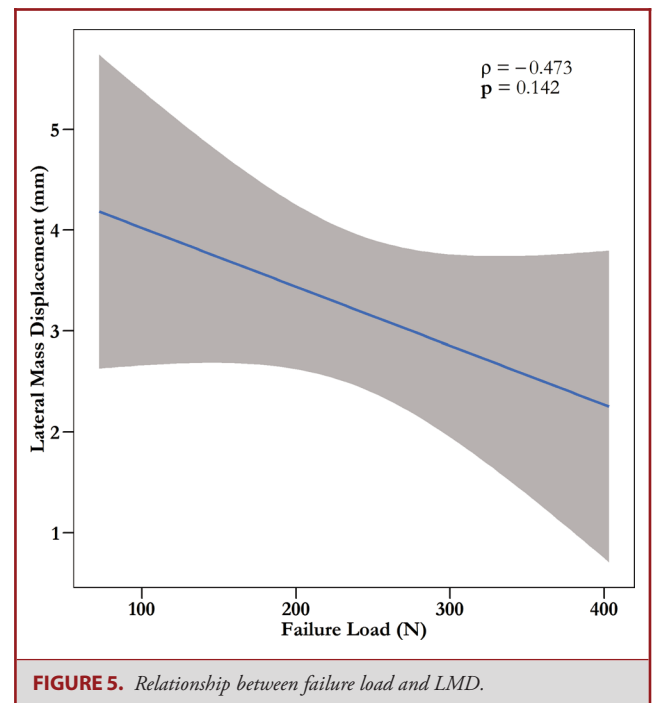
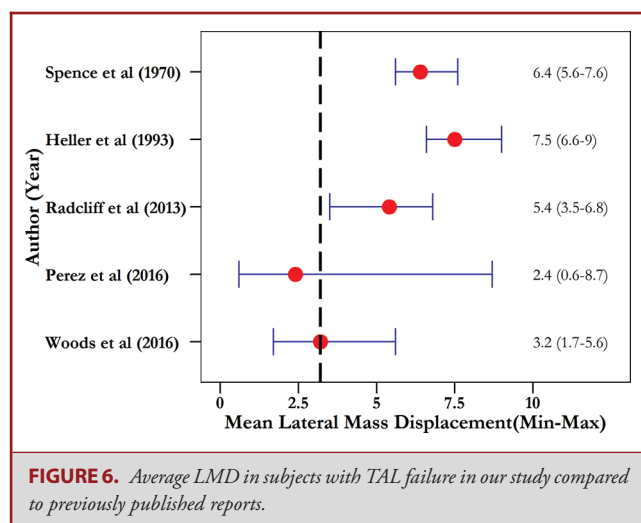


FIGURE 5. Relationship between failure load and LMD.



DISCUSSION

This study supports that LMD is a useful clinical tool to assess TAL integrity. Disconnection of the anterior and posterior arches of C1 (as seen in Jefferson's fracture) is a prerequisite for spreading of the lateral masses (Figure 1). Logically, it makes sense that if the lateral masses spread beyond a threshold, the TAL will be compromised. From our literature review this threshold value is controversial and the rule of Spence, which has been widely cited since its publication in 1970 lacks biomechanical support.

According to Spence et al,⁴ the mean excursion to rupture the TAL was 6.3 mm (range of 5.6-7.6 mm). The method of deriving the cutoff value of 6.9 mm was not clear in Spence's paper. Additionally, they concluded that if the LMD was less than 5.7 mm, there was a low probability of TAL injury and these patients should be treated conservatively. This is inconsistent with our findings, which show a high probability of TAL failure if LMD exceeds 3.8 mm. One explanation for this discrepancy is the difference in techniques used to derive this threshold value. In our study, when the TAL undergoes stretch, it fails abruptly at a well-defined displacement; this is evident on both gross visualization and the sudden decrement in the load. We utilized a high-speed camera to identify this failure threshold. In the Spence et al study,⁴ the threshold breaking width was defined as the transverse diameter of the C1 ring after TAL failure had occurred, which will overestimate the breaking point. Also, in the Spence et al study,⁴ force was applied to the lateral mass with steel pins, which could bend and confound the results.

In 2013, Radcliff et al⁹ performed radiographic measurements of LMO on coronal CT scans in 18 patients with Jefferson-type fractures. They evaluated TAL integrity using MRI scans according to a previously published report.¹¹ In their series, the 33% of patients (n = 6) with TAL injury on MRI had an average LMO of 5.3 mm, which contradicts the rule of Spence but supports our findings. Conversely, the remaining 67% patients

(n = 12) with normal MRI findings in this series had an average LMO of 5.4 mm. This infers that there is a subset of Jefferson's fractures that exceed our threshold that do not show TAL injury on MRI. In our experiment, we demonstrated that TAL failure either occurs from rupture of the ligament or avulsion from the lateral mass, which supports an earlier published classification by Dickman et al.¹² We argue that in patients with TAL avulsion, MRI has low sensitivity for detecting TAL failure; if the substance of the ligament remains intact, MRI will unlikely demonstrate T2 signal abnormality. To this end, we recommend that a high clinical index of suspicion for TAL failure be maintained if LMD exceeds 3.8 mm despite normal MRI findings.

Similarly, several authors have reported successful nonoperative treatments for patients with Jefferson's fractures that did not meet Spence's criterion.¹³⁻¹⁷ The question remains, why is conservative management successful if the TAL is incompetent in these patients? The TAL has a very high tensile strength, requiring an average force of 241 N to cause failure in our experiment; consequently, avulsion of the ligament sometimes occurs before injury to the substance of the ligament as we demonstrated in 2 of our 11 specimens (18%). This concept of TAL avulsion was first reported by O'Brien et al in 1976¹⁸ and has been subsequently reported by numerous authors. We purport that in TAL avulsion, osseous union is possible, which may explain why some patients with LMD beyond threshold heal without surgical intervention. CT scans may be useful in these patients for detecting TAL avulsion. It is also important to note that there are other tissues that restrict motion and help maintain atlantoaxial stability despite TAL failure; these other contributing factors may facilitate the success of nonoperative treatment in patients with TAL failure.²

Perez-Orribo et al¹⁰ also performed a retrospective radiographic review and showed that of 11 cases with documented TAL injury on MRI, 10 patients (90.9%) did not meet the rule of Spence criterion. The average LMO in these 10 patients with TAL injury was 2.4 mm (range 0.6-8.7 mm).¹⁰ These findings corroborate our results.

Another important consideration is that the LMD seen on imaging is not necessarily representative of the maximum LMD during injury. Consequently, fractures that do not meet our failure measurements could potentially have TAL injury. Given these aberrations, we encourage clinicians to obtain MRI scans whenever possible in determining the best treatment option. We support the use of LMD in evaluating TAL integrity but recommend its use as an adjunctive tool rather than an absolute rule.

Limitations

One criticism of our study is that in 5 of the 11 specimens we tested, we obtained baseline lateral mass distance measurement with 5 N of preload applied to the TAL to remove any slack in the ligament. We believe this very closely approximates normal physiological measurements because the TAL is notably taut in



FIGURE 7. After cutting the C1 ring and applying 20 N preload with the odontoid (blue arrow) in place, the distance between the lateral masses (red arrows) was remeasured. Less than a millimeter and a half stretch in the TAL (yellow arrow) from baseline was noted.

its neutral zone prior to removal of the odontoid process. To support this theory, we measured baseline lateral mass distance in 6 additional specimens with intact C1 rings (Figure 2); we then cut the C1 ring and applied 20 N of preload with the odontoid process in place and remeasured the lateral mass distance (Figure 7). There was less than a millimeter and a half change when preload was applied. Furthermore, there was no significant difference in the failure LMD between the 2 subgroups ($P = .16$). The potential difference in lateral mass distance with 5 N of preload from physiological baseline is negligible due to the relative inelasticity of the TAL. Additionally, there was no difference in the mean load to failure among the 2 subgroups ($P = .94$).

One other limitation of our study was the relative small number of specimens tested. We tested 11 cadaveric specimens ($n = 11$). Increasing this number would undoubtedly refine the failure threshold value; however, from our literature review this is comparable to other biomechanical studies looking at atlantoaxial stability, including Spence's original study where $n = 10$.^{4,19,20}

The age of the cadavers used is another potential drawback of this study. The mean age of our cadavers was 67 yr at time of death (range 24–100 yr). We do not recommend using these data in the pediatric population because the TAL could have different biomechanical properties compared to adults. However, most Jefferson's fractures occur in the elderly, and the mean age of our cadavers is representative of Jefferson's fractures demography.¹ Also, regarding the biomechanical properties of the TAL, we recognize that cadaveric tissue may differ from live tissue and this is an inherent limitation to any cadaveric study. Despite these limitations, we believe this experiment represents the most

accurate data regarding the relationship between LMD and TAL integrity to date.

CONCLUSION

Our findings suggest that although the rule of Spence is a conceptually valid measure of TAL integrity, TAL failure occurs at an average LMD of 3.2 mm, which is significantly less than reported by Spence et al⁴ ($P < .001$). Based on our findings and literature review, LMD is not a reliable independent indicator for TAL failure. We recommend that LMD be used as an adjunctive clinical tool rather than an absolute rule, as it has historically been coined. Additionally, MRI and CT scans should be obtained whenever possible to ascertain TAL rupture or avulsion and used in conjunction with LMD and atlantodental interval to determine operative vs nonoperative management of a Jefferson's fractures.

Disclosures

Dr Cheng receives research support from Medtronic, Biomet, NuVasive, K2M; is a speaker/instructor for Alphatec Spine, Depuy/Synthes, Globus, K2M; and received the cadavers used in this study as a donation from Synthes. Dr Danisa received royalties between \$100 000 and \$500 000 from Globus Medical, was the recipient of an education grant (paid directly to the institution) of \$10 000 from the Musculoskeletal Tissue Foundation. The other authors have no personal, financial, or institutional interest in any of the drugs, materials, or devices described in this article.

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Figure 1 was created by a paid medical illustrator (Patrick Gallagher).

COMMENTS

In this manuscript, the authors present the results of a biomechanical study of the TAL. Five cadaveric isolated ligaments underwent displacement controlled loading to failure. The mean load to failure was 242 N, which occurred at a mean displacement of 3.2 mm. The authors then correlate these data to the rule of Spence, noting a discrepancy between this rule and the experimental results. They suggest that the rule of Spence is not a very good predictor of TAL integrity, and that TAL injury should be strongly suspected at a much lower value.

This is a very elegant experiment that does a good job of quantifying the biomechanical properties of the TAL, particularly the mean load to failure. As was pointed out in the discussion, the results are somewhat at odds with a number of previously published clinical and laboratory studies. The authors offer several potential explanations for these discrepancies. It should be noted, however, that no ligament failed at greater than 5.6 mm displacement, yet the literature is replete with patients that did not have tubercle avulsion who underwent successful non-surgical treatment with that degree of displacement. Further studies are needed to better understand this phenomenon.

Christopher Wolfla
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In this biomechanical investigation of 11 TAL specimens (from cadavers aged 24 and above), the investigators have studied the tensile strength of TAL and its failure. Assigning a point of reference, the investigators calculated and pictured the gap produced following failure and proposed that in clinical scenarios when the LMD was more than 3.8 mm, there was a 95% chance that the TAL had ruptured and was incompetent. The mean force needed to produce such a failure of tensile strength was 242 N. Only less than 2% of all spine injuries have Type II Atlas fractures and less than $\frac{1}{2}$ of these will suffer ruptured TAL. Since the original biomechanical studies of Spence in 1970, other investigators have studied the biomechanical vulnerability of TAL. Panjabi et al (authors' reference # 6) observed that up to 3000 N axial load was needed to produce Type II Atlas fractures with or without TAL rupture. Beckner et al (reference # 20) had to apply up to 2000 N of distraction in order to cause Type II Atlas fracture with or without disruption of TAL. Evidence indicates that LMD is not a good indicator of major disruption of TAL. Radcliff et al and Perez-Orribo et al (references 9 and 10) noticed that bony displacement on coronal CT was not a reliable indicator of ruptured TAL. Most of the neurosurgeons at the present time rely heavily on MRI to visually confirm whether TAL is intact or ruptured. Only MRI in addition to ADI and LMD can prescribe conservative versus operative management of patients with Jefferson fracture and torn TAL.

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This is an interesting laboratory investigation addressing a relevant clinical question regarding C1 burst fractures. The authors used a modern methodology to study TAL biomechanical characteristics. The average LMD to failure was 3.2 mm, at an average load of 242 N, differing from the classical rule of Spence. This results support the concept that for assessing TAL integrity, which is of great importance to determine stability of C1 fractures, measuring LMD is not enough, and should not be a substitute for a detailed evaluation with MRI.

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