Internal Forces Sustained by the Vertebral Artery During Spinal Manipulative Therapy

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Abstract

Background: Spinal manipulative therapy (SMT) has been established as a clinically effective modality for the management of several musculoskeletal disorders. One major issue with the use of SMT is its safety, especially with respect to neck manipulation and the risk of stroke in the vertebrobasilar system.

Objectives: Our objectives were to quantify the strains and forces sustained by the vertebral artery (VA) in situ during SMT.

Study Design: This was a cadaveric study.

Methods: Six VAs were obtained from 5 unembalmed postrigor cadavers. The cephalad/distal (C0-C1) and caudad/proximal (C6-subclavian artery) loops of the VA were carefully exposed and instrumented with a pair of piezoelectric ultrasonographic crystals. The strains between each crystal pair were recorded during range of motion testing and diagnostic tests and during a variety of SMT procedures. The VA was then dissected free and strained on a materials testing machine until mechanical failure occurred.

Results: SMT performed on the contralateral side of the cervical spine resulted in an average strain of 6.2% ± 1.3% to the distal (C0-C1) loop of the VA and a 2.1% ± 0.4% strain to the proximal (C6) loop. These values were similar to or lower than the strains recorded during diagnostic and range of motion testing. Failure testing demonstrated that the VAs could be stretched to 139% to 162% of their resting length before mechanical failure occurred. Therefore the strains sustained by the VA during SMT represent approximately one ninth of the strain at mechanical failure.

Conclusions: SMT resulted in strains to the VA that were almost an order of magnitude lower than the strains required to mechanically disrupt it. We conclude that under normal circumstances, a single typical (high-velocity/low-amplitude) SMT thrust is very unlikely to mechanically disrupt the VA. (J Manipulative Physiol Ther 2002;25:504-10)

Key Indexing Terms: *Chiropractic Manipulation; Vertebral Artery; Stroke*

Introduction

Spinal manipulative therapy (SMT) has now been established as a clinically effective modality for the treatment of patients with low back pain and other musculoskeletal disorders. An increasing number of nonchiropractic health care providers such as nurses, physicians, physical therapists, and orthopedic specialists are incorporating SMT into their treatment repertoire. However, despite this increasing popularity of SMT, there is little basic research into the mechanisms underlying spinal manipulation and its pathophysiologic effects on the human body.

SMT typically consists of a high-velocity, low-amplitude thrust delivered to a specific landmark on the spine in a specific direction. We have previously characterized the mechanics of SMT by measuring the forces exerted by clinicians during SMT delivered to the cervical spine,[1,2] the thoracic spine,[3,4] and the sacroiliac joint.[3-5] A typical SMT

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Table 1. *Summary of cadaver characteristics*

Cadaver no.	Age (y)	Sex	Cause of death	VA harvested
2	84	F	Cardiac failure	Right
3	85	M	Atherosclerotic disease	Right
4	99	M	Aspiration pneumonia	Left
5	84	F	Atrial fibrillation	Left
6	80	F	Emphysema	Bilateral

treatment delivered to the cervical spine will produce peak forces of approximately 100 to 150 N,[1,2] whereas treatments on the other areas of the spine are associated with average peak forces of 400 to 500 N.[5,6] These forces are generally delivered within 200 ms[3,4] and thus may produce substantial local accelerations. However, these measurements have all been performed on the body surface; it is not known how these forces applied externally to the skin are transmitted through the various soft-tissue layers and bones into the deeper anatomic structures.

One major issue with the use of SMT is its safety, especially with respect to neck manipulation and the risk of stroke. Conservative estimates of the risk of a stroke associated with SMT are on the order of 1 per million,[7] but the actual number remains unknown; reports in the literature vary between 1 in 5000 to 1 in 10 million.[7-12] Although this risk is small, the serious and irreversible nature of vascular accidents[13] makes this a material risk. The earliest documented reports of fatal vascular accidents after spinal manipulation can be traced back to the case of Foster versus Thornton[14] in 1934 and Pratt-Thomas and Beyer[15] in 1947. The vast majority of these incidents have involved the vertebrobasilar system, specifically the cephalad/distal loop of the vertebral artery (VA) as it exits the foramen transversarium of C1 and travels posteriorly into the foramen magnum.[10] Because of this unique configuration of the VA, it has been suggested that the VA experiences considerable stress and stretch during extension and rotation of the neck, which may lead to hemodynamic occlusion,[16] physical damage, or both. Consequently, it has been hypothesized that SMT may also cause similar types of damage because of its high-velocity and high-acceleration nature.

The purpose of this study was to characterize the nature and magnitude of the strains and elongations of the VA during SMT and then to compare these values against the ultimate failure loading strain of the VA. Based on failure testing of the VA, we can also calculate indirectly the forces experienced by the VA during SMT. A number of different SMTs and procedures were investigated in this study including range of motion (ROM) testing and vertebrobasilar insufficiency (VBI) testing.

Methods

Subjects

An initial pilot study was performed on 2 embalmed cadavers to determine the feasibility of the experimental protocol (data not included). Six vertebral arteries were then obtained from 5 fresh, unembalmed, postrigor cadavers from the Department of Anatomy, Faculty of Medicine, University of Calgary. The details concerning these specimens are summarized in Table 1.

Dissection

The vertebral artery was exposed by blunt dissection with an anterolateral approach. The distal extracranial loop of the VA as it exits the foramen transversarium of C1 and travels posteriorly into the foramen magnum was carefully exposed, along with the proximal/caudad loop as it originates from the subclavian artery (SA) and ascends into the foramen transversarium of C6. In general, minimal dissection was performed to preserve the in situ mechanical behavior of the VA as much as possible; only 1 to 2 tablespoons of tissue were removed, and none of the muscles or ligaments was transected.

Treatments

First, ROM testing in flexion, extension, rotation, and lateral bending was performed. During the ROM testing, the head was moved passively to the end-range point, when no further movement could be produced. Next, VBI testing by placing the neck into extension plus rotation (ie, Houle's test) was performed. The SMTs consisted of a combined lateral/rotary "break" adjustment with a second metacarpal contact with the cadaver supine and a pure lateral and a pure rotatory adjustment. These SMTs were delivered to specific levels of the cervical spine: C1/C2, C3/C4, and C6/C7.

In Situ Strain Measurements

Two pairs of piezoelectric ultrasonographic crystals were sutured onto the upper and lower loops of the VA (4 crystals in total per VA). Three noncollinear sutures were used to fix each crystal to the VA to prevent any movements of the crystal relative to its attachment site. Each crystal was designated as a transmitter and receiver. The crystals were completely covered in commercially available ultrasound gel to enhance the transmission of the ultrasound signals. The time it takes for an ultrasound signal to travel from a transmitter crystal to its paired receiver was measured, and the strain of the VA between the 2 crystals was calculated as: Strain = td - ti/td, where *td* is the time it takes for the ultrasound signal to travel from the transmitter to the receiver crystal with the head in neutral position (supine), and *ti* is the instantaneous time for the ultrasound signal to travel from the transmitter to the receiver crystal with the head in various positions. The ultrasound signals were measured for approximately 3 seconds before the test movement to 3 seconds after. The signals were amplified and recorded with a PC at 2000 Hz/channel and were stored off-line for subsequent analysis. The resolution of this ultrasound system is 0.016 mm according to the manufacturer. We confirmed the resolution independently by measuring the distance between 2 ultrasound crystals in an Instron materials testing machine, in which the distance between the crystal pair could be changed by 0.000254-mm increments (ie, a value 63 times smaller than the resolution of this system).

Ex Vivo Force Versus Strain Measurements

Once the in situ strains were ascertained, the VA was carefully harvested from the subclavian artery to its entry into the foramen magnum and placed in phosphate-buffered saline solution. The piezoelectric crystals remained sutured in position during the resection. The VA was then clamped into the materials testing machine (Instron 1122) in a vertical orientation. Care was taken to clamp the VA at the remnant subclavian artery inferiorly and as cephalad as possible from the superior crystal pair. The VA was continuously moistened with phosphate-buffered saline solution and was covered with ultrasound gel to prevent drying and to enhance ultrasound signal conduction. The VA was then stretched until mechanical failure occurred. Mechanical failure was defined as the first point at which the elongation of the VA produced a decrease in force. The elongation was performed at 5 mm/min and at 500 mm/min in random order. No differences were observed between the 2 loading speeds, and thus the results were treated identically. The faster 500 mm/min elongation corresponded approximately to the strain rates observed during high-speed, low-amplitude cervical SMTs (unpublished observations). The strains experienced by the VA were measured by the piezoelectric crystals in a manner identical to the in situ strain testing. The forces during failure testing were measured by the Instron force transducer at a setting of 10 V = 20 N. The force resolution level was 0.005 N, and the natural frequency of the force transducer exceeded 1000 Hz. The forces were recorded online to a PC at 200 Hz/channel.

Data Analysis

For all diagnostic procedures (eg, ROM testing and VBI testing) and SMTs, the peak strains were determined for each procedure, and the absolute peak strains were expressed as a percentage ratio relative to the mean strain with the neck in the neutral position. For comparative purposes the strains were also expressed as a percentage ratio relative to the strain determined at mechanical failure for that VA. For the failure testing, the failure forces and strains were determined at the first point of mechanical failure as described previously. The peak forces acting on the VA during the diagnostic procedures and SMTs were derived from standard force-strain curves obtained during the failure testing.

Table 2. *Summary of ROM and VBI testing*

Test	Distal (C0-C1) strain (% neutral)	Proximal (C6-SA) strain (% neutral)
Flexion	3.6 ± 2.4	2.4 ± 1.9
Extension	1.2 ± 0.6	2.8 ± 2.0
Ipsilateral rotation	5.3 ± 3.2	3.2 ± 2.1
Contralateral rotation	12.5 ± 10.1	4.8 ± 4.5
Ipsilateral lateral bending	3.3 ± 3.2	2.0 ± 1.8
Contralateral lateral bending	5.5 ± 2.1	2.2 ± 2.2
Ipsilateral VBI	4.2 ± 2.2	3.2 ± 2.4
Contralateral VBI	11.8 ± 8.6	4.9 ± 4.2

The strain values are expressed as a percentage ratio over the mean strain measured with the neck in neutral position. *%ROM*, Range of motion; *SA*, subclavian artery; *VBI*, vertebrobasilar insufficiency screening.

Results

The characteristics of the cadavers studied are listed in Table 1.

Diagnostic Testing

The strains experienced by the proximal (C6-SA) and distal (C0-C1) segments of the VA are listed in Table 2. In general, the strains experienced by the VA contralateral to the side subjected to testing were greater than in the ipsilateral VA. For example, right lateral bending of the neck causes more strain on the left VA than on the right VA. Second, the distal (C0-C1) loop of the VA was typically subjected to more strain during the same procedure than the proximal (C6-SA) segment of the same VA. The greatest strains observed during ROM testing were for rotation, followed by lateral bending. On the other hand, extension caused very little stretching of the VA. Vertebrobasilar testing resulted in fairly high strains in the distal (C0-C1) loop of the contralateral VA, which were comparable to those experienced during extreme rotation. A sample trace of the raw ultrasonographic signals recorded during a flexion-extension procedure can be seen in Figure 1.

SMT Procedures

Overall, contralateral SMT to the cervical spine between C2-C6 resulted in a 6.2% ± 1.3% strain in the distal

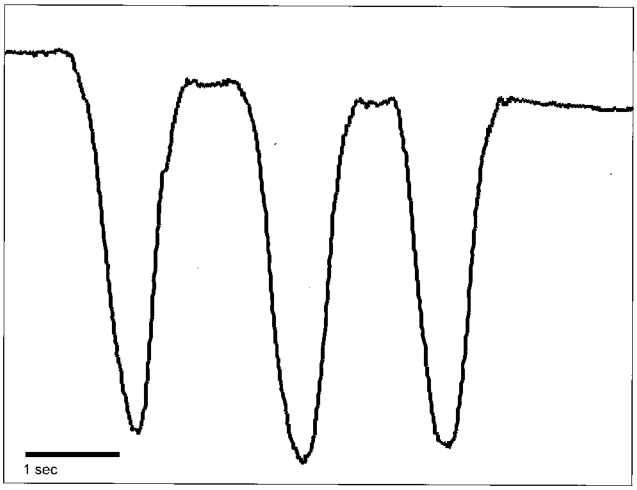

Fig 1. *A sample ultrasonographic trace of the raw data obtained during a flexion-extension procedure. This trace was recorded from the distal (C0-C1) segment of the left vertebral artery of cadaver number 6. In this procedure the head is initially placed in the neutral position with respect to the neck. The head is then slowly moved from full extension into full flexion 3 times and then returned to neutral. The initial intercrystal distance in neutral position was approximately 6.75 mm and varied from approximately 7.1 mm (extension) to 6.55 mm (flexion). Further details of this procedure are described in the Material and Methods section of the text.*

(C0-C1) VA loop and a 2.1% ± 0.4% strain in the proximal (C6-SA) segment of the VA. In other words, the distal VA stretched an average of 6.2% of its resting (neutral) length during SMT delivered to the opposite side of the neck. This 6.2% strain represents approximately 10% of the ultimate failure strain of the VA, whereas the 2.1% strain in the proximal segment represents approximately 4% of the ultimate failure strain. These data are summarized graphically as histograms in Figure 2.

The strain values for each manipulative procedure are summarized in Table 3. The high strains observed during ipsilateral SMT may be an artefact of this procedure, because the contact hand was directly over the crystals when the manipulative thrust was applied. Therefore we focused on the strains sustained by the contralateral VA. The strains experienced by the distal (C0-C1) loop of the VA were always greater than those observed in the proximal segment for all types of SMT. If one compares the 3 manipulative techniques at the C3/C4 level only, as expected, the rotatory adjustment produced the greatest strain (7.0%) on the distal VA, followed by a combined adjustment (5.2%) and a pure lateral adjustment (4.5%). However, the greatest strain on the distal VA was generated during SMT to the "lower" cervical spine, that is, the C6/C7 break adjustment. This occurrence was probably due to the fact that the head had to be placed into extreme flexion, lateral flexion, and rotation to "lock" the joint out before the manipulative thrust could be delivered, thus stretching the VA. It is also important to note that ROM testing produced strains in the range of 1% to 12%, and that all of the manipulative procedures produced strains within this range.

Failure Testing

The details of the failure testing are listed in Table 4. The distal (C0-C1) VA loop failed at 153% strain, which corresponded to a force of approximately 8.2 N. In other words, the distal loop stretched to 53% of its resting length before it began to fail mechanically, at an applied force of 8.2 N. In contrast, the proximal VA segment (C6-SA) failed at 162% strain and 8.8 N.

Discussion

An ischemic event sustained in the vertebrobasilar system during SMT can arise from a variety of causes such as pinching or kinking of the VA during neck movement, vasospasm of the VA, systemic shock or hypotension, physical obstruction of the VA by a dislodged thrombus, embolus, or atherosclerotic plaque, and a traumatic tear in the VA. This study focused on the last possibility by directly evaluating the strains and forces exerted on the VA itself during SMT.

The forces applied by chiropractors were first measured by Adams and Wood[17,18] in 1984. With an instrumented manipulation "dummy," they compared the forces exerted by experienced and student chiropractors during SMT of the sacroiliac joints. We have previously measured the forces exerted by chiropractors and the subsequent vertebral movements for a variety of treatments.[1-6,19,20] However, with the exception of the intervertebral disk,[21] there have been no previous studies measuring the internal forces generated during SMT. Therefore this study represents a novel approach into quantifying the biomechanical effects of SMT.

Although its efficacy is equivocal in the literature,[8,22,23] VBI testing by positioning the neck into extension plus rotation is currently the clinical standard for screening against potential stroke. Our data showed that VBI screening resulted in 4% and 12% strain to the ipsilateral and contralateral distal (C0-C1) loops of the VA, respectively. In addition, rotation of the neck resulted in 5% and 13% strain to the ipsilateral and contralateral distal (C0-C1) loops of the VA. In contrast, other cervical ROMs resulted in only 2% to 6% strain (Table 2). These values suggest that similar strains were placed on the VA during both procedures and support the contention that rotation may be a potential mechanism for causing VBI.[16]

Our results indicated that cervical SMT averaged 6% strain to the distal (C0-C1) VA loop and 2% strain to the proximal (C6-SA) segment of the VA. These values are lower than those observed during VBI screening and neck rotation. Indeed, the maximal strain produced during SMT was 11% (ipsilateral C3/C4 break) compared with the 12% and 13% strain produced during contralateral VBI screening

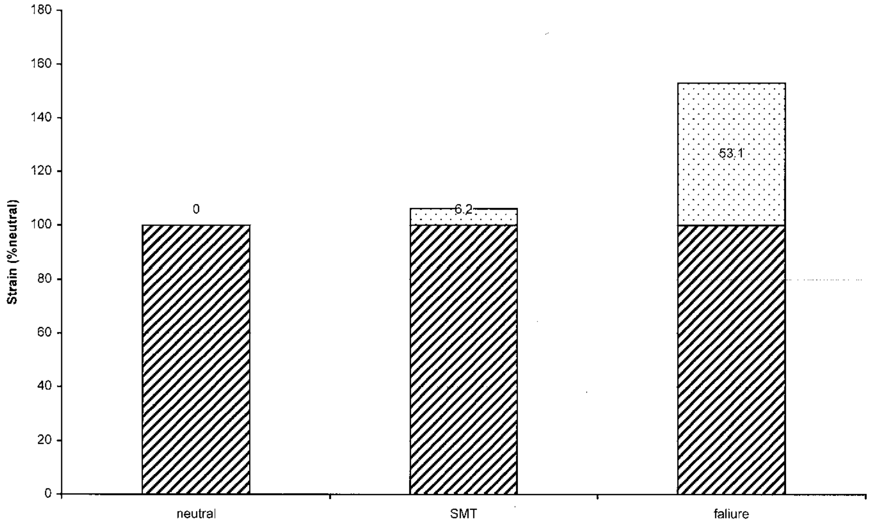

Fig 2. *Graphic representation of the strains sustained by the distal (C0-C1) VA. The cross-hatched area represents neutral or "zero" strain. The definitions of zero strain and failure are described in the Material and Methods section of the text. SMT, Spinal manipulative therapy; VA, vertebral artery.*

Table 3. *Summary of strains during SMT*

Procedure	Distal (C0-C1) strain (% neutral)	Proximal (C6-SA) strain (% neutral)
Ipsilateral C3/C4 break	10.7 ± 5.5	7.5 ± 4.6
Contralateral C3/C4 break	5.2 ± 4.9	2.7 ± 1.5
Contralateral C3/C4 lateral	4.5 ± 1.0	1.4 ± 0.7
Contralateral C3/C4 rotation	7.0 ± 6.1	2.5 ± 0.7
Contralateral C1/2 break	6.5 ± 6.1	2.0 ± 1.9
Contralateral C6/7 break	8.0 ± 3.6	2.1 ± 1.4

The strain values are expressed as a percentage ratio over the mean strain measured with the neck in neutral position. Descriptions of the manipulative procedures are provided in the Materials & Methods section of the text. *%SA*, Subclavian artery.

Table 4. *Summary of the failure testing data*

	Distal (C0-C1) VA loop	Proximal (C6-SA) VA segment
Failure strain (% neutral)	153.1 ± 2.9	162.2 ± 8.0
Failure force (N)	8.2 ± 3.4	8.8 ± 5.4

and rotation, respectively. These values suggest that SMT results in strains that are within the range of strains produced during normal, physiologic motion of the cervical spine.

Few data are available in the literature regarding the mechanical properties of the VA. Yamada[24] defined the VA as a "muscular" artery and reported average longitudinal failure strains of 1.4-fold in people 20 to 39 years old. This is lower than our findings of 153% to 162% strain before mechanical failure. Johnson et al[25] recently reported mechanical failure of the VA in 16 cadavers 28 to 90 years old at age of death at a mean longitudinal elongation of 38.7%, which is also lower than the values we obtained in an older population (Table 1). However, 1 of the difficulties in comparing failure strains across studies is the assumption of what constitutes 0 or resting/baseline strain. Here, we defined 0 strain as the strain recorded in situ with the head in a neutral position; the length of the VA segment in this position was taken as the baseline value. In contrast, Johnson et al[25] defined 0 strain at the first appearance of measurable force; the length of the VA segment at that point was considered to represent baseline. During the failure testing, however, we observed that we could elongate the VA considerably from its 0 strain length before measuring any detectable force. Therefore one would expect greater failure strain values in our study as compared with that of Johnson et al.[25] Furthermore Johnson et al[25] used 2 × 20 mm strips of the VA, whereas we tested the VA intact. These differences in methods may have also contributed to the lower failure strain values they obtained compared with our results, particularly because the strip specimens used by Johnson et al[25] must have been prone to failure at the gripping sites. Unfortunately, they do not report the location of failure of their specimens.

One of the limitations of this study was the use of cadaveric specimens. Panjabi et al[26] reported that the biomechanical properties of cadaveric spinal specimens did not alter significantly even after 232 days of storage at –20°C, and Yamada[24] showed that the tensile properties of common carotid arteries harvested from cattle did not change appreciably after 4 days of refrigeration in normal saline solution. Another consideration is the lack of muscle tone in cadavers. However, in our experience most patients are relaxed before SMT, and there is a force-time delay of at least 150 to 300 ms after the onset of the treatment before the muscles begin to respond to the manipulation.[27] Because most SMTs are completed within 150 ms, and because the muscular forces evoked by SMT start at the earliest at 150 ms after the onset of the thrust, the muscular forces opposing the treatment are of little or no concern, except in those patients who have spasticity in the muscles near the treatment area. This contention is also supported by observations from other investigators.[28-30]

It is important to note that another factor in the use of cadaveric specimens is the condition of the individual. In these experiments it is likely that the failure strains we obtained for the VA were disproportionately low (and thus the relative strains during SMT high) for the following reasons. First, we studied an older population (average: 86.4 ± 7.3 years old; range: 80 to 99 years), most of whom died of cardiovascular diseases (Table 1). Indeed, in cadaver number 4, there was a large aneurysm in the left VA between C3-C4, which did not rupture during the experiment or during the mechanical failure testing (data not shown). Second, although great care was taken during the dissection, it is possible that the VA was nicked or otherwise compromised during the experiment or during removal for the failure testing. Third, the connective tissues, fascial layers, and supporting ligaments may have been separated or removed during the dissection, thus rendering the environment of the VA less stable. Fourth, despite the discussion in the preceding paragraph, there may have been some decay in the VA over the 72 hours after death that weakened the biomechanical integrity of the VA. Fifth, up to 40 trials of ROM/diagnostic testing plus SMT were performed while the VA was exposed and perhaps desiccating, before the VA was removed for failure testing, which may have also compromised the blood vessel. Finally, our cadavers were generally quite thin, with little musculature around the cervical spine. However, all of these potential errors tend to make our specimens a "worst-case scenario," and we are confident that our estimates of the forces and strains sustained by the VA during SMT are very conservative.

We observed large individual variations in the behavior of the VA. For example, we recorded absolute failure forces for individual VAs (proximal and distal segments) ranging from 4.2 N to 18 N and at strains ranging from 31% to 75% above the resting, neutral strain (data not shown; only mean values are presented in Tables 2, 3, and 4). The raw strain values measured during SMT ranged from 0.5% (contralateral C1/C2 break) to a maximum of 14.7% (ipsilateral C3/C4 break) for individual VAs (data not shown; only mean values are presented in Tables 2, 3, and 4). This large variability was also echoed by Johnson et al.[25]

Another assumption in this study is that the forces acting on the VA during SMT occurred in a linear, longitudinal fashion as opposed to a radial, transverse, or other 3-dimensional (eg, spiral) fashion. Because the VA loops backwards around the C1 transverse process in vivo, the results from failing it in a longitudinal direction ex vivo should be interpreted with caution. Johnson et al[25] tested their VA specimens both radially and longitudinally. They observed that the strains were significantly lower longitudinally (38.7%) than radially (59.4%). Based on those results, they speculated that longitudinal extension as measured in this study would likely be the primary cause of VA injury.

The clinical relevance of these results is equivocal, mainly because these were single, manipulative thrusts in a non-living subject. Although we can comment on the biomechanical properties of the VA, we cannot interpolate these results into a living system. For example, we cannot predict the results of repetitively stretching the VA in vivo to 6% strain over a period of time, nor can we comment on the development of microtears and so on in the walls of the VA. These questions are currently being pursued in our laboratory with the use of an animal model.

Conclusions

SMT resulted in strains sustained internally by the VA that were similar to those experienced during neck ROM testing and VBI screening. These strains were almost an order of magnitude lower than those required to mechanically disrupt the VA. We conclude that under normal circumstances, a single, typical (high-velocity/low-amplitude) SMT thrust is very unlikely to tear or otherwise mechanically disrupt the VA.

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