NOTE   *Surgery*

Biomechanical evaluation of three ventral fixation methods for canine atlantoaxial instability: a cadaveric study

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ABSTRACT.   We evaluated comparatively the mechanical strength in three kinds of surgical fixation techniques for canine atlantoaxial joint. Atlantoaxial plate fixation (APF), polymethylmethacrylate (PMMA) fixation (PMF) and transarticular fixation (TAF) were applied to the atlas and axis harvested from healthy beagle dogs, and then, the specimens were tested. The PMF group had significantly higher resistance to flexion than the APF group (P=0.030) and the TAF group (P=0.004). There were no significant differences in resistance to torsion between the APF group and the PMF group, while the APF group had significantly higher resistance to torsion than the TAF group (P=0.037). Considering the possible drawbacks of using PMMA, the APF method is proposed as an alternative to the PMF method.
KEY WORDS: atlantoaxial plate fixation, flexural stress, polymethylmethacrylate fixation, torsional stress, transarticular fixation

Atlantoaxial instability (AAI) is characterized by various degrees of spinal cord injury in the region of the cervical spine and is commonly encountered in the field of veterinary neurosurgery [3, 6, 16, 29, 34]. AAI has been reported not only in small-sized dogs, but also in large-sized dogs and cats [12, 27, 32, 35]. AAI occurs, because of congenital dysplasia of the atlantoaxial joint (AAJ), including odontoid hypoplasia, non-fusion, incomplete ossification and malformation, as well as acquired trauma-related instability, subluxation or dislocation (fracture or ligament rupture) [6, 16]. Surgical treatment is recommended for most AAI patients with congenital lesions and neurological abnormalities, severe neck pain, and lack of response to conservative treatment [10, 16, 26]. Two techniques are used for surgical treatment, namely, ventral stabilization and dorsal stabilization. Currently, the former is widely used because the success rate of the surgery is high, and the necessity for re-operation and surgery-related mortality rate are low [2, 3, 6, 9, 13, 22, 24, 34]. In addition, because the articular cartilage of the AAJ is removed and a cancellous bone is grafted during ventral fixation, bone fusion might be promoted with this approach [4, 9, 22, 24]. In the ventral approach, after reduction of the subluxated AAJ, the odontoid can be removed under visual inspection, if necessary. Stabilization of the AAJ is performed using a transarticular fixation (TAF) method that employs bone screws or positively threaded profile pins (PPP), using a supportive fixation method that employs bone screws, PPP and polymethylmethacrylate (PMMA), or employs PPP and PMMA, and using a plate fixation method, with the final goal being bony fusion of the AAJ [1, 2, 7, 9, 16, 17, 21–26, 28–31, 35]. Stabilization from the ventral aspect is an established surgical procedure, which is a widely used surgical method. Because the AAJ has torsional mobility centered on the odontoid process of the axis, it is important in ventral fixation surgery for AAI to ensure not only resistance against flexural loading, but also against torsional loading, until the AAJ bone is fused. Though many reports exist about various techniques for AAI and pathophysiology of AAI, to our knowledge, there is little biomechanical study. Reber *et al.* reported that the alar ligaments seem to be the most important ligamentous structures for stabilization of the AAJ under shear load [18]. Forterre *et al.* reported that the increased range of motion was observed during lateral bending as well as flexion in AAI [8]. Riedinger *et al.* reported that ventral fixation achieved by transarticular screws and ventral plate provided greater AAJ stabilization under shear loading than dorsal clamp fixation [20]. The objective of this study was to compare the mechanical strength in three kinds of surgical fixation techniques for canine AAJ, including atlantoaxial plate fixation (APF), multiple metallic implant and PMMA fixation model (PMF), and TAF. TAF was performed with each of the techniques used.

The atlas and axis were harvested from 18 healthy Beagle dogs (11 males and 7 females; weight: mean 10.6 kg, range 9.0–14.6 kg; and age: mean 30.2 months, range 12–75 months) that were euthanized by intravenous administration of barbiturates for reasons unrelated to this study. Euthanasia of the dogs was performed in accordance with the Guideline for Care and Use of Laboratory Animals of Nippon Veterinary and Life Science University (approval No. 46J-27). To facilitate installation into the jig of the test

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equipment and to avoid extraneous influences, the bones were cleared of the surrounding soft tissue, including the dorsal atlantoaxial ligament, the transversal ligament and the articular capsule, as much as possible. Specimens were then immersed in 70% ethanol for delipidation and cryopreserved at −30°C before preparing the fixation model. The anatomical dimensions of the specimens are presented in Table 1.

In this study, we designed and created a prototype of the atlantoaxial fixation plate to fit a Beagle dog of 10−15 kg in body weight, based on DICOM CT data of Beagle dogs, for the purpose of safe and secure ventral fixation of the AAJ in dogs. The plate was designed so that locking screws could be used in most cranial screw holes on the most cranial side of the plate, and cortex screws could be used in all the other screw holes. In particular, the screw hole of the cranial side of the plate was designed to incline 5 degrees to the outside, and the most caudal side of the plate was designed to incline 15 degrees to the outside, so that entering the spinal canal could be avoided. The fixation procedure was as follows. First, φ1.4-mm Kirschner *wires* (Setagayaseiki Co., Machida, Japan) were inserted through the holes of the atlantoaxial fixation plate on both sides of the cranial ridge of the ventral aspect of the axis and advanced bilaterally into the pedicles of the atlas for TAF. Next, using a φ1.5-mm drill bit, pre-drilling was carried out through the screw holes of the atlantoaxial fixation plate, followed by completion of atlantoaxial TAF with φ2.0-mm cortex screws (length 22 mm, Setagayaseiki Co.) with proper positioning [27]. Subsequently, two φ2.0-mm cortex screws (length 18 mm, Setagayaseiki Co.) were inserted bilaterally on the caudal side of the pedicle of the axis (one screw each side) through the screw holes of the atlantoaxial fixation plate. Two φ2.4-mm locking screws (length 22 mm, Setagayaseiki Co.) were also inserted into the pedicle of the vertebral arch of the atlas to complete plate fixation (Fig. 1). The plate consisted of pure titanium (ASTM F67 Grade2, Setagayaseiki Co.), while the screws and wires consisted of titanium alloy (ASTM F136, Setagayaseiki Co.). Six fixation models were prepared using the same method.

The PMF method was performed with minor modifications of the method reported by Schulz *et al*. [24]. Kirschner *wires* (φ1.4-mm, MIZUHO Co., Tokyo, Japan) were inserted bilaterally from the cranial ridge of the ventral aspect of the axis and were advanced bilaterally into the pedicles of the atlas for TAF. Subsequently, pre-drilling into the pedicle of the atlas was carried out bilaterally using a φ1.7-mm drill bit, and two φ2.4-mm cortex screws (length 22 mm, MIZUHO Co.) were inserted. Then, pre-drilling was carried out on the caudal aspect of the pedicle of the axis using a φ1.5-mm drill bit. After inserting two φ2.0-mm cortex screws (length 18 mm, MIZUHO Co.), supportive fixation was achieved with PMMA (Stryker Co., Kalamazoo, MI, U.S.A.) (Fig. 2). The supportive fixation screws were completely covered with PMMA, which was subsequently covered with the longus colli muscle. We presumed that the thickness of the longus colli of beagle dogs with a similar frame exceeded 10 mm, after measuring X-rays images. Measurement of the applied PMMA was as follows: length all 39 mm; width

Table 1. The size of the atlas and axis of each fixation group

		APF	PMF	TAF
Atlas	Length	25.5 ± 1.7	26.0 ± 0.8	25.5 ± 1.3
	Width	65.3 ± 5.6	66.5 ± 2.4	66.8 ± 1.3
	Height	25.5 ± 1.7	24.5 ± 1.3	26.5 ± 1.3
	Vertebral canal diameter	14.7 ± 0.6	14.5 ± 0.6	14.5 ± 0.6
Axis	Length	37.5 ± 4.7	38.3 ± 0.5	37.8 ± 2.5
	Width	30.8 ± 1.3	31.0 ± 1.6	33.0 ± 1.2
	Height	31.0 ± 2.4	32.8 ± 0.5	33.5 ± 0.6
	Vertebral canal diameter	8.7 ± 0.6	8.8 ± 0.5	8.5 ± 0.5

The 18 specimens tested in the present study were not statistically significantly different in terms of the sizes of the atlas and axis.

28–33 mm (mean 30 mm); and thickness 9–10 mm (mean 9.75 mm). The area of the cross section of the applied PMMA was 351−390 mm^2 (mean 380.3 mm^2). The implants were made of stainless steel (SUS316L, MIZUHO Co.). Six fixation models were prepared using the same method.

The TAF method was performed as reported by Sorjonen *et al*. [30]. Gliding holes were created in the cranial aspect of the axis using a φ2.5-mm drill bit bilaterally from the cranial ridge of the ventral aspect of the axis. Then, thread holes were created in the pedicle of the atlas by advancing a φ1.7-mm drill bit. Cortex screws (φ2.4 mm and length 22 mm, MIZUHO Co.) were inserted, and TAF was carried out using the lag screw fixation method (Fig. 3). The implants consisted of stainless steel (SUS316L, MIZUHO Co.). Six fixation models were prepared using the same method.

Three fixation models were used from each group, yielding a total of nine fixation models for the flexural strength test. Flexural testing equipment (SHIMADZU Co., MST-1, Kyoto, Japan) was used in this test. A cylindrical metal atlas fixation jig (φ10 mm) and metal axis fixation jig (φ8 mm) were inserted into the spinal canal of the atlas and axis of each test model and secured with dental resin (GC Co., Tokyo, Japan). The axis fixation jig was secured in a device, and the exposed part (10 mm) of the atlas fixation jig was loaded from the vertical direction, which is the major axis of the atlas fixation jig. A load was applied to the atlas in the ventral direction by moving the atlas fixation jig. The test speed of the flexural testing equipment was 10 mm/min throughout. By increasing the load, the maximum load that caused failure (the breaking point) and the failure site in each test model were recorded.

Three fixation models were used from each model group, yielding a total of nine fixation models for the torsional strength test, which was performed using screw clamping testing equipment (Japan Instrumentation System Co., MST-500NM, Sakurai, Japan). A hexagonal fixation rod (φ7 mm) was inserted into the spinal canal of the atlas and axis of each test model and was secured with dental resin. The hexagonal fixation rod was positioned at 35 mm between the chuck of the fixation side and the axis on the axis side, and at 45 mm between the chuck of the torsion side and the atlas on the atlas side. The torsional strength test was carried out by fixing the axis side and rotating the atlas side in a counterclockwise
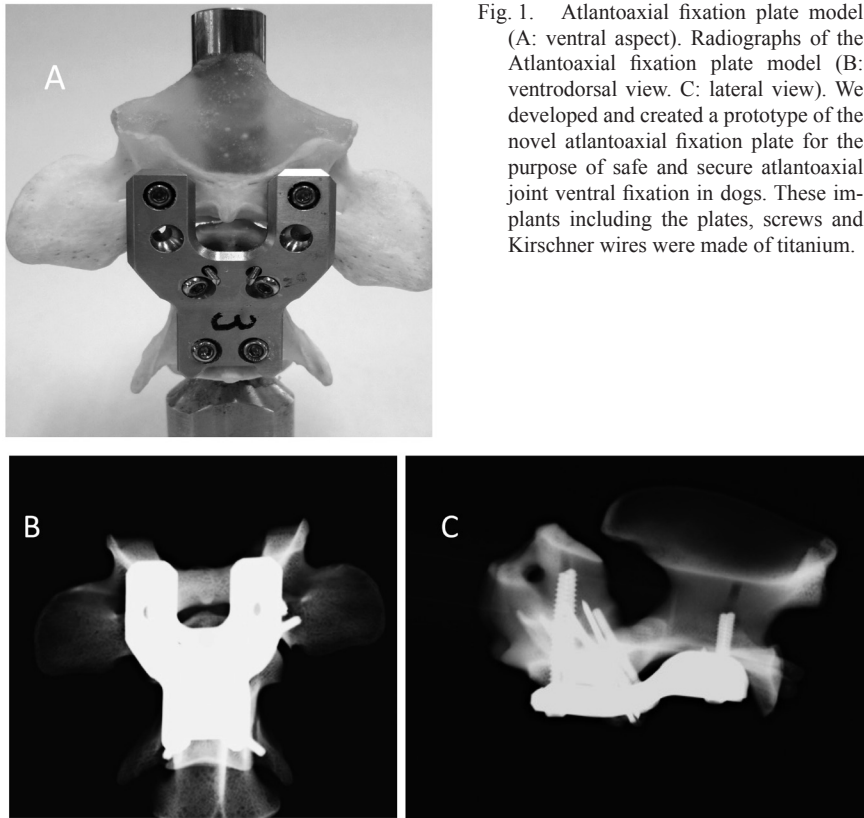
Fig. 1. Atlantoaxial fixation plate model (A: ventral aspect). Radiographs of the Atlantoaxial fixation plate model (B: ventrodorsal view. C: lateral view). We developed and created a prototype of the novel atlantoaxial fixation plate for the purpose of safe and secure atlantoaxial joint ventral fixation in dogs. These implants including the plates, screws and Kirschner wires were made of titanium.

direction as viewed from the cranial aspect. It was rotated at a test speed of 6 degrees/sec. The maximum load that caused failure and the failure site of the test models were recorded.

Statistical analysis was performed using statistical software (SPSS version 22.0, Chicago, IL, U.S.A.). If the P-value in the test for homogeneity of variance exceeded 0.05, the Bonferroni method was applied, and if it was smaller than 0.05, the Kruskal-Wallis test was used. The Bonferroni method was used to compare the atlas length and width, while the Kruskal-Wallis test was used for evaluation of the atlas height, vertebral canal diameter and the axis length, width and height. In addition, the Bonferroni method was used to compare the maximum load in the flexural strength test and the torsional strength test. The significance level was set at $P<0.05$ for all tests.

The 18 specimens tested in the present study were not statistically significantly different in terms of the sizes of the atlas and axis. Thus, the same standard bone specimens were used in each group in the present study, and the mechanical test results were not affected by the physical size of the specimens. In the flexural strength test, the PMF group could bear a significantly higher maximum load than the APF group ($P=0.030$) and the TAF group ($P=0.004$, Table 2). There were no significant differences in the maximum load between the APF group and TAF group. In the torsional strength test, the APF group showed the highest average maximum load of the three groups. There were no significant differences in the maximum load between the APF group and the PMF group,

as well as between the PMF group and the TAF group. The APF group had a significantly higher maximum load than the TAF group ($P=0.037$, Table 2). Fracture was observed in the cranial part of the axis in almost all fixation models in both the flexural strength test and the torsional strength test. No implant damage or deformation was found in any of the plate and screws in all fixation models.

In this study, we developed a prototype of a novel atlantoaxial fixation plate. This custom plate for atlantoaxial fixation is a titanium implant; thus, it may exhibit a high affinity for bone, avoid the PMMA-related complications and accelerate bony fusion of the AAJ. In addition, it has been generally recognized that AAI occurs more frequently in toy-sized breeds. Therefore, in future, we will develop a small plate suitable for dog breeds with a predilection for AAI. With the recent increase in the frequency of craniocervical junction abnormality (CJA), congenital malformations occurring from the occipital bone to the upper cervical spine, with complications, such as hydrocephalus and syringomyelia, postoperative MRI evaluation of titanium implants is becoming feasible [14].

In the present study, we used bone specimens of the atlas and axis, which had been prepared by delipidation with alcohol after removing the surrounding soft tissue prepared, for the following two reasons. First, we wanted to clarify and compare the strength of the various fixation methods by excluding the possible effect of soft tissue supporting the AAJ, including the dorsal atlantoaxial ligament and the transversal
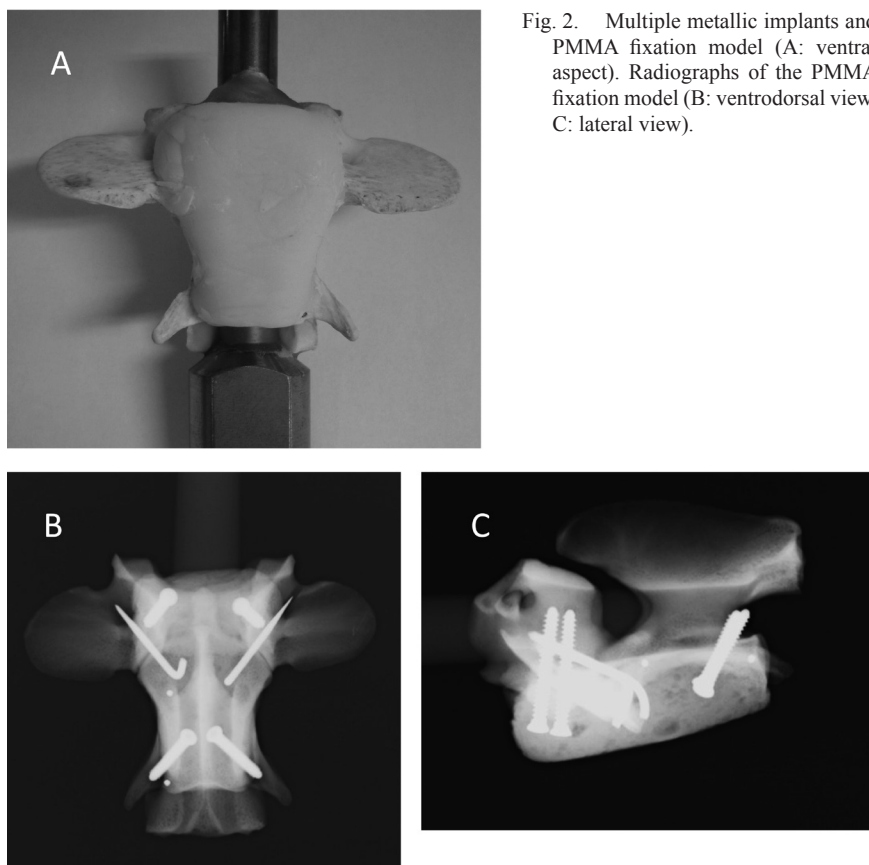
Fig. 2. Multiple metallic implants and PMMA fixation model (A: ventral aspect). Radiographs of the PMMA fixation model (B: ventrodorsal view. C: lateral view).

ligament. Second, this preparation allowed for rigid installation of the fixation models in the jig of the test equipment.

In the flexural strength tests, the PMF group withstood significantly higher maximum load than did the APF group and the TAF group, and showed a high fixation strength against flexural load. However, there were variations in the maximum load of each sample in the PMF group, which was presumed to be due to a difference of fixation strength in each PMF model. The causal factor was not clear, but may have involved differences in the insertion position, the insertion angle of the screw, a slight difference of PMMA volume, and the degree of fixation between the PMMA and screw. In practice, such variation in fixation strength for the same surgical procedure would be problematic, as it would be important to provide constant stability. On the other hand, there was little variation in the maximum load in APF group, because the disposition and angle of the screw were constant, which is advantageous. However, as a disadvantage, this may lead to damage of vital structures in some cases, if the screw insertion position and angle were incorrect. In addition, in the TAF group, which had approximately a third of the maximum load of the PMF group in the flexural strength test, and in which the same standard specimens were used, the insertion position and angle of the TAF screw were virtually fixed and force variation was small.

In the torsional strength test, the maximum load did not differ significantly between the APF group and the PMF group, but the APF group had a significantly higher maximum load compared with that of the TAF group. Implant failure could not be seen in either the flexural strength test or the torsional strength test, but failure was also seen in the cranial aspect of the axis in almost all fixation models in the torsional strength test, similar to that of the flexural strength test. This finding was in agreement with clinical experience, in which the traumatic fracture of the axis tends to involve the cranial portion of this bone. Because this site becomes the narrow articular surface, which is considered to be the point where force is concentrated in the AAJ [11, 33]. In this study, we experienced no problems with implant component strength. In future, it would be important to apply the newly developed titanium atlantoaxial fixation plate in dogs in clinical practice. Among the currently employed ventral fixation methods, the amount of PMMA used in the PMF has not been clearly stipulated. Moreover, there are reports on the disadvantages of using PMMA, such as polymerization heat, which can negatively affect the AAJ fusion site and the surrounding tissue, infection, mechanical pressure on the esophagus and trachea, and breaking of fixation implants [5, 15, 19].

In conclusion, in this study, we prepared atlantoaxial fixation models using atlantoaxial specimens harvested from healthy beagle dogs as a preclinical stage evalua-
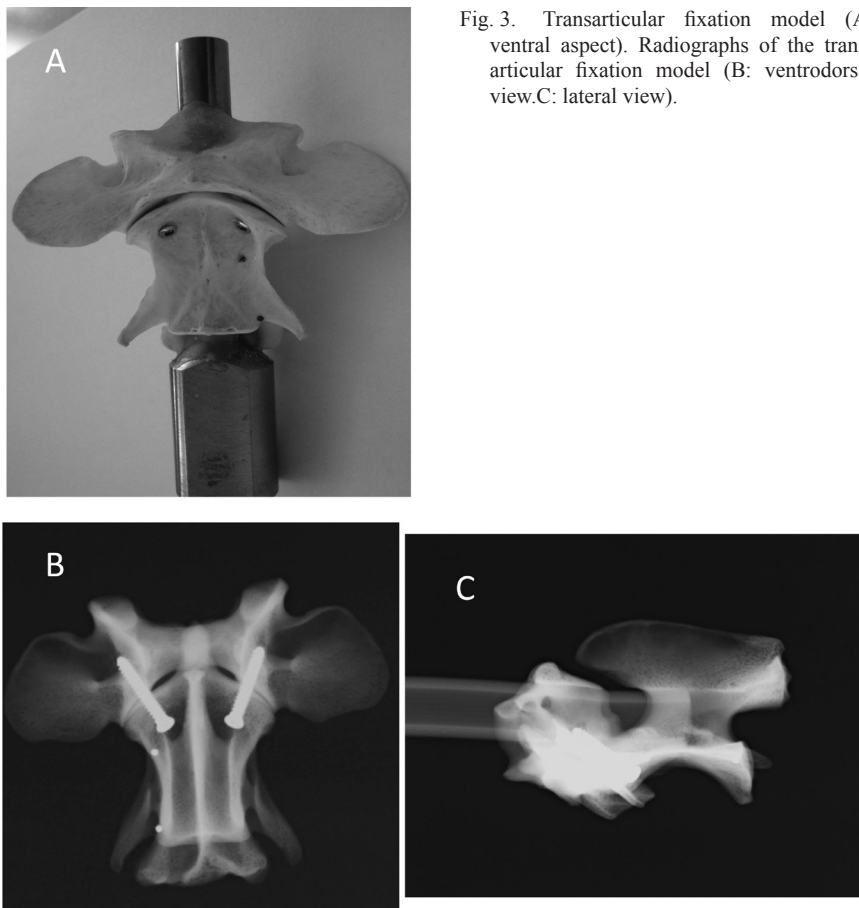
Fig. 3. Transarticular fixation model (A: ventral aspect). Radiographs of the transarticular fixation model (B: ventrodorsal view.C: lateral view).

Table 2. Comparison of the mean maximum load of flexural strength test and torsional strength test in each fixation model group

	APF	PMF	TAF
Flexural strength test the mean (±SD) maximum load (N)	280.0 ± 14.1[*a)]	510.0 ± 122.3[*a,b)]	159.5 ± 41.1[*b)]
Torsional strength test the mean (±SD) maximum load (Nm)	17.0 ± 4.7[*c)]	15.0 ± 1.7	8.4 ± 1.4[*c)]

a) The PMF group had a significantly higher maximum load compared with the APF group (P=0.030). b) The TAF group had a significantly lower maximum load compared with the PMF group (P=0.004). c) The APF group had a significantly higher maximum load than that in the TAF group (P=0.037).

tion of a newly developed titanium atlantoaxial fixation plate for dogs. We compared the mechanical strength, in terms of flexural and torsional force, among the TAF and the PMF and the APF. The currently used PMF was once again proven to be a useful fixation method for AAJ fixation, with the highest fixation strength in flexural test, and with no significant differences in the maximum load between the APF group and the PMF group in torsional test. In addition, considering the drawbacks of using PMMA and because resistance of the torsional load in the AAJ is similar to that of the PMF, less variable results in terms of fixation strength can be obtained using the atlantoaxial fixation plate. Thus,

the APF is considered an alternative fixation method to the PMF. In future, it will be important to apply the titanium atlantoaxial fixation plate *in vivo* in clinical practice and to analyze the results of AAJ bony fusion as a final outcome in AAI surgical treatment.

The patent application about this plate does not go, and the authors declare no conflict of interest.

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