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Bending Laser Manipulator for Intrauterine Surgery and Viscoelastic Model of Fetal Rat Tissue

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***Abstract*— A bending laser manipulator of 2.4 mm in diameter has been developed for intrauterine fetal surgery. This manipulator deflects a laser fiber in any direction thorough 90 degrees. The results of a positioning test and *in vitro / in vivo* tests are reported. Meanwhile, creep tests for fetal rat tissue of 16 to 20 days in gestation were performed to evaluate fetal tissue fragility. Unique features of fetal rat tissue compared to other soft organs are discussed and a viscoelastic model of the fetal rat tissue was proposed. The result of the modeling will be used not only for fabricating fetal tissue phantom but also for the force control of robotic application for fetal surgery.**

I. Introduction

RECENT progresses in prenatal diagnosis have enabled accurate identification of fetus with treatable congenital malformation. Fetal intervention has been developed over last two decades to provide better perinatal prognosis for the fetus with the diseases which deteriorate before birth. Open fetal surgery has successfully treated a number of fetuses, but its invasive technique including maternal laparotomy followed by hysterotomy occasionally causes critical problems; preterm labor or premature rupture of the chorioamniotic membrane. Meanwhile, minimal access fetal surgery has been introduced in the hope that less invasive surgery will result in better therapeutic outcomes with shorter hospital stay and smaller expenses [1].

Minimal access fetal surgery now achieves better therapeutic results, however, the access to the surgical target in the uterus using the conventional rigid tools through both abdominal and uterine walls is difficult for surgeons. Besides, the technical difficulty for handling a fetus of fragile tissue in amniotic fluid prevents further expansion of minimal access fetal surgery. For these reasons, robotic fetal surgery is expected to overcome the technical difficulties and provide safer operative techniques.

In this paper, a bending laser manipulator of 2.4mm in diameter has been developed to deflect a laser fiber freely *in utero*. The results of its positioning test and *in vitro /in vivo* tests are reported. For handling fragile fetal tissue with robotic tools, the fetal tissue fragility was evaluated as a first step. Shear creep tests for fetal rat tissue at 16 to 20 days gestation were performed to measure its properties. Other soft organs (brain, lung and liver of an adult rat) were also tested in the same condition to illustrate the unique features of fetal tissues. Finally, the prototype of a robotic patch stabilizer and future works are discussed.

II. Fetal Surgery

A. Clinical Targets

Our target surgical procedures are laser photocoagulation of placental vessels in twin-twin transfusion syndrome (TTTS) [2] and intrauterine repair of fetal myelomeningocele (MMC) [3]. TTTS is seen in 10 to 15 % of monochorionic diamniotic twin pregnancies (single placenta and two amniotic sacs). In TTTS, one twin (donor) and the other (recipient) have imbalanced blood flow through anastomotic vessels in the shared placenta. The donor is accompanied by significantly less blood supply resulting in definitely decreased amniotic fluid, whereas the recipient with much increased blood flow presents with a large amniotic fluid volume. Without any prenatal treatment, both twins are likely to die or have irreversible brain damages. Currently, intrauterine laser photocoagulation of placental anastomotic vessels has been performed to interrupt responsible blood flow using a Nd:YAG laser fiber mounted on a fetoscope. When the placenta is located anteriorly (anterior placenta, 40 % of the whole pregnancy), an available window on the maternal abdominal wall is occasionally quite limited to avoid intraoperative placental injury. Therefore, we have proposed a bending laser manipulator that deflects a laser fiber freely *in utero* to treat TTTS with an anterior placenta (Fig.1) [4].

The other target disease, myelomeningocele (MMC), is congenital anomaly having spinal bone defects with open spinal canal. MMC is not life-threatening, but mechanical and chemical stimulus to the exposed spinal code and spinal fluid leakage worsens postnatal infant's neurologic function with resultant life-long disabilities. Recently, intrauterine patch

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coverage of the spinal defects has been reported as a temporal protection method of the diseased part before birth[5]. Although a patch is sutured on the defect area in the technique, we proposed less invasive procedure to attach a collagen patch onto the fetus using laser [6]. In the proposed procedures, A collagen patch is stabilized on to the fetus using a robotic patch stabilizer while the laser from the bending laser manipulator welds the patch to the fetal tissue (Fig.2).This robotic surgery is expected to enable easier manipulation and shorter operation time.

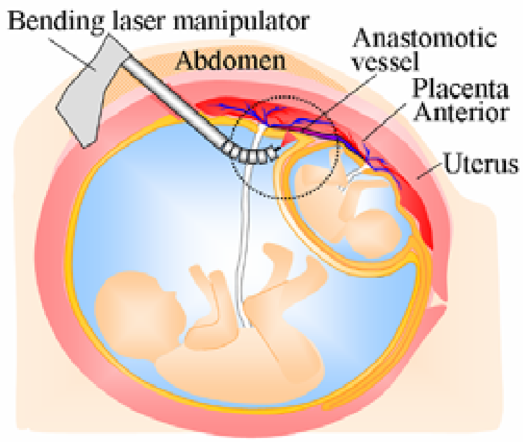

Fig. 1. Proposed TTTS surgery with a bending laser manipulator

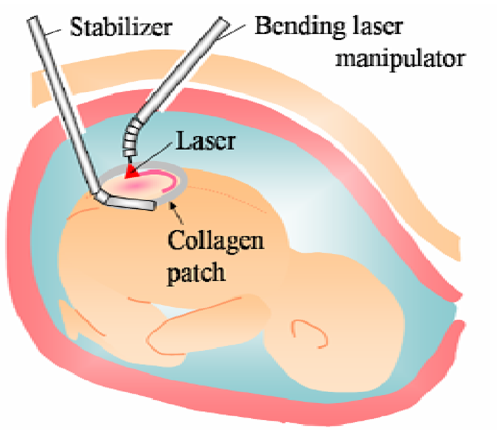

Fig. 2. Proposed MMC patch coverage procedure with a bending laser manipulator and a robotic patch stabilizer.

B. Surgical Robots for Fetal Surgery

Many studies have conducted to enhance the endoscopic operability and some commercial surgical robots [7] are used in clinical cases. These robotic techniques are expected to be introduced also in minimally invasive fetal surgery. However, experiments applying commercial surgical robots to fetal animal surgery [8-10] reported many problems. Commercial surgical robots of 5 mm or more were too big for the allowable surgical incision. Moreover, one report found that although the surgical robot is costly and required long setup time, clinical outcomes differed little.

In the meantime, researchers have studied to develop surgical devices specially designed for fetal surgery including a fetal blood sampling robot [11], a forceps manipulator [12], laser device [13], a microfabricated instrument for haptic tissue recognition [14] and a three components force sensorized tip [15].

Our approach is to develop inexpensive, simple, thin robotic manipulators available for fetal surgery. The evaluation of fetal tissue fragility is also studied for the force control of the robots. The developed manipulators are expected to be useful not only in fetal surgery but also in other kinds of minimally invasive surgery.

III. Bending Laser Manipulator

A. Bending mechanism

Many kinds of bending mechanism have been studied for surgical manipulators or catheters of small diameter. Such devices includes a SMA actuated catheter [16], wire-actuated manipulators [17-19], hydrodynamic active catheter [20], manipulators with a linkage design [12, 21], and snake-like units using flexible backbones [23].

The bending mechanism of our bending laser manipulator is shown in Fig.3 and its photos are shown in Fig.4 and Fig.5. The diameter was designed to be 2.4 mm so that the manipulator can be inserted into a 3 mm trocar. When the size of incision in the uterus is less than 3 mm, the risk of premature rupture of chorioamniotic membrane is small. The premature rupture of chorioamniotic membrane must be avoided since the fetus at the surgical period cannot survive outside the uterus. Besides, the incision less than 3mm need not sutured since the contractive force of the uterus itself closes the small hole unaided. This unaided incision closure results in faster operation and less chance of amniotic fluid leakage.

The developed bending mechanism is composed of cylindrical parts having four holes and spheres with a hole, and it is assembled without any small gear and pin. These parts are easily assembled just inserting four wires and a central tool. The number of joints can be changed according to the stiffness of the centrally inserted tool. This mechanism enables maximum curvature without adding the breading force to the centrally inserted tool. The maximum curvature is also preferable for the bending motion in a small surgical space. Four wires are moved using two ultrasound motors to control the bending angle through 90 degrees in any direction (up to 180 degrees bending is possible when the centrally inserted tool is soft). The bending angle was commanded either with a handheld 4-directional switch or executing pre-programmed motion.

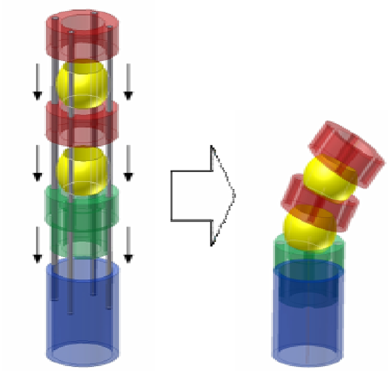

Fig. 3. Bending mechanism (without any gear and pin)

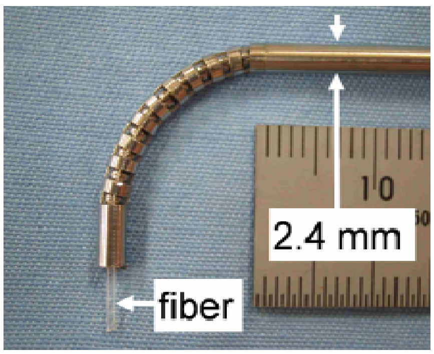

Fig. 4. The bending laser manipulator (2.4 mm in diameter, 2 D.O.F) with a centrally inserted laser fiber (0.7 mm in diameter whose central core is silica glass of 0.4 mm in diameter)

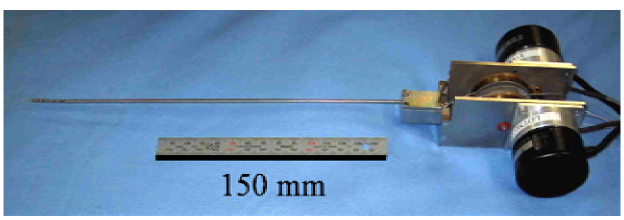

Fig. 5. Bending laser manipulator

B. Kinematics

The kinematics of the bending laser manipulator approximates that of a continuum robot with a backbone [23]. In this paper, the bending curvature was supposed to be constant.

The static deformation of the bending laser manipulator (Fig.6) is described with (1) and (2), where κ is curvature, *F* is wire tension, *a* is the distance from the fiber's center to the hole for the wires, *E* is the fiber's Young's modulus, *I* is the fiber's cross-sectional moments of inertia, and *s* is a parameter of bending arc length (s=*L* at the distal end when the length of the bending part is *L*).

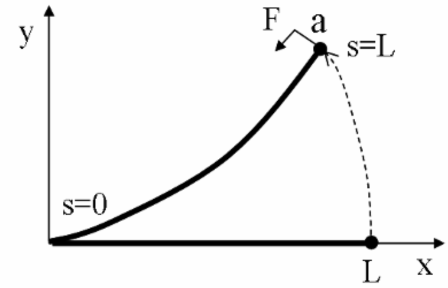

Fig.6 Defined coordinate for a manipulator deflection

$$\kappa = \frac{F \cdot a}{E \cdot I} \tag{1}$$

$$x(s) = \frac{1}{\kappa} \cdot \sin(\kappa \cdot s) \qquad y(s) = \frac{1}{\kappa}\{1 - \cos(\kappa \cdot s)\} \tag{2}$$

Since the designed length of the bending part in the 10-joint prototype in Fig.4 is 19.9mm, the curvature κ is 78.7 m^{-1}. The measured *F* necessary to bend the manipulator to 90 degrees was about 14.7 N. The designed *a* is $0.9 \cdot 10^{-3}$ m, then *EI* is $1.8 \cdot 10^{-4}$ $N \cdot m^2$.

Although the fiber's Young's modulus is unknown (fiber core: silica glass, 0.4 mm in diameter, *E* is $73.5 \cdot 10^5$ N/m^2; fiber coat: polymer, 0.15 mm in thickness), its Young's modulus is equivalent to the silica glass fiber of 0.47 mm in diameter calculated back using (1). This equivalence is reasonable and suggests that precise positioning is possible with wire tension sensing and this deformation model.

C. Positioning test

Sequential bending motions through ± 90 degrees were commanded to evaluate the repeatability of the motion. Two markers were attached to the fiber tip and their positions were tracked using a matching technique of image processing to figure out the bending angle (Fig.7). The result is shown in Fig. 8 and high repeatability was confirmed. The asymmetric motion depending on the direction is due to the difference of initial tension of wires since the initial tension was manually set. The gradual angle change around 0 degree is due to insufficient initial wire tension and small gaps between the fiber and holes in the joint spheres. Although the precise setting of the initial wire tension is important, this high reparability is sufficient for controlling the bending angle with the handheld 4-directional switch under direct vision.

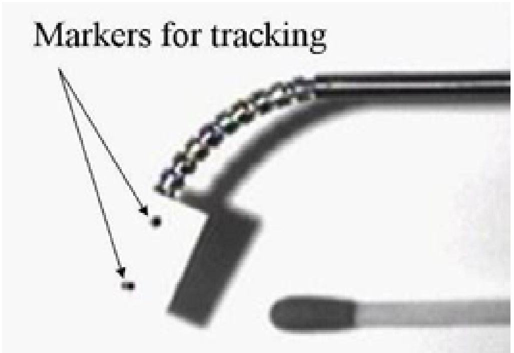

Fig.7 Image processing of tracking two makers for bending angle detection (a matchstick is just for size reference)

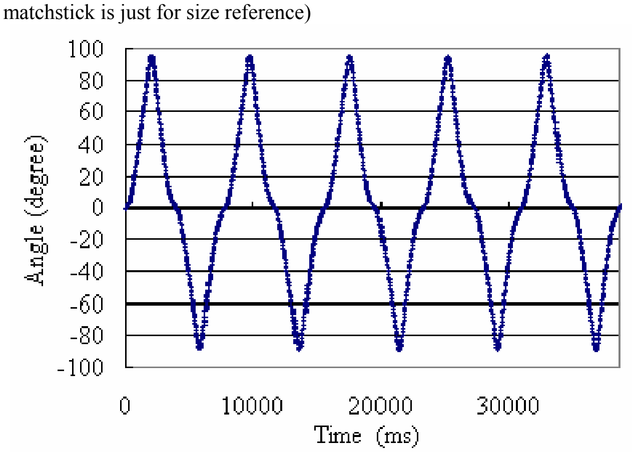

Fig.8 Positioning test for 1 D.O.F bending motion

D. In vitro / in vivo test

In vitro and *in vivo* tests were performed as shown in Fig.9. In the *in vitro* test, red colored guide laser was irradiated on the surface of a Macaca fascicularis's placenta underwater and the bending angle was changed with the 4-directional switch. The result showed that the laser target point was able to cover the large area of the surface while the manipulator itself is fixed.

For the *in vivo* test, Nd-YAG laser photocoagulation was performed for the mesenteric vessels of a rat. The interrupted blood flow of the photocoagulated vessels was confirmed, which showed that this bending mechanism can deflect the thin fiber of 0.7 mm without damaging it.

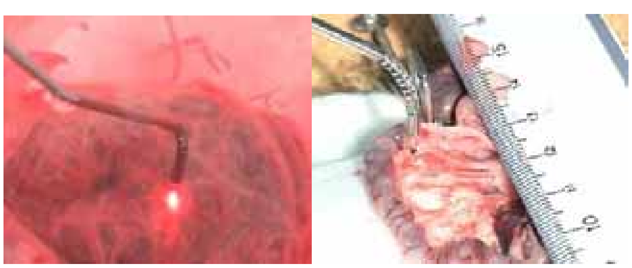

Fig.9. In vitro and In vivo tests (Left: guide laser positioning test for Macaca fascicularis's placenta underwater (in vitro), Right: laser photocoagulation test for the mesenteric vessels of a rat (in vivo))

E. Discussion

Good performance of the developed manipulator was confirmed in the *in vivo* test. When the manipulator was controlled with the switch under the direct vision of the target, the operator easily controlled the tip of the manipulator to his/her target point. Improvement of the positioning accuracy will enable the combination of the manipulator and navigation systems using endoscopic image, ultrasound or MRI data.

On the other hand, problems with the handheld manipulator interface were observed. When operators were allowed to move the manipulator around a trocar while controlling bending motion, they found it difficult to combine all movements to position the manipulator's tip as they want. This problem was remarkable when the target area was placed upper side. Another problem is the stagger caused by the pushing the switch when the switch is attached to the manipulator. Handheld manipulators such as [12] are studied since the interface is expected to reduce the cost and be familiar for surgeons, but its usability needs further study.

IV. Viscoelastic Model of Fetal Rat Tissue

A. Goals

Fetal tissue is described by surgeons as soft, fragile, gelatinous, and difficult to handle. The fragility is one of the technical difficulties of fetal surgery. However, the overall mechanical properties of fetal tissue have rarely studied. To establish fetal model based on its properties is important for developing surgical robots such as a robotic patch stabilizer in Fig.2 because the precise and delicate force control will be necessary. Some studies insist that robotic force control using organ model is important for handling soft organs [24,25].

In the following, the shear creep tests for fetal rat tissue are reported and a viscoelastic model is proposed. Brain, lung and liver tissues of an adult rat are also tested under the same test conditions to illustrate the unique features of fetal rat tissue.

B. Methods

Shear creep tests were conducted for the fetal rat tissue of 16 to 20 days gestation (Wistar rat: usually born at 21 to 22 days gestation). A circular test piece of 8 mm in diameter was cut out from the abdominal wall of each fetal rat. The abdominal wall was chosen as a test piece to avoid the influence by growing (hardening) bones. The back skin of the fetal rat would be better as a test piece, but the skin was too thin to perform the creep tests.

A rheometer (AR550, TA-Instrument, New Castle, DE, USA) was used to perform creep tests at 0.1, 0.2, 0.3, 0.4, 0.5 kPa and 5 minutes for loading and 5 minutes for relaxing. 0.05, 0.075, 0.1kPa were loaded to the fetal tissue of 16 days gestation since it fractured around 0.2 to 0.4 kPa. The test piece was placed on a piece of sandpaper attached to the specimen tray to fix the test piece in position. The test piece was then pressed by a geometry plunger (8 mm in diameter) to 0.1 N then shear stress was loaded. A piece of sandpaper is also attached to the tip of the plunger for avoiding slip. Saline water at 36 °C was filled in the specimen tray to simulate intrauterine environment. These tests were performed within 12 hours after the sample resection.

All experimental procedures were performed according to our institutional animal ethics guidelines, which are based on those of the National Institutes of Health of USA.

C. Results

The creep compliance of fetal rats (16 days at 0.1 kPa, 17-20 days at 0.5 kPa), adult rat brain(0.3 kPa), adult rat lung(0.5 kPa), and adult rat liver(0.5 kPa) was shown in Fig. 10. Although the stress dependence was observed, all test results showed viscoelastic properties with the features of instantaneous deformation, retardation and residual strain.

The initial creep compliance represents the instantaneous deformation due to the elasticity of the tissue. The gradual increase represents the time-dependent deformation change due to the viscosity of the tissue.

This result showed the big change of fetal tissue property from 18 days to 19 days in gestations. In visual observation, the fetal tissue is gelatinous before 19 days. It is known that human fetal tissue property is also dramatically changed around 19 weeks in gestation. The equivalent age of human fetus is unknown, it is supposed that so-called gelatinous human fetal tissue is similar the fetal rat tissue before 19 days in gestation.

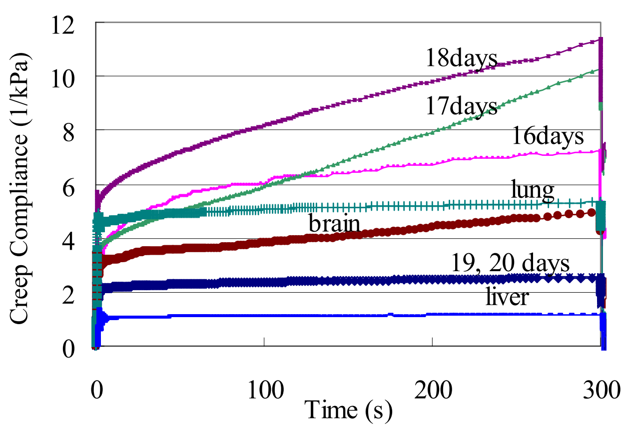

Fig. 10. Creep compliance of fetal rats (16 days at 0.1kPa, 17-20 days at 0.5kPa), adult rat brain(0.3kPa), adult rat lung(0.5 kPa), and adult rat liver(0.5 kPa).

D. Viscoelastic Model

As the first step toward establishing a fetal rat model, the four element model (Burger's model) was used to compare the fetal rat tissue with other soft organs. The four element model is often used for modeling biomaterials and it is expressed with the combination of the Maxwell model and Voigt model as shown in Fig. 11. The creep compliance behavior of the model is expressed in (3) and (4), where J is creep compliance, G_m is elastic coefficient of Maxwell element, η_m is viscous coefficient of Maxwell element, G_v is elastic coefficient of Voigt element, η_v is viscous coefficient of Voigt element, τ is shear stress and U is step input.

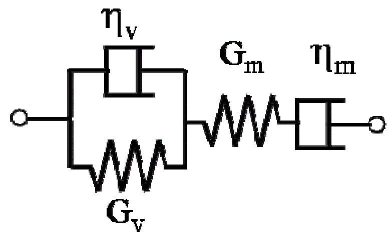

Fig. 11. Four element model (Burger's model) for viscoelastic materials

$$J(t) = \left[\frac{1}{G_m} + \frac{1}{\eta_m} \cdot t + \frac{1}{G_v} \cdot \left\{ 1 - \exp\left(\frac{G_v}{\eta_v} \cdot t \right) \right\} \right] \cdot [U(t)] \tag{3}$$

$$\tau(t) = \tau_0 \cdot [U(t)] \tag{4}$$

The results of the experiments showed in Fig.10 were fitted to the four element model to figure out the parameter values. The identified coefficient values of each material are shown in Table I.

Table I. Identified coefficient values of the four element model

	Gm	hm	Gv	hv	SSE
16 days	0.3	0.7	7.1E-05	0.7	13.1
17 days	0.3	4.8	-7.1E-05	5.4	1.5
18 days	0.2	11.0	1.6E-02	15.9	2.8
19 days	0.5	23.5	5.4E-03	25.0	0.1
20 days	0.5	24.6	7.2E-03	26.3	0.1
brain	0.3	11.8	2.2E-03	13.0	0.9
lung	0.2	13.1	4.2E-03	14.1	0.7
liver	1.0	9.5	4.8E-04	9.6	0.1

E. Discussion and Future works

The identified coefficient value demonstrates the differences between materials. Low elasticity and low viscosity are unique features of fetal tissue and its behavior is totally different from other soft tissues.

Low elasticity and low viscosity means that the tissue is easy deformable and its difficult to keep a constant stress on it. The robotic patch stabilizer in Fig.2 needs to touch a fetus during surgery while keeping adequate force on it because the patch and the fetus must be in contact. The unique features of fetal tissue require precise force control of the robotic patch stabilizer to keep the close contact on it. Since it is supposed to be very difficult for surgeons to control the force while controlling the bending laser manipulator in the procedure in Fig.2, semi-automatic or automatic force control will be useful.

For the future works, the fabrication of fetal phantoms having the similar mechanical properties of fetal rat is in process. A prototype of the robotic patch stabilizer (2.4mm in diameter, 2 D.O.F) has been developed using the same bending mechanism as shown in Fig.12. We have confirmed that the force on the tip of the stabilizer is estimated by measuring wire tension, the next step is to develop a force control method using the fetal phantom.

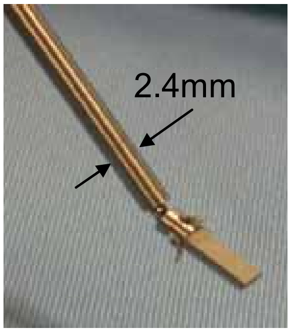

Fig. 12. A prototype of the robotic patch stabilizer

V. Conclusion

The feasibility of the developed bending laser manipulator was confirmed *in vivo*. Further improvement of the positioning accuracy using wire tension sensors is future work to achieve the combination of the manipulator and navigation systems. The evaluated features of fetal rat tissue and the proposed viscoelastic model will lead to the development of a fetal phantom and a force control method of the robotic patch stabilizer or other robotic applications.

Acknowledgment

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