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Progress in cardiovascular anastomoses: will the vascular join replace Carrel's technique?

Piergiorgio Tozzi [a,*], Enzo Borghi [d], Eric Haesler [b], Giuseppe Siniscalchi [a], Alessandro Motti [c], Daniel Hayoz [b], Ludwig K. von Segesser [a]

[a] *Cardiovascular Surgery Department, University of Lausanne, CHUV, Lausanne, Switzerland*
[b] *Vascular Medicine Department, University of Lausanne, CHUV, Lausanne, Switzerland*
[c] *Intensive Care Unit, University of Lausanne, CHUV, Lausanne, Switzerland*
[d] *Idee & Sviluppo, LLC, Bologna, Italy*

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Abstract

Background: Vascular reconstructions are becoming challenging due to the comorbidity of the aging population and since the introduction of minimally invasive approaches. Many sutureless anastomosis devices have been designed to facilitate the cardiovascular surgeon's work and the vascular join (VJ) is one of these. We designed an animal study to assess its reliability and long-term efficacy. **Methods:** VJ allows the construction of end-to-end and end-to-side anastomoses. It consists of two metallic crowns fixed to the extremity of the two conduits so that vessel edges are joined layer by layer. There is no foreign material exposed to blood. In adult sheep both carotid arteries were prepared and severed. End-to-end anastomoses were performed using the VJ device on one side and the classical running suture technique on the other side. Animals were followed-up with Duplex-scan every 3 months and sacrificed after 12 months. Histopathological analysis was carried out. **Results:** In 20 animals all 22 sutureless anastomoses were successfully completed in less than 2 min versus 6 ± 3 min for running suture. Duplex showed the occlusion of three controls and one sutureless anastomosis. Two controls and one sutureless had stenosis >50%. Histology showed very thin layer of myointimal hyperplasia (50 ± 10 μm) in the sutureless group versus 300 ± 27 μm in the control. No significant inflammatory reaction was detected. **Conclusions:** VJ provides edge-to-edge vascular repair that can be considered the most physiological way to restore vessel continuity. For the first time, in healthy sheep, an anastomotic device provided better results than suture technique.

Keywords: Sutureless vascular anastomosis; Vascular connector; Suture technique

1. Introduction

Since the beginning of cardiovascular surgery, proximal and distal anastomoses have been done with hand-held sutures based on the principles of the suture technique described by Alexis Carrel in 1902 [1]. Despite the fact that about 60 other anastomotic techniques have been proposed over the last 100 years, we still use Carrel's technique just because it is reliable and provides the best long-term results. Reliability and excellence of long-term results are the two key elements for any medical device or surgical technique to be widely accepted.

The surgical environment is becoming increasingly challenging for the cardiovascular surgeon ever since minimally invasive approaches and beating heart surgery have been introduced. For example, manual suturing of coronary anastomosis in video-assisted port access surgery on the beating heart, despite the aid of a master-slave robotic surgery system, has proved to be prohibitively difficult [2,3]. Besides, target vessels are increasingly smaller and diseased and surgeons have to deal with vascular reconstructions that are very complex due to the aging of the population and the increasing number of patient's comorbidity.

Surgeons are looking for alternative ways to construct vascular anastomoses in order to reduce the technical demand and improve the quality of the surgical procedure.

The vascular join (VJ) (Idee & Sviluppo Sarl, Bologna, Italy) represents a new anastomotic technology that should reduce the inter-surgeons variability in the anastomosis construction while expediting the anastomosis procedure and seems to fulfill the needs of today's surgeon. In the past 5 years, several sutureless anastomotic devices have been brought to the attention of cardiovascular surgeons [4]. Almost all have excellent early patency rates and are very seductive, however, when we look at long-term results and

* Corresponding author. Address: Cardiovascular Surgery Department, Centre Hospitalier Universitaire Vaudois (CHUV), Rue du Bugnon 46, 1011 Lausanne, Switzerland. Tel.: +41 21 314 23 08; fax: +41 21 314 22 78.
E-mail address: Piergiorgio.Tozzi@hospvd.ch (P. Tozzi).

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compare them with historical patency rates as recommended by the FDA in March 2004, the enthusiasm is over. Several connectors have been withdrawn from the market and others never came forth due to poor long-term outcome.

Therefore, based on this detrimental experience, we designed this animal study bearing in mind that the most important aspect is the long-term patency of the sutureless anastomoses with respect to standard running suture technique.

2. Methods

2.1. Device description

Vascular join allows the construction of end-to-end and end-to-side anastomosis. It consists of two metallic rings fixed to the extremity of the two conduits being joined together. A third polymeric element keeps the two rings together with a snap-on system and guarantee the continuity of the severed conduit in such a way that vessel edges are joined layer by layer (edge-to-edge repair). The ring stays outside the vessel and the connection between the ring and the vessel is made by pins that penetrate into the vessel wall in such a way that there is no contact between the device and the blood stream. Pins (from 6 to 18 depending on vessel diameter) enter the vessel wall from the outside (adventitia) with an angle of 5°, pushed by the delivery system toward the free end of the vessel. During this phase, inside the vessel there is metallic tutor that keeps the correct orientation of the vessel. There is no foreign material (metal or polymers) exposed to blood because part of the device is within the vessel wall, the rest being outside the vessel (Fig. 1). The smallest size being 2 mm, the biggest 30 mm, this device allows the construction of virtually any vascular anastomosis.

In the end-to-side, having a 45° takeoff angle configuration, a saddle element is attached outside the target vessel by means of hooks that penetrate the vessel wall without going trough it. An oval arteriotomy is created using a dedicated rotary blade. The graft, with a premounted 45° ring, is then inserted to complete the anastomosis (Fig. 2).

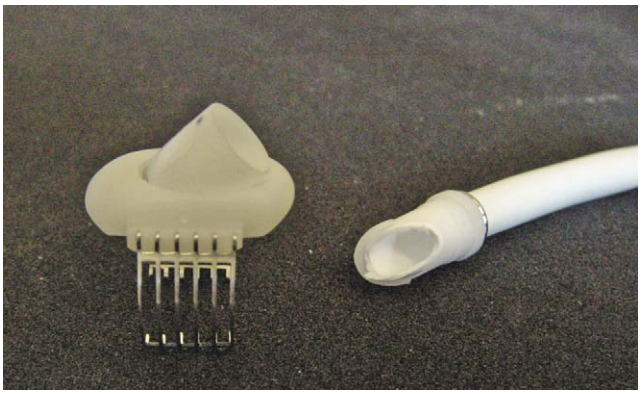

Fig. 2. Vascular join end-to-side anastomotic device. The saddle element is positioned onto the vessel (side part), vessel-device connection is ensured by extravascular hooks. The end side has been loaded on e-PTFE prosthesis.

2.2. Study endpoints

(1) Consistency and reproducibility of the sutureless anastomosis in restoring the vessel continuity avoiding bleeding and/or flow turbulence.
(2) Verification of the 'layer by layer' vessel apposition.
(3) Verification of the absence of foreign material in the vessel lumen.
(4) Consistency and reproducibility of the sutureless anastomosis with an artificial conduit (e-PTFE graft).
(5) Early and long term anastomoses patency rates in comparison to the running suture technique.

2.3. Experimental set up

In adult sheep, 45—55 kg, under general anaesthesia, ECG, and O_2 saturation monitoring, left femoral artery was isolated and a catheter for arterial blood pressure was inserted. Both carotid arteries were isolated and the carotid flow measured using a Doppler probe (Medistim). After administration of Heparin 100 U/kg to keep the activating clotting time above 200 s, one carotid artery was clamped, severed and anastomosed in end-to-end fashion using the connector (Fig. 3). The same procedure was repeated on the other side with the anastomosis constructed using the running suture technique (6/0 polypropylene) as a control.

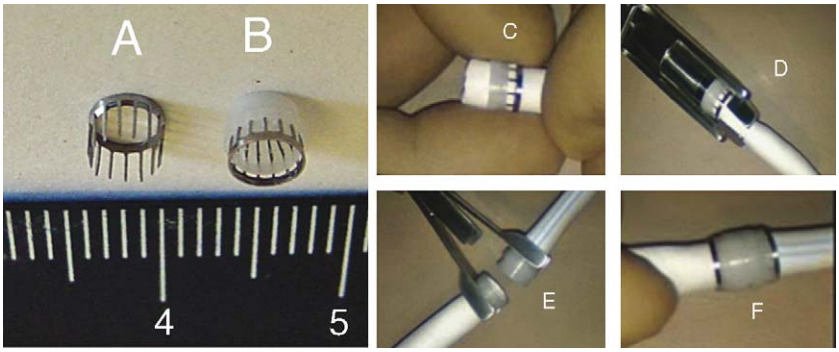

Fig. 1. Vascular join description. The connecting element consists of stainless steel crown (A) inserted in polymeric ring (B). Both are positioned outside the vessel (C) and inserted onto the vessel end using the delivery device (D). The same procedure is repeated on the other end of the severed vessel and the two elements are snapped on (E) to complete the anastomosis (F).

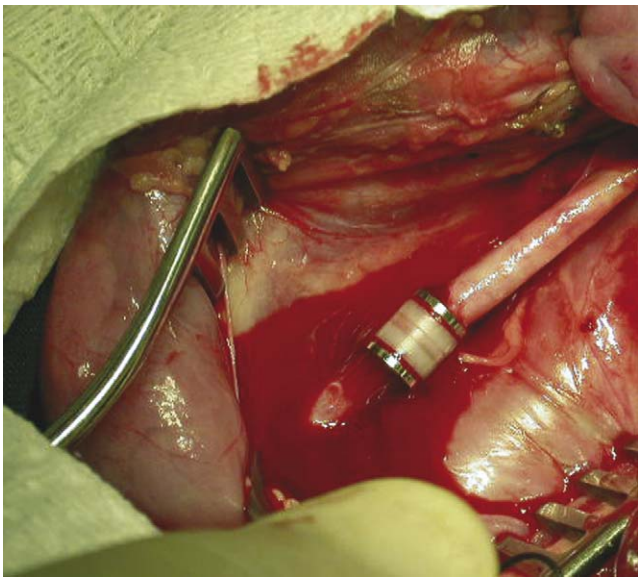

Fig. 3. Surgical technique. The sutureless edge-to-edge anastomoses is completed.

In two animals, a 25 mm segment of both carotid arteries was replaced by 6 mm Ø, 30 mm long e-PTFE thick wall graft. On one side the anastomoses were constructed with the sutureless device, on the other side with the running suture technique.

After the procedure, the carotid flow distal to the anastomosis was measured using Doppler probe.

Two animals received carotid angiogram and intra vascular ultra sound (IVUS with Sonicath Ultra™ 3.2, 20 MHz-Imaging Catheter, Medi.tech® Boston Scientific Corporation) to acquire images on anastomosis quality. IVUS was also used to measure anastomotic diameters in systole and diastole 1 mm proximal and distal to the suture line. These data were used to calculate the anastomotic cross-sectional compliance. Assuming that the anastomosis has a circular shape, anastomotic area (AA) has been calculated with: $AA = \pi r^2$, where r is the anastomotic radius. Cross-sectional anastomotic compliance (CSAC) was calculated as: $CSAC = \Delta AA/\Delta P$, where ΔP is the mean pulse pressure and ΔAA is the mean difference between systolic and diastolic AA.

Animals received Aspirine 100 mg per day. All anastomoses were followed up with Echo-color Doppler control at 3, 6, 9 and 12 months.

After 12 months, animals were sacrificed and both carotid arteries were harvested keeping the inner pressure above 100 mmHg. Histological analysis was carried out to evaluate anastomotic stenosis due to myointimal hyperplasia, thrombosis and vessel inflammatory reaction.

2.4. Specimen preparation

Anastomoses made with the device were fixed in formaldehyde 10%, imbedded in a special acrylic resin, and cut with a diamond-coated wire saw developed for cutting tissue samples with metallic implants in situ. Slices' thickness were between 30 and 100 μm. Anastomoses done with the running suture technique were fixed in formaldehyde 10%, included in paraffin and cut with standard microtome. All specimens were stained with hematoxyline—eosine and elastine or toluidine blue.

All animals received human care in compliance with the European Convention on Animal Care and our institutional ethics committee has approved the study.

Data are presented as mean and standard deviation and paired student t-test is applied for statistical analysis.

3. Results

Procedure was successfully performed in 20 animals. Mean carotid artery diameter was 6 ± 0.3 mm. During the procedure, mean blood pressure was 83 ± 12 mmHg and mean activating clotting time was 198 ± 49 s. Twenty-two 6 mm sutureless devices were used and no technical failure occurred. Mean carotid blood flow was for sutured anastomoses 307 ± 55 ml/min before the anastomosis construction and 320 ± 42 ml/min after; for sutureless anastomoses 304 ± 50 ml/min before the anastomosis construction and 320 ± 40 ml/min after.

No bleeding was observed in 18 out of 20 sutureless anastomosis. In two cases a trivial leak occurred and it was controlled with sponge compression over 2 min.

Sutureless anastomoses were completed in less than 2 min versus 6 ± 3 min for the running suture.

Two animals received post-operative angiogram that showed patent anastomoses without stenosis.

In two animals IVUS was used to assess anastomoses quality and demonstrated the correct apposition of each vessel wall layer (Fig. 4). No intimal flaps or dissections were detected.

Mean cross-sectional anastomosis compliance (CSAC) was 3.1×10^{-3} mm^2/mmHg for the control group and 3×10^{-3} mm^2/mmHg for the sutureless group. Detailed results are reported in Table 1.

The Echo-Doppler ultrasound detected one sutureless anastomosis occluded at 12 months and one with stenosis greater than 50% at 3 months control. Twenty out of 22 sutureless (90.9%) anastomoses were wide open with a maximal flow velocity of 100 cm/s (Fig. 5), meaning that

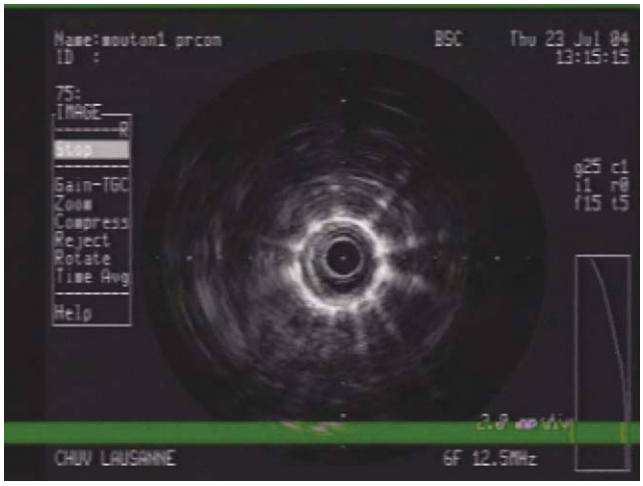

Fig. 4. Animal 2. The intravascular ultrasound (IVUS) has been used to assess the quality of the junction between the two parts of the severed vessel. No intimal flap or dissection have been detected.

Table 1
Cross-sectional anastomotic compliance measured 1 mm proximal and 1 mm distal to the suture line

Anastomosis	Systolic AA (mm^2)	Diastolic AA (mm^2)	ΔAA (mm^2)	ΔP (mmHg)	CSAC ($\times 10^{-3}$ mm^2/mmHg)
Running suture	28.7 ± 0.2	27.6 ± 0.1	1.1 ± 0.1	35 ± 3	3.1 ± 0.1
Vascular join	29.7 ± 0.9	28.8 ± 0.2	0.9 ± 0.6	30 ± 3	3 ± 0.2

Values are expressed as mean and SD.

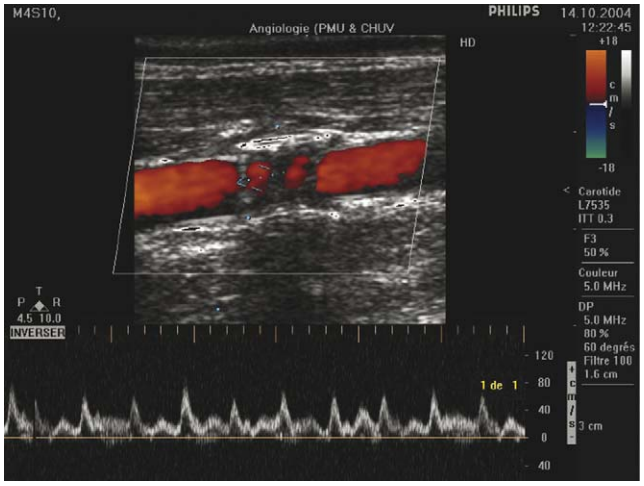

Fig. 5. Twelve-month follow-up. Flow is laminar, without acceleration or turbulence. The mean flow velocity at the anastomotic site is 43 cm/s.

there were no stenosis. Seventeen out of 22 (77.2%) control sutures were wide open with a maximal flow velocity of 100 cm/s. Three control anastomoses were occluded at 3 and 6 months and two had stenosis greater than 50% (mean flow velocity >3 m/s). Anastomoses involving PTFE graft were widely open.

Histology work up showed that metallic connector parts were within the vessel wall. No foreign material was detected in the vessel lumen confirming the 'edge-to-edge' vessel apposition. In the sutureless group, very thin layer of myointimal hyperplasia (50 ± 10 μm) is present, versus 300 ± 27 μm in the control (Fig. 6).

There were no signs of acute or chronic inflammation in any of the specimens.

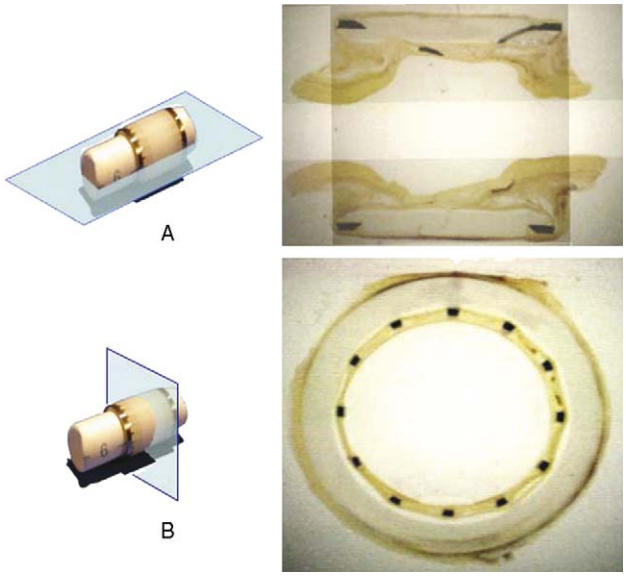

Fig. 6. Histology analysis of the connector explanted 12 months after the procedure (A, axial section; B, coronal section). Anastomosis is wide open. Connector metallic parts are within the vessel wall and there is no foreign material in the vessel lumen, therefore, no contact between the blood stream and device components. 'Layer by layer' vessel apposition is confirmed.

4. Discussion

Cardiovascular surgeons are always receptive to new technologies that can potentially facilitate their everyday work in dealing with complex vascular reconstructions. Furthermore, it is a fact that when the surgical procedure becomes very technically demanding the surgical risk increases as well.

In our hands, vascular join has proven to be a reliable surgical instrument providing consistent and reproducible vascular anastomoses. This surgical technique is simple and intuitive. The deployment system is easy to use, the anastomosis construction takes less than 2 min and no major bleeding has been experienced. However, these characteristics are common to all anastomotic devices developed in the last 10 years [4–6], and in a way, can be considered as a standard requirement for an anastomotic device.

One of the original elements of the VJ is the complete absence of foreign material (metal or polymers) in the vessel lumen, thus in contact with blood stream. IVUS images acquired soon after the anastomoses construction in two animals and histology examination of all anastomoses, including the occluded one, confirm that metallic pins stay in the vessel wall, in the media layer and, in the majority of the specimens, do not even reach the lamina basalis (figure dettaglio isto). Pins have a diameter of 100 μm and their traumatic action on the vessel wall can be compared to that of a 7-0 needle.

Lac of foreign material in the vessel lumen reduces flow disturbances and may reduce the disposition toward the development of intimal hyperplasia or thrombosis [3,8] and data presented seems to support this principle (83% suturless vs 71% sutured anastomoses open, $p = 0.001$). The 12-month follow-up shows excellent results since the luminal width is comparable to that of the native vessel and the flow is laminar as documented by duplex scan. Moreover, the two connectors having important myointimal hyperplasia, leading in one case to vessel occlusion, were the two investigated with IVUS. We could speculate that IVUS catheter had caused intimal lesions that triggered the myointimal proliferation.

Scheltes and co-workers [7] introduced the concept of the Blood Exposed Non Intimal Surface (BENIS) and compared the BENIS of different connectors with the conventionally sutured anastomoses. The sutured anastomosis BENIS area is about 1.3 mm^2 and this was considered as the reference value. Approximate BENIS of several connectors varies from 4.3 to 80 mm^2, depending on anastomotic orifice size, wall thickness, and bonding components' location and size. They concluded that BENIS = 0 is practically impossible to obtain because it would require the complete eversion of the vessel wall that causes prohibitive high wall shear stress eventually leading to vessel occlusion. The VJ is the only exception to this rule: it has BENIS = 0 and the wall shear stress, even if it has not been measured in this study, is probably very close to that of the natural vessel because there is no wall eversion. From this point of view, the suture technique with its BENIS of 1.3 mm^2 has a higher tendency to fail with respect to the sutureless technique examined.

Histology also shows that intima, media and adventitia of the severed vessel, are joined in a physiological way, avoiding the vessel wall eversion. The three layers of the artery wall are faced 'layer by layer' so that intima is in contact with intima, media with media and adventitia with adventitia. This is the first time a surgical technique for vascular anastomosis provides such a natural physiologic vascular reconstruction. The risk of intimal dissection, however, could be a major limiting factor of this physiological reconstruction, even if experimental results do not support it. We can imagine that pins in the vessel wall can play a role in providing some intima layer stabilization.

One potential drawback of this technique is the compliance of the anastomosis because metallic components can alter the elastic properties of the vessel wall. The suture material and the suture technique employed can influence the size and the distensibility of the anastomotic lumen, the wall shear stress and the axial stress eventually affecting the vascular reconstruction outcome [9–11]. As a general assumption, the more the vascular anastomosis is compliant, the less the probability that it could develop a stenosis due to myointimal hyperplasia is. Direct measurement of CSAC confirms that VJ anastomoses are less compliant than the running suture anastomoses, (3.1×10^{-3} mm^2/mmHg vs 3×10^{-3} mm^2/mmHg) even if the difference is not statistically significant ($p = 0.5$). Our previous study [12] demonstrates that suture technique has a substantial effect on CSAC of end-to-side anastomoses. Interrupted suture provides a considerably higher CSAC than continuous suture and can be reasonably considered the most 'physiologic' suture because it keeps the biomechanical properties of arterial wall as close as possible to those of the native vessel [10]. This anastomotic behavior appears to result mainly from the elastic recoil of the arterial wall constituents, which is better preserved with interrupted suture [9]. However, there is no clear evidence that interrupted suture technique provides better long-term results than running suture, and data presented in this study support the hypothesis that CSAC probably plays a less important role than believed in determining long-term anastomoses patency. In fact, even if VJ anastomoses are less compliant, long-term results are significantly improved.

The two techniques show similar behavior since the regression coefficient is almost the same ($R_{sutured} = 0.64$ vs $R_{sutureless} = 0.62$) meaning that the foreign material present outside the vessel and in the vessel wall does not significantly affect the distensibility of the sutured artery. The CSAA slightly increase during systole causing a reduction in vascular resistance and this can improve the blood flow through the anastomosis as first hypothesised in 1960 by Szilagyi and co-workers [13]. However, when we measured the flow through the anastomosis we did not find any difference in systolic outflow between the two techniques and this is probably due to the sensibility of the flowmeter probe.

None of the existing sutureless anastomotic devices can be used with synthetic grafts because of the stiffness of their wall. Two e-PTFE thick wall grafts were implanted using the VJ without any technical failure and this is another important improvement that VJ brings to anastomotic technology. Moreover, the more the vessel wall is calcified, thus rigid, the easier VJs pins penetrate into it for a safe connection.

4.1. Study limitations

Only the end-to-end device has been studied, and even if the end-to-side device works on the same principles, conclusions cannot be extended to it.

The animal model chosen had normal vessels, and even if the VJ works better with rigid conduits, the assumption that it is the ideal device for calcified vessels has to be confirmed by clinical study.

We have learned from the recent past, that even the most attractive and promising sutureless devices have failed in long-term clinical results stifling our enthusiasm. Therefore, to became widely accepted, a sutureless device must fulfill three essential characteristics: easiness, precision and, above all, evidence of long-term effectiveness. We definitely need prospective clinical studies to prove the long-term effectiveness of this helpful device.

Acknowledgement

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