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STATE-OF-THE-ART PAPER

Selection of Coronary Stents

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In clinical practice, the operator must decide which stent is most appropriate for the patient. This article focuses on the features of stent design that make a specific stent more or less suitable for a particular type of lesion or anatomy: the "average" coronary lesion, the lesion situated on a curve, the ostial lesion, the bifurcational lesion, the lesion located at the left main stem, the calcified lesion, the chronic total occlusion, the small vessel, the saphenous vein graft, acute or threatened vessel closure, and special situations such as coronary aneurysms and perforations. (J Am Coll Cardiol 2002;40:1021–33) © 2002 by the American College of Cardiology Foundation

The implantation of coronary stents is an integral part of most interventional procedures for percutaneous revascularization. The wide acceptance of coronary stenting was based on the results of the BElgian NEtherlands STENT (BENESTENT) (1) and the STent REStenosis Study (STRESS) (2) trials and was facilitated by the elimination of anticoagulant therapy after stent implantation (3–5).

The growing use of stents has stimulated the introduction of a number of different stent designs. Table 1 illustrates the characteristics of most of the stents available in 2002. The rapid increase in the number of designs makes any list quickly outdated. Some stent designs are similar, whereas others differ significantly. There are many reasons why different designs have been proposed. Besides the legal requirement to overcome a specific patent, there are concepts of physiologic mechanisms that stimulated inventors to introduce new designs. A primary concern of stent development was the need to increase flexibility to facilitate safe delivery. Manufacturers try to achieve this goal without compromising radial support and lesion coverage. Another element important for optimizing the clinical utility of a stent is its radiologic visibility.

Many of the engineering considerations in stent design were adopted to improve the global acceptability of the device, rather than making a stent design for a specific type of coronary lesion. In clinical practice, the operator must decide which stent is most appropriate for the patient. This article focuses on the features of stent design that make a specific stent more or less suitable for a particular type of lesion or anatomy.

Types of stents. Stents can be classified according to their mechanism of expansion (self-expanding or balloon-expandable), their composition (stainless steel, cobalt-based alloy, tantalum, nitinol, inert coating, active coating, or biodegradable), and their design (mesh structure, coil, slotted tube, ring, multi-design, or custom design) (Table 1). According to the manufacturers, all stents are suitable for implantation in native coronary arteries of the appropriate size. Some stents are approved for implantation in vein grafts. Few stents are specifically designed to be implanted in a particular lesion. The absolute or relative contraindications to the use of stents apply to stents in general and not to a specific stent. Possible exceptions are the Multilink Ultra Stent (Guidant, Temecula, California), which is designed for vein graft implantation with a nine-cell design, by contrast with the six-cell design of the Multilink Tetra. The JoMed polytetrafluoroethylene (PTFE)-covered stent (JoMed, Rangendingen, Germany) is specifically made for uncommon applications such as coronary ruptures, aneurysms, and degenerated saphenous vein grafts.

Different characteristics such as strut thickness, metal to artery ratio, degree of radiopacity, degree of foreshortening, and recoil of many currently used stents are shown in Table 1. All stents are now available premounted on a dedicated delivery system. The capacity of a stent to span a lesion depends not only on the diameter of the crimped stent (Table 2), but also on the amount of friction of the delivery system and stent, flaring of the distal struts during interaction with the lesion, flexibility of the stent and of the delivery balloon, and pushability of the delivery system. It is not surprising to observe a stent with a larger crossing profile cross a lesion easier than a narrower stent with less flexibility.

Two interesting findings came from the stent versus stent randomized trials: 1) the GR-II stent (Cook, Bloomington, Indiana) proved clearly inferior—as far as early complications, binary restenosis, and target lesion revascularization rate—to the Palmaz-Schatz stent (Cordis, a Johnson & Johnson Company, Warren, New Jersey) (6); and 2) the performance of the various other stents and the associated clinical outcome were not different from the Palmaz-Schatz stent. The slightly better deliverability of some stents compared with the Palmaz-Schatz stent, as seen in some of equivalency trials, has now only historical value. Stents used nowadays perform significantly better than any of the early generation devices.

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Abbreviations and Acronyms
IVUS = intravascular ultrasound
PTFE = polytetrafluoroethylene
PTCA = percutaneous transluminal coronary angioplasty

Based on our experience with multiple stent systems, we submit the following observations concerning the application of different stents for specific lesion subsets.

The "average" coronary lesion. Stents were initially indicated for proximal, non-angulated lesions, whereas subsequent generation stents were developed for lesions of tortuous anatomy and complex situations. Some stents are more flexible than others or have a smaller profile and therefore are more deliverable. These extra features become necessary only in selected situations. Most stents currently available are suitable for the majority of coronary lesions, with some exceptions.

The stents to be used in the "average" coronary lesion are the new slotted, tubular stents and some new designs of ring stents.

The primary goal for stenting most coronary lesions is to achieve the optimal lumen cross-sectional area without traumatizing the artery. Currently, the achievement of a large final lumen diameter is the most secure means of limiting restenosis (7). Other appropriate concerns for stent choice are adequate lesion coverage, minimal recoil, and limited plaque prolapse. In addition, because stent length is an independent predictor of restenosis, it is preferable to avoid the use of excessive metal (8,9).

The Palmaz-Schatz stent led the way but now has passed the baton to the BxVelocity (Cordis), as demonstrated in the Very Early Nimopidine Use in Stroke (VENUS) trial, a multicenter registry of the Cordis BxVelocity stent (10). It is likely that the BxVelocity stent will be replaced by the sirolimus-coated BxVelocity (11,12). The BxVelocity stent is applicable for everyday use, and there are only a few conditions in which this stent may not be satisfactory. The BxVelocity stent is available in three different patterns of cells according to the vessel size in which the stent will be implanted: six cells for vessels up to 3 mm, seven cells for vessels up to 4 mm, and nine cells for vessels up to 5 mm. The new version, BxSonic (Cordis), has the same stent mounted on an improved delivery system that is compatible with the 5F guiding catheter (lower profile proximal hypotube shaft, 1.9F vs. 2.6F shaft of the BxVelocity, and 0.5-mm balloon overhang on each side).

The heparin-coated Palmaz-Schatz stent had a low incidence of subacute stent thrombosis, with only five thrombotic events (0.4%) in 1,169 patients treated with this stent in the following trials: the BENESTENT II pilot study (13), BENESTENT II randomized study (14), and the Total Occlusion Study of CAnada (TOSCA) (15), as well as in two protocols involving patients with acute myocardial infarction: the stenting in Primary Angioplasty in Myocardial Infarction (PAMI) pilot study (16) and the stent PAMI randomized study (17). A multicenter feasibility study (use of the Hepacoat BxVelocity stent and an antithrOmbotic regimen of asPirin alonE [HOPE]) is under way to examine the safety of the heparin-coated BxVelocity stent (Hepacoat, Cordis) in "low-risk" patients treated with antiplatelet therapy consisting of only aspirin. The initial results in 202 patients showed no acute stent thrombosis and a rate of 1% of subacute thrombosis (one patient with thrombocytosis and one with post-trauma) (18).

The Multilink Tetra stent (Guidant) has functional characteristics that are similar to the BxVelocity stent. The overall performance of these two stents is excellent, with only selected situations where the Tetra appears to be more deliverable. A unique feature of the Tetra delivery system (similar to the Ultra) is its shaft length of 143 cm, which is 3 cm longer than the BxVelocity stent, whereas all the other delivery systems are 138 or 135 cm long. Compared with the Multilink Tetra stent, the Multilink Penta stent (Guidant) has a modified link pattern, which improves flexibility and scaffolding and maintains side-branch access with the possibility to expand the cell toward the side branch up to 4 mm in diameter.

The careful observer may find more stent-to-vessel conformability with the Tetra stent, but no one knows whether this feature has any clinical consequences. Preserving the original shear stress pattern of the arterial segment may lower the amount of tissue hyperplasia (19).

The NIR stent (Medinol, Jerusalem, Israel; and Scimed, Boston Scientific, Maple Grove, Minnesota), with its new "sox" delivery system, is another important stent to be considered for the "average" lesion. The NIR stent provides excellent plaque coverage, which may be an advantage in lesions prone to plaque prolapse. Plaque may prolapse between stent struts in large vessels with a reference diameter ≥4 mm. The NIR stent is available with a seven-cell or nine-cell structure, which improves plaque support in large vessels, including saphenous vein grafts. The sox delivery system protects the stent while negotiating through calcified lesion or crossing another stent. These features are unique to this type of stent delivery system.

The performance of this stent was evaluated against the Palmaz-Schatz stent in the NIR Vascular Advanced North American (NIRVANA) trial randomized study (20). This trial reported a follow-up restenosis rate of 19.3% for the NIR stent and 22.4% for the Palmaz-Schatz stent. The moderate rigidity of the NIR stent discourages its use through tortuous segments and for lesions located at a severe bend. Because the NIR stent becomes rigid on deployment, this stent may produce a hinge effect that is associated with an increase in restenosis (21). Figure 1 demonstrates the hinge effect caused by the NIR stent. This lesion restenosed four months later at the distal extremity of the stent (Fig. 2). The operator should foresee this possi-

bility and select a more flexible type of stent in lesions with a small radius of curvature.

The positive features of these three stents are also related to the delivery balloon: 1) there is now near perfect retention, which has eliminated the problem of stent loss; 2) there is minimal overhang of the delivery balloon from the stent, which limits trauma and the risk of peri-stent dissection; and 3) there is low compliance, which assures a more homogeneous stent deployment (Fig. 3).

The beStent (Medtronic AVE, Minneapolis, Minnesota) and now the beStent 2, with a closer strut design, are other stents to consider. The unique feature of this stent is the presence of proximal and distal gold markers that allow very precise placement. Another positive feature of the beStent, but not the beStent 2, is the presence of a large or open cell design that facilitates access to side branches.

The Biodivysio stent (Biocompatibles, Galway, Ireland) is another sturdy device with optimal scaffolding that can be considered for most lesions. This stent is available also with an open-cell design that is suitable for lesions involving the origin of side branches. Compared with the open-cell design, the added support design has an extra strut between interlocking arrowheads, which provides greater coverage for lesions that require additional support.

The Biodivysio stent was recently evaluated against the Duet stent (Guidant) in a randomized trial (bioDIvysio STent IN randomized Control Trial [DISTINCT]). Both stents showed an excellent low restenosis rate of 19% in selected favorable lesions. The standard Biodivysio stent delivery system appears to be more rigid compared with other stents and is not ideal for very tortuous arteries. New versions of the delivery system will soon be released to overcome this potential limitation. The availability of a small-vessel design with this stent, which is very trackable and has a low profile, should be kept in mind when confronted with complex anatomy. A unique feature of the Biodivysio family is their phosphorylcholine coating, which lowers platelet adhesion to the stent struts and may be used as a platform for drug delivery.

Among the ring stents, the new S7 (Medtronic AVE) provides more plaque coverage than the S670 and has an angiographic appearance very similar to the slotted, tubular stents. This stent is appropriate for most lesions. In addition, the flexibility, conformability, and lower friction typical of the S7 ring design improves deliverability in complex anatomies or when passing through a stent. An important characteristic of the AVE delivery system is minimal balloon overhang (Fig. 3).

Among the stainless-steel stents with a good track record, the family of stents from PURA (Devon Medical, Hamburg, Germany) and the V-Flex plus (Cook) should be mentioned.

To make the choice more difficult, the interventionist is confronted with other excellent stents such as the Sorin Sirius Carbostent (Sorin Biomedica Cardio, Saluggia, Italy), with its recently refined delivery system (Sorin Synero Carbostent). This stent performs quite well in difficult anatomies and lesions, has platinum end markers, and is covered with a thin layer of turbostratic carbon with the intent to decrease its interaction with platelets. A recent registry report showing a restenosis rate of 11% and a bimodal distribution of the loss index (22) raises the possibility of enhanced biocompatibility of the carbon-coated stent for subjects with an allergy to metal components present in stainless steel (23). At least four other carbon-coated stents are currently available in Europe: the BioDiamond (Plasma Chem, Mainz, Germany), the Diamond Flex (Phytis, Dreieich, Germany), the MAC carbon stent (AMG, Raesfeld-Erle, Germany), and the Tenax (Biotronik, Berlin, Germany). Randomized trials are in progress to test the hypothesis that these inertly coated stents may have advantages over the stainless-steel stents.

Lesions situated on a curve (≥90°) or immediately followed by a curve. Changing the natural conformation of a coronary vessel may have an unfavorable effect on flow dynamics and increase the risk of adverse events during follow-up (24).

For this reason, we prefer stents that conform to the longitudinal profile of the vessel without producing plaque prolapse in the curved segment. The traditional ring design, such as the S670, is quite conformable but may allow too much plaque protrusion when opened in a curved segment. In this respect, the new S7 is a significant improvement. Slotted, tubular stents with thin struts are also conformable (PURA AS and AL 0.07, 0.075-mm beStent, 0.075-mm Sorin Carbostent, 0.08-mm Tenax, 0.09-mm Biodivysio, and 0.09-mm JoStent). Strut thickness is not the only variable that may affect conformability; the complete stent design may be more important. For example, the NIR stent, which is thinner (0.1 mm) than the BxVelocity (0.14 mm), has lower conformability. The Tetra and Penta stents have variable strut thicknesses (0.091–0.124 mm), with excellent conformability. The NIRflex, the new version of the NIR stent, also has excellent conformability.

Ostial lesions. Ostial lesions are classified as either aorto-ostial or coronary-ostial. For aorto-ostial lesions, the slotted-tube design, preferably with strong radial support, low recoil, and radiologic visibility, is the most appropriate one (25). New ring designs such as the S670 and S7 are also appropriate in this setting.

The recent availability of stents with end markers may improve precise positioning. These stents have thin struts, so our preference is to implant them only in coronary-ostial rather than aorto-ostial locations. The strong elastic recoil inherent to the aorta favors the use of thicker struts to provide greater resistance when dealing with lesions involving the true coronary ostia or the aortic insertion of a saphenous vein graft.

When considering the gold-plated NIR Royal for an aorto-ostial lesion, the operator must balance its advantage of better visibility and more precise positioning with its disadvantage of having a higher angiographic restenosis rate

able 1. Stent Engineering Data

Product	Manufacturer	Structure	Material	Strut (Wire) Thickness (mm)	Metal/Artery (%)*	Recoil (%)	Shortening (%)	Radiopacity	Markers	Lengths (mm)	Diameters (mm)
VE S670	Medtronic	Sinusoidal ring	Stainless steel	0.127	19	3	3	Medium	No	9, 12, 15, 18, 24, 30	3.0, 3.5, 4.0
VE S7	Medtronic	Sinusoidal ring	Stainless steel	0.102	17–23	2	3	Medium	No	9, 12, 15, 18, 24, 30	3.0, 3.5, 4.0
eStent 2	Medtronic	Slotted tube	Stainless steel	0.085–0.095	12–17	2	0	Low	Yes	9, 12, 15, 18, 24, 30	2.5, 3.0, 3.5, 4.0
iodivysio AS	Biocompatibles	Slotted tube	Stainless steel	0.091	19–25	2	4	Low	No	11, 15	3.0, 3.5, 4.0
iodivysio OC	Biocompatibles	Slotted tube	Stainless steel	0.091	9–12	4	4	Low	No	15, 18, 22, 28	3.0, 3.5, 4.0
xVelocity/Hepacoat	Cordis, Johnson & Johnson	Slotted tube	Stainless steel	0.14	15	2.5	1.7	Medium	No	8, 13, 18, 23, 28, 32	2.25, 2.5, 2.75, 3.0, 3.5, 4.0, 4.5, 5.0
xSonic	Cordis, Johnson & Johnson	Slotted tube	Stainless steel	0.14	15	2.4	1.7	Medium	No	8, 13, 18, 23, 28, 33	2.25, 2.5, 2.75, 3.0, 3.5, 4.0
arbostent Sirius	Sorin	Slotted tube	Stainless steel	0.075	12–17	3–5	0	Low	Yes	9, 12, 15, 19, 25	2.5, 3.0, 3.5, 4.0
arbostent Syncro	Sorin	Slotted tube	Stainless steel	0.075	12–17	3–5	0	Low	Yes	9, 12, 15, 19, 25	2.5, 3.0, 3.5, 4.0
ook V-Flex	Cook	Slotted tube	Stainless steel	0.07	15	21	0	Low	No	12, 16, 20, 24	2.5, 3.0, 3.5
iamond Flex AS	Phytis	Slotted tube	Stainless steel	0.075	10–18	3–5	1	Low	No	9, 12, 16, 20, 25	2.5, 3.0, 3.5, 4.0
Stent Flex	Jomed	Slotted tube	Stainless steel	0.09	16	4	5	Low	No	9, 16, 26, 32	2.0, 2.5, 3.0, 3.5, 4.0, 4.5
Stent Plus	Jomed	Slotted tube	Stainless steel	0.09	16	4	5	Low	No	9, 17, 27, 33	2.0, 2.5, 3.0, 3.5, 4.0, 4.5
Stent Graft	Jomed	Slotted tube	Stainless steel	0.20	100	2	3	High	No	9, 12, 16, 19, 26	2.5, 3.0, 3.5, 4.0, 4.5, 5.0
P Stent	Boston Scientific	Slotted tube	Stainless steel	0.1	15	2	3–5	Low	No	8, 12, 18, 24	2.5, 30, 3.5, 4.0
IAC Carbon Stent	AMG	Slotted tube	Stainless steel	0.085	8–15	3	1	Low	No	9, 13, 17, 22	2.0, 2.5, 3.0, 3.5, 4.0, 4.5
legaflex Genius	Eurocor	Slotted tube	Stainless steel	0.12	20	1	1	High	No	9, 12, 13, 15, 16, 17, 19, 23	2.5, 2.75, 3.0, 3.5, 4.0
ultilink Tetra	Guidant	Slotted tube	Stainless steel	0.091–0.124	12–20	2–3	3–4	Medium	No	8, 13, 18, 23, 28	2.5, 2.75, 3.0, 3.5, 4.0
ultilink Penta	Guidant	Slotted tube	Stainless steel	0.091–0.124	12–16	2–3	3–4	Medium	No	8, 13, 15, 18, 23, 28, 33	2.75, 3.0, 3.5, 4.0
ultilink Ultra	Guidant	Slotted tube	Stainless steel	0.127–0.101	15–25	2	5	Medium	No	13, 18, 28, 38	3.5, 4.0, 4.5, 5.0
IR, 7 cells and 9 cells	Medinol, Boston Scientific	Multicell design	Stainless steel	0.1	11–18	3	3	Low	No	9, 16, 25, 32	2.0, 2.5, 3.0, 3.5, 4.0, 4.5, 5.0
IR Royal	Medinol, Boston Scientific	Multicell design	Stainless steel, gold	0.1	11–18	5	3	High	No	9, 16, 25, 32	2.0, 2.5, 3.0, 3.5, 4.0, 4.5, 5.0
xpress	Boston Scientific	Multicell design	Stainless steel, gold	0.132	11–17	5	5	High	No	8, 12, 16, 20, 24, 28, 32	2.25, 2.5, 2.75, 3.0, 3.5, 4.0, 4.5, 5.0
-S 153	Cordis, Johnson & Johnson	Slotted tube	Stainless steel	0.062	18	5	8	Medium	No	8, 9, 14, 18	3.0, 3.5, 4.0
URA-A	Devon	Slotted tube	Stainless steel	0.12	10–15	2	1–5	Low	No	7, 15	3.0, 3.5, 4.0, 4.5, 5.0
URA Vario AL	Devon	Slotted tube	Stainless steel	0.07	10–18	3	5	Low	No	6, 10, 16, 24, 28	3.5, 4.0
URA Vario AS	Devon	Slotted tube	Stainless steel	0.07	10–18	3	7	Low	No	6, 10, 16, 24, 28	2.5, 3.0
eneo Tenax-XR	Biotronik	Slotted tube	Stainless steel	0.08	14–22	5	3	Low	Yes	10, 15, 20, 25, 30	2.5, 3.0, 3.5, 4.0
sunami mall-vessel stents	Terumo	Slotted tube	Stainless steel	0.08	18	5	5	Low	No	10, 15, 20, 30	2.5, 3.0, 3.5, 4.0

(continued)

Table 1. Continued

Product	Manufacturer	Structure	Material	Strut (Wire) Thickness (mm)	Metal/Artery (%)*	Recoil (%)	Shortening (%)	Radiopacity	Markers	Lengths (mm)	Diameters (mm)
AVE S660	Medtronic AVE	Sinusoidal ring	Stainless steel	0.127	20	2	1.5	Medium	No	9, 12, 15, 18, 24	2.5
beStent (4 crowns)	Medtronic AVE	Slotted tube	Stainless steel	0.085–0.095	12–17	1.6–2.2	0	Low	Yes	9, 12, 15, 18, 24, 30	2.5
Biodivysio SV	Biocompatibles	Slotted tube	Stainless steel	0.05	9	1	4	Low	No	10, 15, 18	2.0, 2.5
BxVelocity	Cordis, Johnson & Johnson	Slotted tube	Stainless steel	0.14	15	2.5	2	Low	No	8, 13, 18, 23, 28, 32	2.25, 2.5, 2.75
Carbostent Sirius, 4 cells	Sorin	Slotted tube	Stainless steel	0.075	12–17	3–5	0	Low	Yes	9, 12, 15, 19, 25	2.5
CoStent Flex	Jomed	Slotted tube	Stainless steel	0.09	16	4	5	Low	No	9, 16, 26, 32	2.0, 2.5
Jostent Plus	Jomed	Slotted tube	Stainless steel	0.09	16	4	5	Low	No	9, 17, 27, 33	2.0, 2.5
Multilink Pixel	Guidant ACS	Slotted tube	Stainless steel	0.099	15	4	11	Medium	No	8, 13, 18, 23, 28	2.25, 2.5
PURA Vario AS	Devon	Slotted tube	Stainless steel	0.07	10–18	3	7	Low	No	6, 10, 16, 24, 28	2.5

*Does not necessarily mean vessel wall coverage.

than the stainless-steel NIR (37.5% vs. 20.6%, $p < 0.001$), as reported in the NIR Ultimate Gold-Gilded Equivalency Trial (NUGGET) (26). Similar findings were reported with a gold-coated stent manufactured by a different company (27).

For aorto-ostial lesions with a reference vessel size of ≥4 mm in diameter, we have had a positive clinical experience with the BxVelocity, the nine-cell NIR, and the Ultra. All of these slotted-tube stents maintain good radial force, even when dilated to large diameters.

Bifurcational lesions. When approaching a bifurcational lesion, it may be preferable to have a stent with large side openings between the struts that can easily permit passage of a balloon or second stent into the side branch. Figure 4 shows several slotted-tube stents with the cross-sectional area of the cell following stent dilation and with the cross-sectional area of the same cell following the maximal opening of a balloon inflated across the cell into the side branch (28). Many slotted-tube stents are suitable for stenting a bifurcation, with the exception of the NIR stent. The closed-cell design of the NIR does not allow significant expansion of the opening toward the side branch, even after crossing and inflating a balloon. If the operator decides to use the NIR stent, the seven-cell design should be used instead of the nine-cell design.

Another option is to use a stent with a large side opening, such as the Biodivysio open-cell design or the S670. The advantage of this decision is that the initial access to the side branch is facilitated. A possible disadvantage is incomplete prolapse of one strut toward the side branch following a "kissing" balloon dilation (i.e., dilating 2 balloons simultaneously into both branches of a bifurcation). The concept of strut prolapse from the main branch toward the side branch has been pioneered by Dr. Marie Claude Morice and Dr. Tierry Lefevre and termed "stenting both branches with one stent." When the design is very open, there is less possibility for a strut to straddle across the side branch. Slotted-tube stents that best demonstrate this feature are the beStent and Carbostent, but the BxVelocity and Tetra are also adequate (Fig. 5).

Whichever stent the operator uses for a bifurcation, it is important to perform a "kissing" balloon inflation at the end of the procedure to correct the stent distortion that occurs after balloon inflation in the side branch (29). If the operator finds it appropriate to stent both branches, we recommend the modified T or V techniques.

Lesions located at the left main stem. Left main stem lesions may involve treatment of an aorto-ostial lesion and/or a lesion located in the body of the left main artery. Occasionally, there is a need to treat the distal left main stem as a bifurcational lesion.

The reference size of the left main coronary artery is favorable to stent implantation in terms of the restenosis rate. The major problem is that in an unprotected left main artery, stent restenosis may manifest either as sudden death or unstable angina rapidly followed by death. For this

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