Clinical research
Interventional cardiology

Neointimal coverage of sirolimus-eluting stents at 6-month follow-up: evaluated by optical coherence tomography

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Received 6 September 2006; revised 3 October 2006; accepted 9 November 2006; online publish-ahead-of-print 29 November 2006

Aims Since the intravascular ultrasound (IVUS) cannot detect neointimal layers in the majority of sirolimus-eluting stents (SES) at the chronic phase, it is still controversial to what extent SES remain uncovered. However, optical coherence tomography (OCT) with excellent resolution may be able to detect thinner neointima.

Methods and results A total of 34 patients (57 SES) underwent OCT and IVUS evaluations at 6-month follow-up. The thickness of neointima on each SES strut cross-section and strut apposition to the vessel wall was evaluated. By OCT evaluation, the median (25th, 75th percentiles) neointima thickness was 52.5 μm (28.0 μm, 147.6 μm) and the prevalence of struts covered by thin neointima undetectable by IVUS was 64%. The average rate of neointima-covered struts in an individual SES was 89%. Nine SES (16%) showed full coverage by neointima, whereas the remaining stents had partially uncovered strut lesions. Among the 6840 struts visualized by OCT in all of the SES, 79 struts showed malapposition without neointimal coverage, and were frequently observed in the areas of SES overlap.

Conclusion At 6 months, most of the SES were covered with thin neointima, but few showed full coverage.

KEYWORDS Sirolimus-eluting stents; Optical coherence tomography; Neointima; Malapposition

Introduction
Results of large-scale clinical trials have established that sirolimus-eluting stents (SES) inhibit neointimal proliferation and reduce in-stent restenosis,1 although the inhibition of stent re-endothelialization may increase susceptibility to late thrombosis. There have been reports that thrombosis occurred in SES after discontinuation of antiplatelet therapy and more than 1 year after implantation,2–4 a relatively rare occurrence in bare metal stents (BMS). Interest has developed in the classification of a lack of neointimal coverage as a chronic condition. A recent intravascular ultrasound (IVUS) study found that intimal hyperplasia is not visible on most SES even at long-term follow-up.5 The question whether the inability of IVUS to visualize neointima on SES results from an actual tissue deficit or from the limitation of IVUS resolution remained unanswered. A recent study by Kotani et al.6 reported that the use of angioscopy resulted in frequent observations of transparent neointima on SES 3–6 months after stent implantation, suggesting the presence of thin neointimal coverage in SES which IVUS cannot detect. Angioscopy is indeed an important tool for visual qualification, but it cannot quantify the proportion and thickness of the neointimal coverage.

Optical coherence tomography (OCT) is a new imaging modality that visualizes the intra-coronary features with high axial resolution (10–20 μm) which is far better than IVUS resolution (100–150 μm), even though the penetration depth of OCT is limited (1.25 mm), which is inferior to that of IVUS (5 mm).7 Kume et al.8 reported that OCT visualized apposition of stent struts and neointima formation in a cadaver specimen that could not be visualized completely by IVUS. We therefore speculated that OCT may provide more precise information about neointimal proliferation on SES struts and make it possible to quantify the thickness of tissue on the surface of the stent struts. In the study reported here, we performed OCT examinations 6 months after SES deployment for a precise evaluation of neointimalization in SES struts at the chronic stage. These findings may provide important information about chronic SES status.

Methods

Study populations and methods
Between August 2004 and April 2005, 194 patients underwent percutaneous coronary intervention (PCI). BMS was implanted in 116...
patients, because 70 had acute coronary syndrome, and 46 patients had to have non-cardiac surgery or an invasive examination soon after PCI. Another 22 patients underwent PCI without the stent (20 cases of balloon angioplasty and one each of directional atherectomy and rotablator). The remaining 56 patients received 105 SES (CYPHER™, Cordis Corp., Miami Lakes, FL, USA) implantations electively at our hospital. Every patient took 100 mg aspirin at least 1 week before intervention, and 200 mg ticlopidine immediately after SES deployment. This study was approved by the Ethical Committee of Kobe University and all the patients enrolled in the study gave their written informed consent.

Prior to SES implantation, IVUS was performed using Atlantis SR Pro™ catheters (Boston Scientific, Natrick, MA, USA) with an automatic pullback device at 0.5 mm/s to measure the vessel size and to identify the location of the plaque. After the stent implantation, IVUS was performed again to ensure that the SES was fully expanded and well-apposed to the vessel wall. If not, additional high-pressure balloon expansion was repeated until examination of the IVUS indicated that the SES was well-apposed.

After each successful intervention, ticlopidine was discontinued after 3 months but aspirin therapy was maintained on a life-long basis. After 6 months, 20 patients did not consent to the invasive examination and the remaining 36 patients (64%) (60 SES) underwent the follow-up angiography and IVUS in the same manner as before. These patients became the candidate for an OCT examination.

IVUS analysis

Quantitative IVUS analysis was performed using commercially available software (NetraIVUS™, ScImage, Los Altos, CA, USA). Before stent implantation, the lumen area and external elastic membrane (EEM) area were measured. After stent implantation, final EEM area and smallest SES area were measured for the proximal, mid, and distal portion of the stented segments. At the 6-month follow-up, the EEM area, SES area, and percentage of the neointimal area, which was defined as the largest neointimal area divided by the SES area, were evaluated.

OCT examination

With the aid of a 6F guiding catheter, an over-the-wire type occlusion balloon catheter (Helios™, LightLab Imaging Inc., Westford, MA, USA) was advanced into the distal end of the SES implantation site under guidance of a 0.014 in. angioplasty wire. The guide wire was then removed and the OCT imaging probe (ImageWire™, LightLab Imaging Inc.) was inserted through the over-the-wire lumen of the occlusion balloon. With the ImageWire held in place, the occlusion balloon was withdrawn until proximal to the SES. To clear blood from the imaging site, the occlusion balloon was inflated to 0.6 atm. and Lactated Ringer’s solution was infused into the coronary artery from the distal tip of the occlusion balloon at 0.5 mL/s. The entire length of the stent was imaged with an automatic pullback device moving at 1 mm/s and the OCT image clearly visualized the stent cross-section.

OCT analysis

OCT images were analyzed by two independent observers who were blinded to the clinical presentations and lesion characteristics and used proprietary off-line software provided by LightLab Imaging Inc. The OCT image of each stent strut was classified into one of the three categories: (i) well-apposed to vessel wall with apparent neointimal coverage, (ii) well-apposed to vessel wall without neointimal coverage, and (iii) malapposed to the vessel wall without neointimal coverage. A stent strut was classified as malapposed when the distance between its inner surface reflection and the vessel wall was >150 μm. This criterion was determined by adding the OCT axial resolution (20 μm) to the actual thickness of an SES strut (130 μm). If the two observers disagreed, a consensus diagnosis was obtained with repeated off-line readings. Representative images of the three strut categories are shown in Figure 1.

![Figure 1](https://example.com/f1.png)

**Figure 1** Classification of SES strut conditions by OCT. (A) Well-apposed with neointimal coverage. (B) Well-apposed without neointimal coverage. (C) Malapposed without neointimal coverage.
If neointimal coverage on the strut was observed, its average thickness was measured. The potential factors that predispose SES to malapposition—chronic total occluded (CTO) vs. non-CTO vessel, implantation in de novo lesions vs. previously stented restenosed lesions, and SES overlapping vs. non-overlapping areas—were noted. In addition, the frequency of thrombus formation in SES was recorded with a thrombus as observed in the OCT image defined as an irregular mass protruding into the lumen, and measuring ≥250 μm at its thickest point.9

Statistical analysis
Qualitative data are presented with frequencies and quantitative data are shown as medians (25th, 75th percentiles) or mean values ± SD as indicated. Comparison of the frequencies of malapposition between the two groups was performed with the χ² test. To assess the inter-observer and intra-observer variabilities, the results were compared using the κ-test of concordance for the categorical data and data of continuous variables were entered into a Bland-Altman plot. A two-sided P-value of <0.05 was considered statistically significant.

Results
Of the 36 cases that underwent follow-up angiography, OCT images could not be obtained for two cases, one because of contraindication involving occlusion of coronary flow in a left main (LM) trunk lesion, and other because of the inability to place the occlusion balloon in a severely calcified tortuous vessel. In the other 34 cases (57 SES), clear OCT images were obtained without any complications. Table 1 shows the baseline characteristics of the study subjects consisting of patients with angina pectoris (24 cases) and old MI (10 cases). Twenty-eight patients received SES treatment for de novo lesions, and six each for in-stent restenosis (SES-in-BMS), and for CTO vessels. The average interval of follow-up angiography was 202 days. The size of SES ranged from 2.5 to 3.5 mm diameter and 13 to 28 mm length and there were two angiographic in-stent restenoses (>50% occlusion) with focal neointimal proliferation.

IVUS data
EEM and SES areas are shown in Table 2. An SES area of more than 6 mm² was attained and after 6 months, the EEM and SES areas had not changed significantly. As for the percentage of the neointimal area, it accounted for only 0–10% in 81% of the SES, because most of the neointima could not be detected by IVUS (Figure 2). 31.5 μm and lower 2SD: –33.7 μm). The median thickness of neointima on an SES strut was 52.5 μm (25th: 28.0 μm; 75th: 147.6 μm). The prevalence of struts covered by thin neointima of <100 μm thickness, which is beyond IVUS resolution, was 64%. (Figure 4).

Classification of stent strut condition in relation to neointimal proliferation
Inter-observer and intra-observer variabilities for the classifications of strut conditions were κ = 0.75 and κ = 0.82, respectively.

Of the 6840 stent struts in 57 SES, 70 (1%) were located at a major side branch and all of these were separated from the vessel wall. Of the remaining 6770 struts, 6236 (91%) were classified as well apposed with neointima, 455 (7%) as well-apposed without neointima, and 79 (1%) as malapposed without neointima (Figure 5).

A comparison of all individual stents showed that nine SES (16%) featured full coverage of every strut by neointima, whereas the remaining 48 stents contained partially uncovered strut lesions. Individual SES showed the following frequencies: 89% had well-apposed struts with neointima; 8% well-apposed struts without neointima; 2% malapposed struts without neointima; and 1% a side branch site.

Factors affecting malapposition
According to the vessel characteristics before stent deployment, the frequency of SES malapposition in CTO vessels, 36/1395 struts (2.6%), was higher than that in non-CTO vessels, 43/5375 struts (0.8%) (P < 0.0001). Overlapping SES struts showed malapposition more frequently, 29/362 struts (8.0%), than did non-overlapping SES struts, 50/6408 struts (0.8%) (P < 0.0001) (Figure 6). In contrast, SES implanted in BMS re-stenosed lesions showed significantly less malapposition, 7/1213 struts (0.6%), than in SES for de novo lesion, 72/5557 struts (1.3%) (P = 0.0496). Representative images of SES malapposition in a CTO lesion, SES malapposition in a segment with two overlapping stents, and a well-apposed SES in BMS restenosis are shown in Figure 7.

Table 1 Patient characteristics

| Number | 34 (Male: 27, Female: 7) |
| 57 stents |
| Age (years) | 66 ± 10 |
| f/u (days) | 202 ± 23 |
| Disease (%) | |
| Angina pectoris | 24 (71) |
| Old MI | 10 (29) |
| Hypertension | 19 (56) |
| Hyperlipidaemia | 23 (68) |
| Diabetes mellitus | 15 (44) |
| Smoking | 20 (59) |
| Vessels LAD/LCX/RCA | 28/14/15 stents |
| Lesion type (%) | |
| De novo | 28 (82) |
| Restenosis | 6 (18) |
| Chronic total occlusion | 6 (18) |

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Table 2: IVUS analysis before and after stent implantation, and at 6-month follow-up

<table>
<thead>
<tr>
<th></th>
<th>Pre-stenting</th>
<th>Post-stenting</th>
<th>6-month follow-up</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Lumen area</td>
<td>EEM area</td>
<td>SES area</td>
</tr>
<tr>
<td>Proximal (mm²)</td>
<td>6.3 ± 2.9</td>
<td>15.2 ± 4.3</td>
<td>7.9 ± 2.1</td>
</tr>
<tr>
<td>Mid (mm²)</td>
<td>4.5 ± 2.3</td>
<td>13.9 ± 4.9</td>
<td>7.9 ± 2.2</td>
</tr>
<tr>
<td>Distal (mm²)</td>
<td>4.6 ± 1.9</td>
<td>12.4 ± 5.5</td>
<td>6.8 ± 2.0</td>
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</tbody>
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Proximal, mid, and distal each refer to one-third segment of the stented lesion.

**Discussion**

This is the first systematic study of SES follow-up using the high-resolution capabilities of OCT imaging. OCT demonstrated its ability to visualize the thin neointima on each stent strut and quantify its thickness. Our study's results indicate that the majority (64%) of SES struts were covered by a thin neointima layer <100 μm thick, which is beyond the capacity of IVUS to detect. In addition, OCT imaging disclosed that almost 90% of the individual stent struts were covered with neointima. However, only a few SES showed full coverage by neointima, with the remaining stents displaying partially uncovered strut lesions.

Stent thrombosis usually results in ST-segment elevation MI or death. A matter of concern is that SES are susceptible to late thrombosis related to delayed re-endothelialization of the stent struts. Following an SES implantation, antiplatelet therapy typically consists of ticlopidine or clopidogrel for more than 3 months and life-long aspirin, based on an empirical protocol. As long as the standard antiplatelet therapy is continued, the real-world data of SES will show the same frequency of stent thrombosis as that in BMS. However, the increasing number of patients with implanted SES, the issue of whether antiplatelet therapy can be discontinued before surgery or invasive examinations remains unresolved. In the case of BMS, Wilson et al. reported that discontinuation of antiplatelet therapy later than 6 weeks was relatively safe for non-cardiac surgery. Ueda et al. found using angioscopy that neointimal coverage of BMS is completed within 3 months after implantation. For SES, however, no major studies have been reported to predict when neointimal coverage will be attained after SES implantation.

In our OCT study of SES, a significant percentage of uncovered SES struts was found 6 months after implantation, indicating that re-endothelialization was suppressed. Although the prevalence of uncovered struts identified by OCT examination was less frequent than IVUS examination alone would indicate, we could not conclude that complete cessation of antiplatelet therapy for SES at 6 months is safe.

In spite of our protocol of life-long aspirin and 3-month ticlopidine, three thrombi attached to SES were detected, one was at a stent fracture site and the other two adjacent to malapposed struts (Figure 8). However, none of these cases showed any evidence of thrombotic events.

**Thrombus attachment to SES**

We detected three SES with apparent thrombus formation attached to the stent struts. One was located at a stent fracture, and the others were at non-fractured sites adjacent to malapposed struts (Figure 8). However, none of these cases showed any evidence of thrombotic events.

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malapposition in SES overlapping segments may be associated with excess inhibition of neointimal hyperplasia due to the double dose of sirolimus. This hypothesis is supported by the study of Finn et al.,17 in which overlapping stent segments exhibited a delayed healing process when compared with proximal and distal non-overlapping segments in animals. Thus, to avoid late malapposition, the length of any unavoidable SES overlap should be minimized. In addition, our study showed less malapposition for SES implanted in BMS restenosis. We speculate that the abundant neointimal growth inside the BMS prior to SES implantation may prevent malapposition of the SES, and that sirolimus may still exert its inhibitory effect on excessive neointimal hyperplasia in the stents. This agrees with previous reports indicating that SES is effective for in-stent restenosis treatment and for reducing re-restenosis, with no evidence of malapposition.18–20

Limitations

In our study, the efficacy of OCT was limited in terms of imaging certain lesions, such as ostial lesions due to the risk of producing a blood-free environment. Also, severely calcified tortuous vessels could not be imaged with OCT due to the difficulty of passing through the lesion with the occlusion balloon. Thus, our study results do not represent an unbiased sampling of all patients who received SES implanta tions, with the nature of SES in ostial lesions, in particular, remaining to be clarified.

Several previous studies have established methods for tissue characterization with OCT, including differentiation of fibrous tissue, lipid and calcium plaque composition, and the presence of thrombus in the lumen.9,21 We diagnosed the tissue surrounding SES as neointima because of its isodensity with the coronary intima. Sousa et al.22 reported that
necropsy findings 4 years after implantation of SES showed >95% of the stent strut surfaces being endothelialized. This neointima consisted of smooth muscle cells and macrophages in a collagen-rich matrix. Additional studies comparing the appearance of cadaver specimens on OCT images with histological verification are needed to confirm the ability of OCT to determine the composition of neointima.

Because the resolution of OCT is 15–20 μm, tissue structures with dimensions <15 μm, such as endothelium, cannot be resolved with OCT. The possibility can therefore not be excluded that OCT images of uncovered SES struts may not be completely devoid of tissue growth. To the best of our knowledge, however, there is no evidence that endothelium covers stent struts without neointimal growth. Finn et al., using scanning electron microscope, reported that at overlapping DES sites, most of the stent struts looked uncovered by endothelial cells. Thus, a certain proportion of SES struts may be devoid of tissue coverage and should thus have thrombogenic potency.

Conclusions

We conclude that OCT is a powerful modality for visualizing the thin neointima covering SES struts. At 6-month follow-up, most of the SES were found to be covered with thin neointima, but few of the SES showed full coverage. To minimize the potential for stent malapposition devoid of neointima coverage, any overlap between adjacent SES should be as short as possible to minimize the potential for late thrombosis. To determine when neointima covers the whole SES, thus warranting discontinuation of antiplatelet therapy, extended long-term follow-up with OCT may be helpful.

Conflict of interest: none declared.
References


