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# Quantitative Angiographic Comparison of Elastic Recoil After Coronary Excimer Laser-Assisted Balloon Angioplasty and Balloon Angioplasty Alone

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**Objectives.** Coronary lumen changes during and after excimer laser-assisted balloon angioplasty were measured by quantitative coronary angiography, and the results were compared with the effects of balloon angioplasty alone.

**Background.** Reduction of atherosclerotic tissue mass by laser ablation in the treatment of coronary artery disease may be more effective in enlarging the lumen than balloon angioplasty alone.

**Methods.** A series of 57 consecutive coronary lesions successfully treated by xenon chloride excimer laser-assisted balloon angioplasty were individually matched with 57 coronary artery lesions successfully treated by balloon angioplasty alone. The following variables were measured by quantitative coronary analysis: 1) ablation by laser, 2) stretch by balloon dilation, 3) elastic recoil, and 4) acute gain.

**Results.** Matching by stenosis location, reference diameter and minimal lumen diameter resulted in two comparable groups of 57 lesions with identical baseline stenosis characteristics. Minimal lumen diameter before excimer laser-assisted balloon angioplasty and balloon angioplasty alone were (mean ± SD) 0.73 ± 0.44 and 0.74 ± 0.43 mm, respectively. Laser ablation significantly improved minimal lumen diameter by 0.56 ± 0.44 mm before adjunctive balloon dilation. In both treatment groups, similar-sized balloon catheters (2.59 ± 0.35 and 2.56 ± 0.40 mm, respectively) were used. After laser-assisted balloon angioplasty, elastic recoil was 0.84 ± 0.30 mm (32% of balloon size), which was identical to that after balloon angioplasty alone, namely, 0.82 ± 0.32 mm (32%). Consequently, both interventions resulted in similar acute gains of 1.02 ± 0.52 and 1.00 ± 0.56 mm, respectively. Minimal lumen diameter after intervention was equal in both groups: 1.75 ± 0.35 and 1.75 ± 0.34 mm, respectively. The statistical power of this study in which a 25% difference in elastic recoil (0.2 mm) between groups was considered clinically important was 95%.

**Conclusions.** In matched groups of successfully treated coronary lesions, xenon chloride excimer laser ablation did not reduce immediate elastic recoil after adjunctive balloon dilation or improve the final angiographic outcome compared with balloon angioplasty alone using similar-sized balloon catheters.

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Transluminal balloon angioplasty (1) remains the most common applied technique in the percutaneous treatment of patients with coronary artery disease. The mechanism by which balloon dilation improves lumen dimensions of stenotic arteries has been investigated by histopathology of human necropsy specimens after balloon angioplasty (2-4) and by intravascular angioscopy (5,6) and two-dimensional ultrasound (7-10). Three important effects of balloon inflation on atherosclerotic vessel segments can be distinguished: 1) plaque rupture, intimal tears and dissections; 2) plaque compression; and 3) stretching of the less diseased part of the arterial wall. The relative contribution of each of these effects to the final outcome of a balloon angioplasty procedure is the subject of ongoing debate (10,11). Angiographic studies of the dilation process have focused on the elastic behavior of the coronary artery during and after angioplasty. Stretching of the vessel segment during balloon inflation is followed by immediate elastic recoil, which has been shown by our group (12,13) and others (14-16) to account for a nearly 50% decrease in lumen cross-sectional area immediately after balloon deflation.

Excimer laser irradiation of cardiovascular tissues in air has been shown to remove tissue precisely with minimal adjacent injury (17-19). The subsequent development of fiberoptic catheters for the transluminal delivery of excimer laser energy cleared the way for clinical application of this treatment modality. Since the first patient with coronary artery disease was treated with a xenon chloride excimer laser in August 1988 (20), excimer laser angioplasty is increasingly being used as an alternative or adjunct to balloon angioplasty, specifically in complex coronary artery lesions (21-25). Although laser angioplasty is currently followed by balloon dilation in >90% of

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cases (to debulk and dilate), it is hypothesized that reduction of atherosclerotic tissue mass by laser ablation with or without adjunctive balloon dilation may be more effective in enlarging lumen diameter than balloon angioplasty alone. Laser angioplasty may favorably modify plastic and elastic properties of the vessel wall, thereby facilitating balloon dilation (23). Also, tissue removal by laser ablation may cause a reduction in the extent of vessel stretching during subsequent balloon dilation, resulting in less elastic recoil and preserved lumen dimensions after balloon deflation. This study was undertaken to determine whether atherosclerotic plaque removal by excimer laser ablation before balloon dilation reduces elastic recoil and improves the immediate outcome compared with balloon coronary angioplasty alone as assessed by quantitative angiography.

## Methods

**Patients.** For the purpose of this study, a consecutive series of 53 patients with 59 native coronary artery lesions successfully treated by excimer laser angioplasty and adjunctive balloon dilation was accumulated. This cohort of patients represents almost a fourth of the patients treated with the excimer laser at our institution until now and reflects our experience with the device after completion of a learning curve. All patients had symptomatic coronary artery disease or objective evidence of myocardial ischemia, or both. The group included 13 patients with 13 chronic total coronary artery occlusions. A successful treatment was defined as procedural success (a residual diameter stenosis <50% at the end of the intervention) without major complications (death, myocardial infarction, coronary artery bypass grafting or repeat angioplasty) during the hospital period. Two patients who underwent successful excimer laser-assisted balloon angioplasty for a chronic total coronary occlusion could not be matched according to the angiographic criteria described later. The study group, therefore, consisted of 51 patients with 57 lesions successfully treated by excimer laser-assisted balloon angioplasty and was individually matched with a group of patients undergoing successful balloon angioplasty as the single treatment. The clinical and quantitative angiographic details of the groups are described in Table 1.

**Laser procedure.** The laser system consisted of a xenon chloride excimer laser (Advanced Interventional Systems, Inc.) emitting light pulses at a wavelength of 308 nm with a pulse duration of ~200 ns and a repetition rate of 20 Hz. Over-the-wire laser catheters 1.3, 1.6 and 2.0 mm in diameter with a concentric multifiber arrangement around a central guide wire lumen were used in 46 patients (52 lesions), and a directional 1.8-mm diameter laser catheter with eccentric multifiber design was used in 5 patients (5 lesions). Laser fluence at the catheter tip was set at levels ranging from 45 to 65 mJ/mm². For anticoagulation, aspirin and heparin were given intravenously, keeping the activated clotting time >400 s for the duration of the procedure, with additional doses of 5,000 IU of heparin. The laser catheter was advanced through a standard 9F coronary angioplasty guide catheter (Schneider, Inc.) and directed over a 0.014- or 0.018-in (0.36 to 0.46 mm) guide wire until its tip was just proximal to the lesion. After flushing with saline solution to remove any intracoronary contrast medium, the laser was activated for 2 to 3 s, and the fiberoptic catheter very slowly advanced while the guide wire was kept under slight tension or slowly retracted. Each 2- to 3-s pulse train was followed by a 3- to 5-s pause, with repositioning of the guide wire into the most distal part of the vessel. Usually, only one pass with a concentric laser catheter was performed through the lesion, after which a control angiogram was made. If the residual diameter stenosis was >50%, the lesion was passed with a larger diameter concentric laser catheter, or adjunctive balloon dilation was performed. In the patients undergoing directional laser atherectomy, the catheter was passed two to three times in the same or another direction (controlled by rotation of the device around the guide wire by a torque-control knob) followed by balloon angioplasty. Before and after the laser procedure or balloon dilation, or both, angiography was performed in multiple projections after intracoronary administration of nitroglycerin to reduce vasomotor tone.

**Quantitative coronary angiography.** All cineangiograms were analyzed using the computer-based Cardiovascular Angiography Analysis System (CAAS), which has been previously described and validated (26–28). This system permits an objective and reproducible quantification of coronary artery

**Table 1.** Baseline Characteristics of Patients and Lesions Before Excimer Laser-Assisted Balloon Angioplasty and Balloon Angioplasty Alone

| | EL-BA | BA |
|---|---|---|
| Patients | 51 | 57 |
| Age (yr) | 55.5 ± 8.8 | 58.3 ± 8.3 |
| Male gender (%) | 78 | 74 |
| Angina class (CCS) (%) | | |
| I | 4 | 4 |
| II | 25 | 25 |
| III | 59 | 58 |
| IV | 12 | 14 |
| Lesions | 57 | 57 |
| Location | | |
| LAD | 28 | 28 |
| RCA | 18 | 18 |
| LCx | 11 | 11 |
| Total occlusions | 11 | 11 |
| Minimal lumen diameter (mm) | 0.73 ± 0.44 | 0.74 ± 0.43 |
| Reference diameter (mm) | 2.66 ± 0.44 | 2.67 ± 0.44 |
| Diameter stenosis (%) | 72 ± 16 | 72 ± 16 |
| Minimal lumen cross-sectional area (mm²) | 0.57 ± 0.47 | 0.58 ± 0.45 |
| Reference area (mm²) | 5.70 ± 1.88 | 5.73 ± 1.92 |
| Area stenosis (%) | 90 ± 8 | 90 ± 8 |
| Lesion length (mm)* | 7.9 ± 3.4 | 6.3 ± 2.9 |
| Plaque area (mm²)* | 9.8 ± 4.7 | 7.6 ± 5.8 |

*For nontotal obstructions only (n = 46 in both groups). Data presented are mean value ± SD, unless otherwise indicated. BA = balloon angioplasty alone; CCS = Canadian Cardiovascular Society; EL-BA = excimer laser-assisted balloon angioplasty; LAD = left anterior descending coronary artery; LCx = left circumflex coronary artery; RCA = right coronary artery.

stenosis and accurate assessment of the lumen changes taking place during angioplasty. In brief, an optically magnified portion (6.9 × 6.9 mm) of a selected 35-mm cine frame encompassing the region of interest is digitized by means of a cine-video converter with a resolution of 512 × 512 pixels and 8 bits of gray level. The coronary segment to be analyzed is determined by selecting a number of centerline points, which are connected by linear interpolation. Contours of the vessel segment are detected automatically on the basis of the weighted sum of the first- and second-derivative functions applied to the digitized brightness profile along scan lines perpendicular to the centerline of the arterial segment. A smoothing procedure is applied to each of the detected contours, and all contour positions are corrected for pincushion distortion. From these contours, the vessel diameter function is determined by computing the shortest distances between the left and right contour positions. The image calibration factor is calculated by measuring the guide catheter with a micrometer and detection of its edges in the cine film not filled by contrast medium (29). The minimal lumen diameter of a coronary segment can then be determined in absolute millimeters. A computer-derived estimation of the original arterial dimension at the site of obstruction (assuming there is no disease present) is used to define the interpolated reference diameter. The percent diameter and area stenosis, as well as the cross-sectional area (in mm$^2$), are then calculated. The length of the lesion (in mm) is determined from the diameter function on the basis of a curvature analysis (26). The area between the actual and reconstructed contours at the obstruction site is a measure of the amount of atherosclerotic plaque and is expressed in mm$^2$. Because the algorithm cannot measure total occlusions, a value of 0 mm was imputed for the minimal lumen diameter. In these cases, the reference diameter after angioplasty was substituted for that before angioplasty.

**Matching process.** To compare changes in coronary lumen dimensions occurring during excimer laser-assisted balloon angioplasty and balloon angioplasty alone, a consecutive series of 57 successfully treated excimer laser-assisted balloon angioplasty lesions were matched with 57 coronary artery lesions successfully treated with balloon angioplasty alone. The coronary artery tree was subdivided into 15 segments according to the American Heart Association guidelines, and the lesions were individually matched according to minimal lumen diameter, reference diameter and vessel location. The principles of matching by quantitative angiography are as follows: 1) the angiographic dimensions of matched lesions are assumed to be identical; and 2) the observed difference in minimal lumen diameter and reference diameter between the two identical lesions must be within the range of twice the variability of the quantitative analysis system (CAAS) of 0.10 mm (1 SD) (26,27). Thus, lesion pairs were selected in which the difference between these angiographic variables did not exceed 0.2 mm (twice the variability; 95% confidence limits). Also, a difference not exceeding 0.2 mm is within the precision of our CAAS system (i.e., the standard deviation of the mean difference between stenosis phantoms and actual measurements), as determined by Haase et al. (28). After completion of matching for these three angiographic variables, the patient's anginal status was introduced as an additional, clinical characteristic to enhance and refine the matching process. Matching was performed by an independent analyst according to the aforementioned criteria. The Thoraxcenter angiographic data base now contains quantitative angiographic data on 3,736 coronary lesions treated by balloon angioplasty, enabling easy and close matching of lesions and patients undergoing different interventions.

**End points.** The mean change in arterial dimensions from before to after laser angioplasty in excimer laser-assisted balloon angioplasty and from before to after balloon angioplasty in excimer laser-assisted balloon angioplasty and balloon angioplasty alone was derived from multiple angiographic projections. Four variables were calculated from the quantitative angiographic data in absolute millimeters that reflect the coronary lumen changes occurring during angioplasty. These were 1) *ablation* (minimal lumen diameter after laser ablation minus minimal lumen diameter before laser ablation); 2) *stretch* (mean balloon diameter minus minimal lumen diameter before balloon dilation); 3) *elastic recoil* (mean balloon diameter minus minimal lumen diameter after balloon dilation); and 4) *acute gain* (minimal lumen diameter after minus minimal lumen diameter before intervention). All four variables were also calculated in units of area (mm$^2$) and normalized for interpolated reference diameter and reference area, respectively, to correct for vessel size. To obtain the mean balloon diameter, the largest balloon at maximal inflation was measured in a nonforeshortened projection; balloon area and balloon/artery ratios were then calculated.

**Statistical analysis.** All values obtained from quantitative angiographic analysis and derived variables are expressed as mean value ± 1 SD. Differences between the two groups and within each group were assessed by two-factor repeated-measures analysis of variance. The Bonferroni correction was applied for multiple comparisons. Linear regression analysis was performed by the least-squares method to calculate correlations and slopes. To compare the linear regressions for the two treatment groups, multiple regression analysis was performed introducing the type of intervention as a separate (dummy) variable. A p value $<0.05$ was considered to indicate a significant difference.

## Results

**Matching.** Baseline clinical and quantitative angiographic characteristics of the excimer laser-assisted balloon angioplasty group and the balloon angioplasty-only group are listed in Table 1. No differences in gender, age or anginal status were observed. Matching for angiographic variables was considered adequate because distribution of stenosis location as well as minimal lumen and reference diameter measurements were not significantly different in both groups: 0.73 ± 0.44 and 2.66 ± 0.44 mm for the excimer laser-assisted balloon angioplasty group and 0.74 ± 0.43 and 2.67 ± 0.44 mm for the balloon angioplasty group, respectively. Other lesion variables (diameter stenosis, minimal lumen cross-sectional area, reference area, area stenosis, plaque area and number of total occlusions) also did not differ significantly between groups, with the sole exception of lesion length, which was 7.9 ± 3.4 mm in the excimer laser-assisted balloon angioplasty group and 6.3 ± 2.9 mm in the balloon angioplasty group ($p = 0.02$) (Table 1). Qualitative descriptors of lesion morphology derived from visual analysis of coronary angiograms included the presence of a branch point in the stenotic segment (46% in the excimer laser-assisted balloon angioplasty group vs. 53% in the balloon angioplasty group), lesion calcification (15% vs. 11%, respectively) and relation of the lesion to a coronary bend (17% vs. 7%, respectively), which were not significantly different between groups. However, the frequency of qualitative characteristics in the treatment groups may be different, but it would require a much larger sample size to exclude such a difference with a high statistical power. Thus, this matching technique resulted in the selection of two patient groups with similar clinical and preprocedural stenosis variables.

**Procedural results.** The immediate efficacy of excimer laser-assisted balloon angioplasty and balloon angioplasty alone as assessed by quantitative angiography is shown in Table 2 and Figure 1. Both interventions resulted in a significant improvement in minimal lumen diameter, from 0.73 ± 0.44 to 1.75 ± 0.35 mm ($p < 0.001$) and from 0.74 ± 0.43 to 1.75 ± 0.34 mm ($p < 0.001$), respectively. Accordingly, diameter stenosis was reduced from 72 ± 16% to 36 ± 9% ($p < 0.001$) and from 72 ± 16% to 34 ± 9% ($p < 0.001$), respectively. Despite a significant initial improvement in minimal lumen diameter from 0.73 ± 0.44 to 1.30 ± 0.28 mm ($p < 0.001$) in the excimer laser-assisted balloon angioplasty group by laser ablation, the final angiographic outcome did not differ between the two treatment groups.

**Table 2.** Comparative Quantitative Angiographic Analysis of the Immediate Results of Excimer Laser-Assisted Balloon Angioplasty and Balloon Angioplasty Alone in 57 Coronary Lesions

| | EL-BA | BA |
|---|---|---|
| Minimal lumen diameter (mm) | | |
| Pre | 0.73 ± 0.44 | 0.74 ± 0.43 |
| Postlaser | 1.30 ± 0.28 | — |
| Postballoon | 1.75 ± 0.35 | 1.75 ± 0.34* |
| Reference diameter (mm) | | |
| Pre | 2.66 ± 0.44 | 2.67 ± 0.44 |
| Postlaser | 2.69 ± 0.46 | — |
| Postballoon | 2.77 ± 0.50 | 2.67 ± 0.45 |
| Diameter stenosis (%) | | |
| Pre | 72 ± 16 | 72 ± 16 |
| Postlaser | 51 ± 10 | — |
| Postballoon | 36 ± 9 | 34 ± 9* |
| Minimal lumen cross-sectional area ($mm^2$) | | |
| Pre | 0.57 ± 0.47 | 0.58 ± 0.45 |
| Postlaser | 1.38 ± 0.60 | — |
| Postballoon | 2.50 ± 1.03 | 2.48 ± 1.03* |
| Reference area ($mm^2$) | | |
| Pre | 5.70 ± 1.88 | 5.73 ± 1.92 |
| Postlaser | 5.84 ± 1.99 | — |
| Postballoon | 6.22 ± 2.27 | 5.75 ± 2.03 |
| Area stenosis (%) | | |
| Pre | 90 ± 8 | 90 ± 8 |
| Postlaser | 75 ± 10 | — |
| Postballoon | 59 ± 12 | 56 ± 12* |
| Lesion length (mm) | | |
| Pre† | 7.9 ± 3.4 | 6.3 ± 2.9 |
| Postlaser | 8.0 ± 3.3 | — |
| Postballoon | 7.7 ± 3.0 | 5.9 ± 2.2 |
| Plaque area ($mm^2$) | | |
| Pre† | 9.8 ± 4.7 | 7.6 ± 5.8 |
| Postlaser | 8.0 ± 4.9 | — |
| Postballoon | 5.6 ± 2.9 | 4.1 ± 2.4* |

*$p < 0.01$ within groups. †Preprocedural (Pre) data are for nontotal obstructions only ($n = 46$ in both groups). Data presented are mean value ± SD. Other abbreviations as in Table 1.

**Ablation, stretch, recoil and gain.** Results of quantitative angiographic analysis of the extent of laser ablation, mean balloon size at maximal inflation, vessel stretching during balloon inflation, immediate elastic recoil after balloon deflation and acute gain for the two treatment groups are summarized in Table 3 and Figure 2. In Table 3, values are expressed in absolute terms, that is, in units for diameter (mm) and area ($mm^2$), as well as in relative terms (i.e., normalized for reference diameter and reference area to correct for vessel size). Figure 2 shows a graphic representation of the results in absolute millimeters. Despite a significant initial improvement in lumen dimensions by excimer laser ablation causing a reduction in vessel stretching during subsequent balloon dilation, elastic recoil after balloon deflation did not differ between treatment groups, resulting in a similar acute gain from preintervention to postintervention. Similar-sized balloon catheters were used in both groups. On average, 32% of the theoretically achievable lumen diameter (i.e., balloon diameter) and 53% of the maximal achievable cross-sectional area (i.e., balloon cross-sectional area) is lost shortly after balloon deflation, whether balloon dilation is preceded by excimer laser ablation or not. When a mean difference in recoil of 25% between groups is considered clinically important (0.2 mm, i.e., the precision of the quantitative analysis system [28]), the statistical power of this investigation reaches a level of 95%. When a 25% mean difference in acute gain between groups (0.25 mm) is considered, the power is 75%.

**Relation among extent of laser ablation, balloon size, vessel stretch and elastic recoil.** In the balloon angioplasty group, where balloon dilation was performed as the single treatment, a linear correlation could be documented between vessel stretching during balloon dilation and subsequent elastic recoil (Fig. 3, top), as previously described (12–16). A similar relation was found in the excimer laser-assisted balloon angioplasty group (Fig. 3, middle), where balloon dilation was preceded by excimer laser ablation. Comparison of these two relations by means of multiple regression analysis showed no significant difference ($p = 0.25$). No relation was observed between the extent of laser tissue ablation (debulking) and the amount of elastic recoil after adjunctive balloon dilation in the excimer

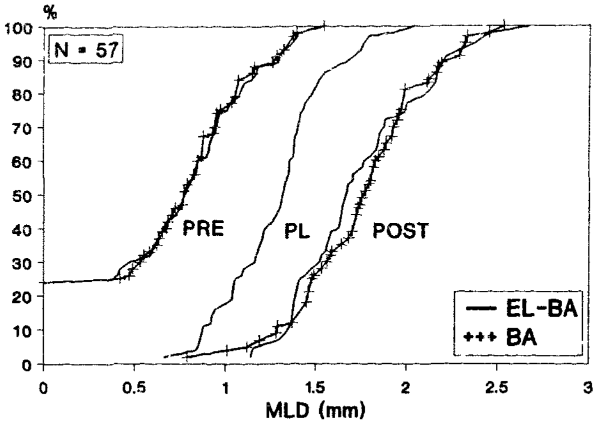

**Figure 1.** Cumulative frequency curves illustrating the immediate changes in minimal lumen diameter (MLD) induced by excimer laser-assisted balloon angioplasty (EL-BA) and balloon angioplasty alone (BA) as assessed by quantitative coronary angiography. PRE = before intervention; PL = after laser ablation; POST = after balloon dilation.

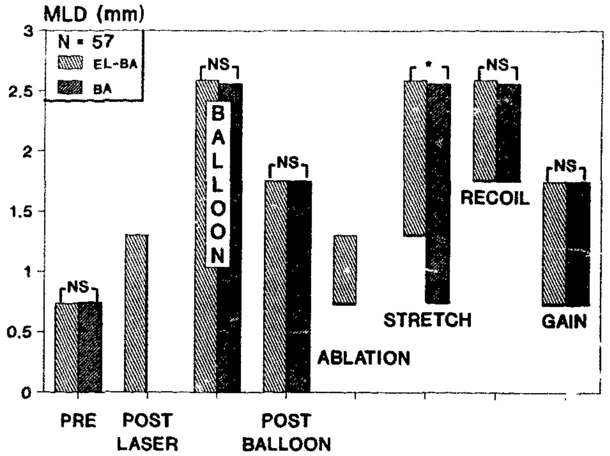

**Figure 2.** Graphic representation of immediate effects of excimer laser-assisted balloon angioplasty (EL-BA) and balloon angioplasty alone (BA), along with derived quantitative angiographic variables, expressed in absolute millimeters. For definition of terms, see text. Despite significant reduction in vessel stretching during balloon dilation after laser ablation, elastic recoil in the excimer laser-assisted balloon angioplasty group after balloon deflation is similar to that after balloon angioplasty alone, resulting in a similar acute gain in both treatment groups. *p < 0.0001. Other abbreviations as in Figure 1.

laser-assisted balloon angioplasty group (Fig. 3, bottom). Figure 4 shows the relation between minimal lumen diameter after balloon dilation and mean balloon diameter during inflation for both treatment groups. At the line of identity, elastic recoil after balloon deflation would be zero (i.e., minimal lumen diameter after balloon deflation equals the balloon diameter). The vertical distance between data points and the line of identity in Figure 4 represents the amount of elastic recoil in absolute millimeters, which can be seen to increase with larger diameter balloons in both groups. Comparison of the linear regressions in Figure 4 by means of multiple regression analysis showed no difference between the two treatment arms (p = 0.92).

## Discussion

**New techniques.** In the past 10 years, a variety of novel techniques and devices have been introduced for the percutaneous treatment of coronary artery disease (11) in an attempt

**Table 3.** Absolute and Relative Changes in Minimal Lumen Diameter and Minimal Lumen Cross-Sectional Area Caused by Excimer Laser Ablation or Balloon Dilation, or Both, in the Two Treatment Groups

| | Ablation | Balloon Size | Stretch | Recoil | Gain |
|---|---|---|---|---|---|
| Absolute diameter (mm) | | | | | |
| EL-BA | 0.56 ± 0.44 | 2.59 ± 0.35 | 1.29 ± 0.40 | 0.84 ± 0.30 | 1.02 ± 0.52 |
| BA | — | 2.56 ± 0.40 | 1.81 ± 0.59 | 0.82 ± 0.32 | 1.00 ± 0.56 |
| p value | — | 0.69 | <0.0001 | 0.65 | 0.87 |
| Normalized for RD | | | | | |
| EL-BA | 0.22 ± 0.18 | 0.98 ± 0.16 | 0.49 ± 0.16 | 0.32 ± 0.13 | 0.39 ± 0.20 |
| BA | — | 0.97 ± 0.14 | 0.69 ± 0.23 | 0.31 ± 0.13 | 0.38 ± 0.21 |
| p value | — | 0.81 | <0.0001 | 0.92 | 0.84 |
| Absolute area (mm$^2$) | | | | | |
| EL-BA | 0.81 ± 0.66 | 5.36 ± 1.43 | 3.98 ± 1.41 | 2.86 ± 1.10 | 1.92 ± 1.08 |
| BA | — | 5.27 ± 1.77 | 4.69 ± 1.82 | 2.79 ± 1.37 | 1.90 ± 1.11 |
| p value | — | 0.78 | 0.02 | 0.76 | 0.91 |
| Normalized for RA | | | | | |
| EL-BA | 0.13 ± 0.14 | 0.92 ± 0.27 | 0.74 ± 0.30 | 0.51 ± 0.24 | 0.35 ± 0.19 |
| BA | — | 0.96 ± 0.26 | 0.86 ± 0.30 | 0.52 ± 0.25 | 0.34 ± 0.18 |
| p value | — | 0.43 | 0.03 | 0.87 | 0.89 |

Data presented are mean value ± SD, unless otherwise indicated. RA = reference area; RD = reference diameter; other abbreviations as in Table 1.

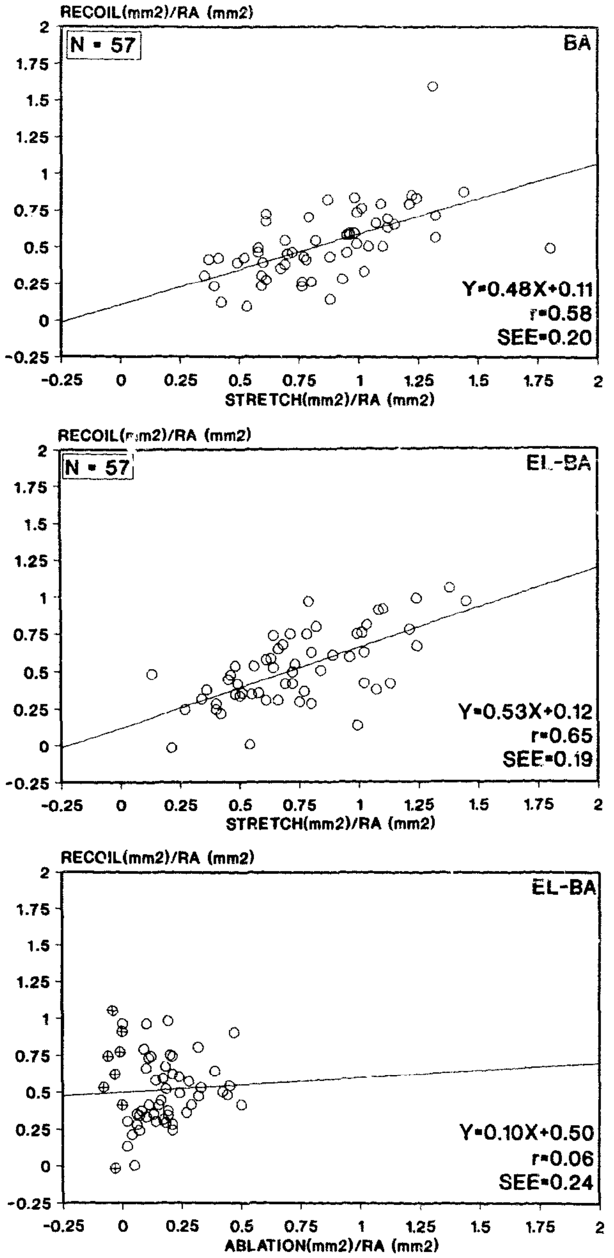

**Figure 3.** Relation between vessel stretching and elastic recoil after balloon angioplasty alone (BA) **(top)** and excimer laser-assisted balloon angioplasty (EL-BA) **(middle)** and the relation between extent of laser ablation and elastic recoil after adjunctive balloon dilation in the excimer laser-assisted balloon angioplasty group **(bottom)**. **Crossed circles** represent procedural data, where excimer laser ablation was associated with deterioration of cross-sectional lumen area. Extent of laser ablation, vessel stretching and elastic recoil have been normalized for reference area (RA) to correct for vessel size. **Solid lines** represent the calculated lines of regression.

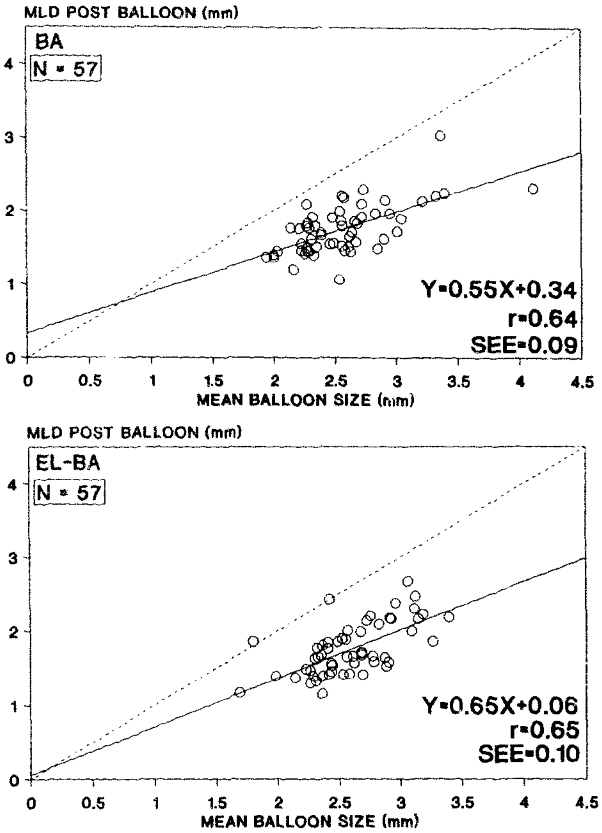

**Figure 4.** Relation between minimal lumen diameter (MLD) after balloon dilation and mean balloon diameter during inflation in balloon angioplasty alone (BA) **(top)** and excimer laser-assisted balloon angioplasty (EL-BA) **(bottom)**. **Dashed lines** connect data points, where minimal lumen diameter after balloon dilation would equal mean balloon diameter, and elastic recoil would be zero. **Solid lines** represent the calculated lines of regression.

to further improve primary success and to reduce acute complication and long-term restenosis rates associated with balloon coronary angioplasty. Current interventional techniques can be separated into two main categories on the basis of their effects on coronary lumen shape or obstruction: 1) remodeling, as with balloon dilation (1–11) and endoluminal stenting (16); and 2) removal of plaque tissue, as in laser angioplasty (17–19) and rotational (30) and directional (31–35) atherectomy. Comparative angiographic studies on the immediate efficacy of coronary atherectomy and balloon angioplasty in matched patients showed that atherectomy produced larger postprocedural lumen diameters (31–35) and less immediate elastic recoil than balloon angioplasty performed with similar-sized catheters (35). By physically removing obstructive atherosclerotic tissue from the arterial lumen, the result of directional atherectomy appears to depend less on plaque compression and stretching of the vascular wall than balloon dilation (7–11). Thus, debulking of plaque tissue by atherectomy may well be responsible for the observed reduction in elastic recoil causing a greater improvement in coronary lumen dimensions (i.e., acute gain), as in balloon angioplasty. In contrast to coronary stenting (16) and directional atherectomy (35), the present investigation did not demonstrate any benefit of atherosclerotic tissue ablation by excimer laser irradiation on elastic recoil and immediate outcome as assessed by quantitative coronary angiography. Despite a significant initial increase in lumen diameter and cross-sectional area of the stenotic segment after passage of the laser catheter(s), no immediate positive effect of excimer laser angioplasty preceding balloon dilation was observed on procedural outcome compared with balloon angioplasty alone of matched coronary lesions performed with similar-sized balloon catheters.

**Laser ablation: tissue removal, shattering or "Dotter" effect?** Pulsed ultraviolet radiation from an excimer laser has been shown to remove arterial tissue precisely in air with minimal thermal or mechanical damage to the remaining vessel wall (17–19). However, when excimer laser irradiation of tissue takes place through an optical fiber or catheter in saline solution, the effects are strikingly different. Recently, van Leeuwen et al. (36) demonstrated that during contact ablation of porcine aorta in saline solution using a pulsed xenon chloride excimer laser, fast-expanding and imploding vapor bubbles were formed within the tissue, causing tissue elevation and arterial wall dissections. Repetitive formation and collapse of vapor bubbles is accompanied by the generation of shock waves (37) in the arterial wall that result in multiple layers of dissection, causing the artery to "puff up," described by Abela (38) as the "mille-feuilles" effect. Coaxial delivery of excimer laser pulses in the iliac and femoral arteries of normal rabbits induced extensive damage to the adjacent arterial wall, including medial necrosis, dissection planes filled with red blood cells and internal elastic laminal abrasion (39). The damage was attributed to microsecond vapor bubble expansion and implosion, causing explosive dilation and invagination of the adjacent arterial segment. The effects of rapidly expanding and imploding vapor bubbles on the arterial segment caused by excimer laser pulses seem rather dilatory and shattering in nature and may perhaps explain our findings in the present study. The marked similarity in immediate angiographic outcome in the two treatment groups indeed points toward a dilatory ("Dotter") effect of excimer laser angioplasty rather than true tissue debulking as in directional atherectomy (31–35). The relative contributions of true debulking (i.e., tissue removal by laser vaporization) and mere mechanical interactions in the recanalization of arterial obstructions by excimer laser angioplasty remain to be determined.

**Angiographic and angioscopic appearance.** Whereas the absence of much laser-induced thermal damage has been confirmed by many in vitro (17–19) and in vivo (36,39–42) investigations, mechanical effects produced by the generation of vapor bubbles and shock waves seem to play an important role in the interaction of pulsed excimer laser radiation with arterial tissue (36–39). Angiographically, the changes induced by laser angioplasty may appear as haziness and dissections, unclear lumen borders of the recanalized lesion or intraluminal lucency (41,43). Angiography alone may be insufficient to determine whether laser ablation was adequate. One histopathologic study, 63 days after stand-alone excimer laser angioplasty of a proximal left anterior descending coronary artery lesion, demonstrated inadequate tissue ablation despite a satisfactory angiographic result with the use of laser catheters up to 1.8 mm in diameter and 45 mJ/mm$^2$ of energy fluence (44,45). Light microscopy revealed an 80% residual stenosis on cross section, although angiography 2 months earlier showed a reduction of the lesion from 90% to 30% diameter stenosis by the laser. Most of the vessel narrowing appeared to be caused by underlying fibrotic plaque, indicative of insufficient tissue removal. Examination by intravascular angioscopy of the morphologic changes induced by pulsed excimer laser angioplasty in peripheral and coronary arteries (40,41,46) revealed flaps, fractures of plaques and abundant tissue remnants that corresponded to angiographic findings as haziness and dissections. Channels recanalized by multifiber laser catheters that emitted fluences of 40 to 60 mJ/mm$^2$ were small and irregular, also indicating insufficient tissue removal using current available laser catheter technology.

**Future directions.** Modifications in procedural protocol and laser catheter design may improve the immediate results of excimer laser angioplasty. To increase the efficiency of ablation, fluence levels emitted from the catheter have been increased from ~40 mJ/mm$^2$ in initial laser procedures to maximal fluences of 65 mJ/mm$^2$, which is well above the ablation threshold of fibrous atherosclerotic plaque (47). Moreover, incorporation of more (hundreds) and smaller (50-$\mu$m diameter) optical fibers has improved catheter flexibility and reduced the so-called dead space, that is, the nonfiber cross-sectional area at the catheter tip. A reduction in dead space may reduce the mechanical dilating or "Dottering" effect of a laser catheter when a more active area of fiberoptics at the tip of the catheter is available for laser ablation. A recent development potentially eliminating dead space almost completely is the design of a modified multifiber laser catheter with a lensed tip that delivers a homogeneous donut-shaped light beam (48). Perpendicular irradiation of segments of fresh porcine aorta in forced contact with the modified catheter and immersed in a saline bath or blood field produced single smooth craters with sharp crater wall edges and no damage to surrounding endothelium (48). To reduce mechanical effects and acoustic trauma caused by rapid bubble expansion and collapse and accompanying shock waves, laser catheter systems are in development that activate separate fiber sections, so that not all fibers in the catheter are activated simultaneously but in a sequence of small fiber sections (49,50). Also, excimer laser irradiation in a saline medium has been shown in vitro and in vivo to reduce the magnitude of bubble formation and shock waves compared with laser–tissue interaction in a blood field (37,51). These techniques may reduce the incidence of significant dissections and shock wave-related trauma resulting from excimer laser angioplasty while the efficiency of tissue ablation is maintained.

**Limitations.** This study has several limitations. First, it is based on relatively early experience with excimer laser angioplasty. Careful patient selection, experience and future modifications in catheter design and treatment protocol may improve immediate results. Second, matching of groups was based on lesion characteristics (minimal lumen diameter, reference diameter) that define elastic recoil in response to a given intervention. However, lesions were matched using preprocedural angiographic variables only by an independent analyst who was unaware of treatment outcome. Third, a comparative study of coronary lumen dimensions after excimer laser-assisted balloon dilation versus balloon dilation alone by quantitative angiography represents an indirect manner of investigating the mechanism of excimer laser angioplasty. A more direct assessment of the effects of excimer laser ablation on the vessel wall would be distensibility measurements by producing balloon pressure–diameter curves for each lesion undergoing angioplasty, as proposed by Hjemdahl-Monsen et al. (14). A lesion (pre)treated by excimer laser angioplasty may be more distensible and easier to dilate than an untreated one, especially a heavily calcified stenosis (23). Another methodologic limitation may be the measurement of mean balloon diameter at maximal inflation instead of minimal balloon diameter because the inflated balloon is not uniform along its entire length. This may have resulted in some variation in the calculated stretch, elastic recoil and balloon/artery ratios, as previously pointed out by Hermans et al. (52). Also, with a sample size of 57 lesions in each group, a difference in elastic recoil of 25% (0.2 mm) can be detected with a statistical power of 95%. A difference in recoil of <0.2 mm may be of no clinical significance, but it cannot be excluded on the basis of the current data. Finally, this is a retrospective, observational study limited to a subset of patients who underwent successful excimer laser-assisted balloon angioplasty or balloon angioplasty alone. Although the two groups are well matched for several angiographic variables, procedural and patient variables (other than age, gender and angina class) are not included in the analysis. The efficacy of all intracoronary interventions will be limited by the problem of restenosis, which necessitates careful and complete angiographic follow-up. A controlled, prospective randomized trial in which patient and lesion characteristics are balanced is currently under way in the Netherlands (Amsterdam-Rotterdam [AMRO] trial) to assess the immediate and long-term efficacy of excimer laser and balloon angioplasty in the treatment of long (>10 mm) coronary lesions (53).

**Conclusions.** In a matched group of successfully treated coronary artery lesions, xenon chloride excimer laser ablation followed by adjunctive balloon dilation did not reduce acute elastic recoil or improve the final angiographic outcome compared with balloon angioplasty alone performed with similar-sized balloon catheters.

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## References

1. Gruentzig AR, Senning A, Siegenthaler WE. Nonoperative dilatation of coronary artery stenosis: percutaneous transluminal coronary angioplasty. N Engl J Med 1979;301:61–8.
2. Block PC, Myler RK, Stertzer S, Fallon JT. Morphology after transluminal angioplasty in human beings. N Engl J Med 1981;305:382–6.
3. Soward AL, Essed CE, Serruys PW. Coronary arterial findings after accidental death immediately after successful PTCA. Am J Cardiol 1985;56:794–5.
4. Farb A, Virmani R, Atkinson JB, Kolodgie F. Plaque morphology and pathologic changes in arteries from patients dying after coronary balloon angioplasty. J Am Coll Cardiol 1990;16:1421–9.
5. Uchida Y, Hasegawa K, Kawamura K, Shibuya I. Angioscopic observation of the coronary luminal changes induced by percutaneous transluminal coronary angioplasty. Am Heart J 1989;117:769–76.
6. Ramee SR, White CJ, Collins TJ, et al. Percutaneous angioscopy during coronary angioplasty using a steerable micrangioscope. J Am Coll Cardiol 1991;17:100–5.
7. Potkin BN, Keren G, Mintz GS, et al. Arterial responses to balloon coronary angioplasty: an intravascular ultrasound study. J Am Coll Cardiol 1992;20:942–5.
8. Honye J, Mahon DJ, White CJ, Ramee SR, Tobis JM. Morphological effects of coronary balloon angioplasty in vivo assessed by intravascular ultrasound imaging. Circulation 1992;85:1012–25.
9. Mintz GS, Kovach JA, Park KS, et al. Conservation of plaque mass: A volumetric intravascular ultrasound analysis of patients before and after percutaneous transluminal coronary angioplasty [abstract]. J Am Coll Cardiol 1993;21:484A.
10. Losordo DW, Rosenfield K, Pieczek A, Baker K, Harding M, Isner JM. How does angioplasty work? Serial analysis of human iliac arteries using intravascular ultrasound. Circulation 1992;86:1845–58.
11. Waller BF. "Crackers, breakers, stretchers, drillers, scrapers, shavers, burners, welders and melters": The future treatment of atherosclerotic coronary artery disease? A clinical-morphologic assessment. J Am Coll Cardiol 1989;13:969–87.
12. Rensing BJ, Hermans WRM, Beatt KJ, et al. Quantitative angiographic assessment of elastic recoil after percutaneous transluminal coronary angioplasty. Am J Cardiol 1990;66:1039–44.
13. Rensing BJ, Hermans WR, Strauss BH, Serruys PW. Regional differences in elastic recoil after percutaneous transluminal coronary angioplasty: A quantitative angiographic study. J Am Coll Cardiol 1991;17:34B–8B.
14. Hjemdahl-Monsen CE, Ambrose JA, Borrico S, et al. Angiographic patterns of balloon inflation during percutaneous transluminal coronary angioplasty: Role of pressure–diameter curves in studying distensibility and elasticity of the stenotic lesion and the mechanism of dilation. J Am Coll Cardiol 1990;16:569–75.
15. Hanet C, Wijns W, Michel X, Schroeder E. Influence of balloon size and stenosis morphology on immediate and delayed elastic recoil after percutaneous transluminal coronary angioplasty. J Am Coll Cardiol 1991;18:506–11.
16. Haude M, Erbel R, Issa H, Meyer J. Quantitative analysis of elastic recoil after balloon angioplasty and after intracoronary implantation of balloon-expandable Palmaz-Schatz stents. J Am Coll Cardiol 1993;21:26–34.
17. Grundfest WS, Litvack F, Forrester JS, et al. Laser ablation of human atherosclerotic plaque without adjacent tissue injury. J Am Coll Cardiol 1985;5:929–33.
18. Isner JM, Donaldson RF, Deckelbaum LI, et al. The excimer laser: gross, light microscopic and ultrastructural analysis of potential advantages for use in laser therapy of cardiovascular disease. J Am Coll Cardiol 1985;6:1102–9.
19. Singleton DL, Paraskevopoulos G, Taylor RS, Higginson LAJ. Excimer laser angioplasty: tissue ablation, arterial response, and fiber optic delivery. IEEE J Quantum Elect 1987;QE-23:1772–82.
20. Litvack F, Grundfest W, Eigler N, et al. Percutaneous excimer laser coronary angioplasty. Lancet 1989;2:102–3.
21. Werner GS, Buchwald A, Unterberg C, Voth E, Kreuzer H, Wiegand V. Recanalization of chronic total coronary arterial occlusions by percutaneous excimer-laser and laser-assisted angioplasty. Am J Cardiol 1990;66:1445–50.
22. Cook SL, Eigler NL, Shefer A, Goldenberg T, Forrester JS, Litvack F. Percutaneous excimer laser coronary angioplasty of lesions not ideal for balloon angioplasty. Circulation 1991;84:632–43.
23. Israel DH, Marmur JD, Sanborn TA. Excimer laser-facilitated balloon angioplasty of a nondilatable lesion. J Am Coll Cardiol 1991;18:1118–9.
24. Bittl JA, Sanborn TA. Excimer laser-facilitated coronary angioplasty: Relative risk analysis of acute and follow-up results in 200 patients. Circulation 1992;86:71–80.
25. Holmes DR, Bresnahan JF, Bell MR, Litvack F. Lesion morphology and outcome after laser angioplasty, a prospective evaluation: Excimer laser

coronary angioplasty registry (ELCA) [abstract]. J Am Coll Cardiol 1993; 21:288A.

26. Reiber JHC, Serruys PW. Quantitative coronary angiography. In: Marcus ML, Schelbert HR, Skorton DJ, Wolf GL, editors. Cardiac Imaging. A Companion to Braunwald's Heart Disease. Philadelphia: Saunders, 1991: 213-80.
27. Reiber JHC, Serruys PW, Kooijman CJ, et al. Assessment of short-, medium-, and long-term variations in arterial dimensions from computer-assisted quantitation of coronary cineangiograms. Circulation 1985;71: 280-8.
28. Haase J, Di Mario C, Slager CJ, et al. In-vivo validation of on-line and off-line geometric coronary measurements using insertion of stenosis phantoms in porcine coronary arteries. Cathet Cardiovasc Diag 1992;27:16-27.
29. Di Mario C, Hermans WRM, Rensing BJWM, Serruys PW. Calibration using angiographic catheters as scaling devices: importance of filming the catheters not filled with contrast medium [letter]. Am J Cardiol 1992;69: 1377-8.
30. Stertzer SH, Rosenblum J, Shaw RE, et al. Coronary rotational ablation: initial experience in 302 procedures. J Am Coll Cardiol 1993;21:287-95.
31. Rowe MH, Hinohara T, White NW, Robertson GC, Selmon MR, Simpson JB. Comparison of dissection rates and angiographic results following directional coronary atherectomy and coronary angioplasty. Am J Cardiol 1990;66:49-53.
32. Muller DWM, Ellis SG, Debowey DL, Topol EJ. Quantitative angiographic comparison of the immediate success of coronary angioplasty, coronary atherectomy and endoluminal stenting. Am J Cardiol 1990;66:938-42.
33. Umans VAWM, Strauss BH, Rensing BJWM, de Jaegere P, de Feyter PJ, Serruys PW. Comparative angiographic quantitative analysis of the immediate efficacy of coronary atherectomy with balloon angioplasty, stenting and rotational ablation. Am Heart J 1991;122:836-43.
34. Umans VA, Hermans W, Foley DP, et al. Restenosis after directional coronary atherectomy and balloon angioplasty: Comparative analysis based on matched lesions. J Am Coll Cardiol 1993;21:1382-90.
35. Kimball BP, Bui S, Cohen EA, Carere RG, Adelman AG. Comparison of acute elastic recoil after directional coronary atherectomy versus standard balloon angioplasty. Am Heart J 1992;124:1459-66.
36. van Leeuwen TG, van Erven L, Meertens JH, Motamedi M, Post MJ, Borst C. Origin of arterial wall dissections induced by pulsed excimer and mid-infrared laser ablation in the pig. J Am Coll Cardiol 1992;19:1610-8.
37. Tomaru T, Geschwind HJ, Boussignac G, Lange F, Tahk SJ. Characteristics of shock waves induced by pulsed lasers and their effects on arterial tissue: comparison of excimer, pulse dye, and holmium YAG lasers. Am Heart J 1992;123:896-904.
38. Abela GS. Abrupt closure after pulsed laser angioplasty: Spasm or a "mille-feuilles" effect? J Interven Cardiol 1992;5:259-62.
39. van Leeuwen TG, Meertens JH, Velema E, Post MJ, Borst C. Intraluminal vapor bubble induced by excimer laser pulse causes microsecond arterial dilation and invagination leading to extensive wall damage in the rabbit. Circulation 1993;87:1258-63.
40. Diethrich EB, Hanafy HM, Santiago OJ, Bahadir I. Angioscopy after coronary excimer laser angioplasty [letter]. J Am Coll Cardiol 1991;18:643.
41. Nakamura F, Kvasnicka J, Uchida Y, Geschwind HJ. Percutaneous angioscopic evaluation of luminal changes induced by excimer laser angioplasty. Am Heart J 1992;124:1467-72.
42. Isner JM, Rosenfield K, White CJ, et al. In vivo assessment of vascular pathology resulting from laser irradiation: Analysis of 23 patients studied by directional atherectomy immediately after laser angioplasty. Circulation 1992;85:2185-96.
43. Karsch KR, Haase KK, Mauser M, Voelker W. Initial angiographic results in ablation of atherosclerotic plaque by percutaneous coronary excimer laser angioplasty without subsequent balloon dilatation. Am J Cardiol 1989;64: 1253-7.
44. Karsch KR, Haase KK, Wehrmann M, Hassenstein S, Hanke H. Smooth muscle cell proliferation and restenosis after stand alone coronary excimer laser angioplasty. J Am Coll Cardiol 1991;17:991-4.
45. Sanborn TA. Early limitations of coronary excimer laser angioplasty. J Am Coll Cardiol 1991;17:995-6.
46. Kvasnicka J, Nakamura F, Dupouy P, Dubois-Randé JL. Angioscopic assessment of coronary arteries following excimer laser coronary angioplasty [abstract]. Circulation 1992;86:Suppl I:I-654.
47. Taylor RS, Higginson LAJ, Leopold KE. Dependence of the XeCl laser cut rate of plaque on the degree of calcification, laser fluence, and optical pulse duration. Lasers Surg Med 1990;10:414-9.
48. Hamburger JN, Gijsbers GH, Sprangers RL, van Gemert MJ, Dunning AJ. Excimer laser tissue interaction using a modified multi fiber catheter [abstract]. J Am Coll Cardiol 1993;21:385A.
49. Xie DY, Hassenstein S, Oberhoff M, Wehrmann M, Haase KK, Hanke H. Preliminary evaluation of smooth excimer laser coronary angioplasty (SELCA) in vitro [abstract]. Circulation 1992;86:Suppl I:I-653.
50. Rosenfield K, Wells L, Grace K, et al. Excimer laser angioplasty with sequential fiber activation: Preliminary analysis of a novel catheter design [abstract]. J Am Coll Cardiol 1993;21:385A.
51. Tcheng JE, Phillips HR, Wells LD, et al. A new technique for reducing pressure pulse phenomena during coronary excimer laser angioplasty [abstract]. J Am Coll Cardiol 1993;21:386A.
52. Hermans WRM, Rensing BJ, Strauss BH, Serruys PW. Methodological problems related to the quantitative assessment of stretch, elastic recoil and balloon-artery ratio. Cath Cardiovasc Diagn 1992;25:174-85.
53. Strikwerda S, Koolen JJ, de Feyter PJ, Sprangers RLH, Tijssen JGP, Serruys PW. Excimer laser coronary angioplasty in the Netherlands: preamble for a randomized study. Am Heart J 1993;125:838-47.