Local drug delivery is the process by which therapeutic agents are administered to targeted segments of the circulatory system to treat vascular disease. The aims are to optimize therapeutic efficacy by direct drug administration and to minimize untoward effects associated with systemic delivery. This is accomplished in humans with drug-eluting stents (DES), drug-coated balloons (DCB), and direct catheter delivery.

Local drug delivery has revolutionized the percutaneous treatment of coronary artery disease. Though many forms of local drug delivery are used, the most significant advance in this vascular bed relates to reductions in restenosis after DES implantation. Interest in translating these successes of local drug delivery from the coronaries to the peripheral vasculature is obvious and desirable, particularly in vascular beds hindered by high restenosis rates.

Paclitaxel is a taxane derivative with antiproliferative properties that make it effective in treating coronary restenosis. Paclitaxel has been used in most vascular beds, and several trials using different methods of local delivery for the treatment of lower-extremity peripheral arterial disease (PAD) have been recently reported. The discussion that follows aims to (1) describe the characteristics of paclitaxel that make it suitable for local drug delivery, (2) review the reported literature of paclitaxel use in noncoronary vascular beds, and (3) compare methods and discuss future directions of local drug delivery for PAD.

Paclitaxel: Antirestenotic Properties

Paclitaxel is a natural diterpenoid found in Taxus species. It inhibits microtubule disassembly and disrupts normal cellular processes including protein signaling, mitosis, and migration. Paclitaxel is generally cytostatic, though higher drug concentrations may cause tissue necrosis. Paclitaxel is highly lipophilic and poorly soluble in water. This promotes rapid tissue uptake, a property that enables brief drug exposure to vessel walls to result in adequate tissue concentrations.

Compared with other antiproliferatives such as sirolimus, the tissue uptake of free paclitaxel is significantly higher than sirolimus when delivered during angioplasty with DCB. In addition, others have suggested that adequate tissue delivery of sirolimus and its analogues may require more prolonged exposures, using sophisticated drug carriers. This may represent an advantage for paclitaxel when considering local drug delivery with stentless mechanisms such as direct catheter delivery or DCB.

Paclitaxel combats restenosis through several mechanisms. Using in vitro methods, Axel et al demonstrated that paclitaxel exposure inhibited proliferation and migration of human smooth muscle cells. Paclitaxel-treated cells deposited less extracellular matrix. Cellular changes were similar irrespective of whether the paclitaxel exposure was 20 minutes or 24 hours in duration. In a rabbit model of atherosclerosis, a 30-second irrigation of paclitaxel through a microporous balloon catheter resulted in marked inhibition of restenosis at 28 days. Similar antirestenotic effects were not demonstrated when paclitaxel was delivered with an infusion catheter before stenting in porcine coronary arteries. This may suggest that the timing of drug delivery as well as the tissue response to stenting influence the antiproliferative effects of paclitaxel.

Heldman et al investigated efficacy of paclitaxel-eluting stents (PES) using a porcine model of coronary restenosis. Neointimal formation decreased significantly in a dose-dependent fashion in paclitaxel-treated arteries. Importantly, paclitaxel-treated vessels had larger luminal areas as the result of both arterial dilation and reductions in medial wall thickness, particularly in the higher-dose groups. Thus, paclitaxel preserves luminal area by other mechanisms, namely vessel enlargement, in addition to inhibiting the development of neointima. Importantly, the preclinical studies demonstrating these antirestenotic effects were not limited to the coronary circulation. Albrecht et al demonstrated reductions in restenosis in peripheral porcine arteries by delivering paclitaxel with DCB.

Local Paclitaxel Delivery and PAD Cerebrovascular Disease

Several reports have described the successful use of coronary PES to treat atherosclerotic cerebrovascular disease (Table 1). These studies were not randomized and did not have control groups for comparison. For vertebral interventions, reported procedural success rates exceed 95%, with only 3% of subjects having periprocedural complications. With varied

Received December 29, 2010; accepted March 4, 2011.
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(Circ Cardiovasc Interv. 2011;4:297-302.)

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Circ Cardiovasc Interv is available at http://circinterventions.ahajournals.org

DOI: 10.1161/CIRCINTERVENTIONS.110.961052
follow-up from 4 to 19 months, angiographic restenosis of >50% is reported to be present in 4.8% to 21.4%, though not all subjects in these studies received imaging surveillance. Ogilvy et al.\(^{26}\) have suggested that DES may reduce rates of restenosis after vertebral angioplasty. For intracranial interventions, no procedural failures have been reported. Complications have been reported in up to 25% of procedures. No angiographically significant restenosis has been identified during follow-up extending to 14 months.\(^{17–25}\)

### Visceral Arteries: Renals and Mesenterics

Table 2 summarizes the published reports of paclitaxel use in renal and mesenteric arteries.\(^{27–32}\) One retrospective series reported outcomes in 16 subjects receiving DES (11 with PES) for renal artery stenosis. Patency rates at 22 months were similar to those receiving a bare metal stent, though the arteries treated with DES were significantly smaller.\(^{33}\) Others have suggested that DES may be the preferred treatment for small, stenotic renal arteries because restenosis rates are significantly increased in these vessels.\(^{33}\) Two successful case reports involving PES to treat mesenteric in-stent restenosis have been reported.\(^{31,32}\)

### Infrapopliteal Disease

Primary patency rates for infrapopliteal intervention have been reported to be as low as 48% at 18 months for angioplasty\(^{34}\) and 17% at 3 years for bare metal stents after suboptimal angioplasty.\(^{35}\) The tibial vessels are comparable in size to the coronary arteries, naturally leading to interest in using DES for their treatment.

Siaibis et al.\(^{36}\) reported 29 patients with 50 infrapopliteal lesions treated with 62 PES. Though the technical success and limb salvage rates were 100% and 89%, respectively, 77% of treated lesions had significant angiographic in-stent restenosis and 30% of patients required repeat revascularization within 1 year. Renal disease and vessel occlusion were associated with worse outcomes.\(^{36}\) Grant et al.\(^{37}\) reported 10 patients of whom 4 received PES to treat infrapopliteal arteries. At 1 year, the target revascularization rate was 10%. Three patients receiving follow-up angiography within 1 year were found to have patent stents. One stent thrombosis occurred 3 weeks after an initially successful procedure. Details regarding outcomes based on the DES type were not reported.\(^{37}\) McMillan et al.\(^{38}\) reported outcomes of 52 tibial vessels treated with PES. Limb salvage was 86% at 26 months; primary patency was 73% at 24 months.

### Table 1. Paclitaxel Use and Cerebrovascular Disease

<table>
<thead>
<tr>
<th>Study</th>
<th>Total Patients/Vessels</th>
<th>Vessels Treated</th>
<th>Procedural Success/Complications (%)</th>
<th>Mean Follow-Up, Months</th>
<th>Long-Term Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sharma(^{21}) (2006)</td>
<td>1/1</td>
<td>Vertebral</td>
<td>100/0</td>
<td>6</td>
<td>Patent on CTA</td>
</tr>
<tr>
<td>Gupta(^{18}) (2006)</td>
<td>59/62 (74% received PES; data based on DES type not provided)</td>
<td>Vertebral (31), IC vertebral or basilar (18), EC internal carotid (5), IC internal carotid (8)</td>
<td>95/3</td>
<td>4.8% With restenosis &gt;50%</td>
<td></td>
</tr>
<tr>
<td>Lin(^{19}) (2008)</td>
<td>11/11 (8 PES)</td>
<td>Vertebral</td>
<td>100/0</td>
<td>18.7</td>
<td>All clinically asymptomatic</td>
</tr>
<tr>
<td>Vadja(^{23}) (2009)</td>
<td>48/52</td>
<td>Vertebral</td>
<td>100/0</td>
<td>7.7</td>
<td>12% With restenosis &gt;50% on angiography</td>
</tr>
<tr>
<td>Yu(^{25}) (2009)</td>
<td>10/10</td>
<td>Vertebral</td>
<td>100/0</td>
<td>12</td>
<td>All clinically asymptomatic</td>
</tr>
<tr>
<td>Werner(^{24}) (2010)</td>
<td>28/28</td>
<td>Vertebral</td>
<td>100/0</td>
<td>16</td>
<td>21.4% With restenosis &gt;50% on angiography</td>
</tr>
<tr>
<td>Abou-Chebl(^{17}) (2005)</td>
<td>4/4</td>
<td>IC internal carotid (2), MCA (1), basilar (1)</td>
<td>100/25</td>
<td>8.5</td>
<td>No restenosis on angiography and/or Doppler</td>
</tr>
<tr>
<td>Qureshi(^{20}) (2006)</td>
<td>4/4</td>
<td>IC internal carotid (2), MCA (1), basilar (1)</td>
<td>100/25</td>
<td>13.7</td>
<td>3/3 patent on angiography, 1 death at 7 mo</td>
</tr>
<tr>
<td>Steinfort(^{22}) (2007)</td>
<td>13/13</td>
<td>IC vertebral (8), basilar (5)</td>
<td>100/8</td>
<td>5.4</td>
<td>No significant restenosis in 9 subjects receiving angiography</td>
</tr>
</tbody>
</table>

CTA indicates computed tomography angiography; PES, paclitaxel-eluting stents; IC, intracranial; EC, extracranial; and MCA, middle cerebral artery.

### Table 2. Reports of PES Implantation in Visceral Arteries

<table>
<thead>
<tr>
<th>Artery</th>
<th>Study</th>
<th>Patient(s)</th>
<th>Follow-Up</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>Renal</td>
<td>Dous(^{27}) (2008)</td>
<td>3 (after transplant with ISR)</td>
<td>19–45 mo</td>
<td>3/3 Patent on duplex</td>
</tr>
<tr>
<td></td>
<td>Granillo(^{28}) (2005)</td>
<td>1</td>
<td>3 mo</td>
<td>No significant restenosis on angiography</td>
</tr>
<tr>
<td></td>
<td>Kakkar(^{29}) (2006)</td>
<td>1 (ISR)</td>
<td>6 mo</td>
<td>No significant restenosis on angiography</td>
</tr>
<tr>
<td></td>
<td>Misra(^{30}) (2008)</td>
<td>11</td>
<td>22 mo</td>
<td>1-Year patency similar (BMS 58% vs DES 78%, (P=NS)), DES arteries smaller (3.4 mm vs 5.3 mm, (P&lt;0.05))</td>
</tr>
<tr>
<td>Mesenteric</td>
<td>Visconti(^{31}) (2008)</td>
<td>1 (celiac ISR)</td>
<td>9 mo</td>
<td>Patent on CT</td>
</tr>
<tr>
<td></td>
<td>Cardaioli(^{32}) (2007)</td>
<td>1 (SMA ISR)</td>
<td>8 mo</td>
<td>Patent on CT</td>
</tr>
</tbody>
</table>

ISR indicates in-stent restenosis; BMS, bare metal stent; SMA, superior mesenteric artery; and CT, computed tomography.
Table 3. Trials of Local Paclitaxel Delivery for Femoropopliteal Disease

<table>
<thead>
<tr>
<th>Trial</th>
<th>Mechanism of Delivery</th>
<th>Dose</th>
<th>Patients Enrolled, n</th>
<th>Lesion Length (Mean, cm)</th>
<th>Follow-Up Duration</th>
<th>Results</th>
<th>Miscellaneous</th>
</tr>
</thead>
<tbody>
<tr>
<td>THUNDER⁴</td>
<td>(1) PCB (2) Paclitaxel-containing contrast</td>
<td>3 µg/mm²</td>
<td>154</td>
<td>7.4</td>
<td>24 mo</td>
<td>LLL at 6 mo, 0.4 mm vs 1.7 mm (P&lt;0.01), favoring PCB</td>
<td>Revascularization rates lower with PCB at 24 mo (15% vs 52%), no benefit with paclitaxel-containing contrast</td>
</tr>
<tr>
<td>FemPac⁴⁵</td>
<td>PCB</td>
<td>3 µg/mm²</td>
<td>87</td>
<td>6.0</td>
<td>24 mo</td>
<td>LLL at 6 mo, 0.5 cm vs 1.1 cm, favoring PCB</td>
<td>Stent fracture rate 0.9%</td>
</tr>
<tr>
<td>ZILVER PTX⁴⁵</td>
<td>PES</td>
<td>3 µg/mm²</td>
<td>479</td>
<td>6.5</td>
<td>12 mo</td>
<td>Primary patency, 83% vs 67%, favoring PES</td>
<td>Revascularization rates lower with PCB at 24 mo (13% vs 50%)</td>
</tr>
</tbody>
</table>

LLL indicates late lumen loss; PCB, paclitaxel-coated balloons; PES, paclitaxel-eluting stents.

PARADISE was a prospective cohort of 106 patients treated with infrapopliteal DES for critical limb ischemia. PES were used in 17% of cases. Amputation and survival rates at 3 years were 6% and 71%, respectively. Notably, restenosis rates were found to be lower with sirolimus-eluting-stents compared with PES.⁴⁹ A recent meta-analysis also suggested better outcomes when using sirolimus-eluting-stents for infrapopliteal disease.⁴⁰

The PICOLLO and PADI trials are ongoing, randomized trials investigating the use of paclitaxel-coated balloons (PCB) and PES to treat infrageniculate disease in subjects with critical limb ischemia.⁴¹,⁴² Their results should help clarify the role of paclitaxel in tibial vessels, but it should be noted that, based on available evidence, sirolimus may be more efficacious in this distribution when using a stent platform for delivery.⁴⁰

**Femoropopliteal Disease**

The THUNDER trial randomly assigned 154 subjects with symptomatic femoropopliteal disease to 1 of 3 treatment strategies: angioplasty (control), angioplasty with PCB, or angioplasty in presence of paclitaxel-containing contrast medium (Table 3). Mean lesion length was 7.4 cm, 27% were occlusions, and 36% had been treated previously. At 6 months, angiographic late lumen loss was significantly lower in the PCB group (0.4 mm versus 1.7 mm, P<0.001). Target lesion revascularization was significantly lower in the PCB group at 6 and 24 months (4% versus 29% at 6 months, P<0.001; 15% versus 52% at 24 months, P<0.001). No benefit was seen in the paclitaxel-contrast group.⁴³

The Femoral Paclitaxel (FemPac) trial randomly assigned 87 patients with femoropopliteal disease to angioplasty or angioplasty using a PCB. Mean lesion length was 6.0 cm, and 16% were occlusions. At 6 months, late lumen loss was 0.5 mm in the PCB group compared with 1.0 mm in the control group (P=0.031). Target lesion revascularization occurred in 7% and 33% of the PCB and control groups, respectively (P=0.045). This difference was maintained at 18 months.⁵

Dake et al⁴ recently reported their 12-month findings from the ZILVER PTX trial, a 479-patient, randomized study comparing a polymer-free PES with angioplasty and bare metal stent for superficial femoral artery disease. Mean lesion length was 6.5 cm. Twenty-seven percent of treated lesions were occlusions; only 5% had been previously treated. Primary patency at 12 months was achieved in 83% of subjects receiving the PES versus 67% of those receiving angioplasty with provisional stenting (P<0.01). In a subgroup undergoing secondary randomization after suboptimal angioplasty, patients receiving the PES had significantly less restenosis than those receiving the same stent without the paclitaxel coating (90% versus 73%, P<0.05). The stent fracture rate was 0.9%. No adverse events attributable to paclitaxel were reported in the THUNDER, FemPac, or ZILVER PTX trials.³–⁵

Latif and Hennebry⁴³ reported the successful treatment of 1 iliac and 1 superficial femoral artery with paclitaxel delivered in saline using a microporous, irrigating catheter (Clearway Catheter, Atrium Medical Corp, Hudson, NH). Both patients remained asymptomatic during a brief follow-up duration of 4 months. An investigator-initiated pilot study evaluating safety and efficacy of this delivery method is now ongoing (IRRITAX, NCT 00821028). This trial is randomly assigning patients with TASC II A-C femoropopliteal lesions to standard therapy versus standard therapy with paclitaxel irrigation. The primary end point is restenosis at 12 months on ultrasonography.

**Comparisons of Local Delivery Methods**

No comparative data exist regarding the optimal drug delivery method for paclitaxel in the peripheral vasculature. Three methods of delivery for femoropopliteal disease have been reported.³–⁵,⁴³ Table 4 summarizes the key distinctions between these methods.⁴²

Coronary PES use polymers for drug binding that alter drug release kinetics to provide a sustained drug release over days to weeks.⁴⁴ This is in contrast to bolus delivery methods such as irrigation or DCB, in which the paclitaxel is administered in higher doses during short exposure times. Either method results in prolonged retention of drug in the vessel wall,⁴⁵ but it is unclear if vessel healing differs between these different mechanisms of delivery, especially in the presence of an indwelling stent.

As the result of stent structure and cell design, the highest tissue concentrations of antiproliferative drug are located at the strut sites. This nonuniform drug distribution may be an important limitation in larger vessels, particularly when the distance between struts increases. Both irrigation and DCB theoretically allow for a more uniform exposure of drug to the targeted vessel wall. Conversely, total drug dosing may be
more precise with DES because significant amounts of drug may be lost downstream with DCB and irrigation methods.

Paclitaxel irrigation occurs during low pressure balloon inflation and after the lesion has received standard angioplasty.43 Other methods use high-pressure inflations for delivery.4 Tissue uptake and vascular response to drug exposure may differ after injury from high-pressure inflations. Similarly, other procedures such as atherectomy may influence tissue responses to local drug delivery.

Differences in DES efficacy and safety have become apparent with the development of new antiproliferative agents and polymers.1 It follows that not all DCB are similarly efficacious. In an animal model of restenosis, the Paccocath PCB recently outperformed the Dior PCB, suggesting that efficacy may differ even among polymer-free PCB.46 Similarly, paclitaxel exhibits much higher solubility in iodinated media than in saline. The currently described methods of paclitaxel irrigation in humans have used saline,43 as did the pioneering work by Axel et al12 in animal models of restenosis. It is unknown at this time what effects alternative irrigation methods might have, though it is noteworthy that the paclitaxel-contrast arm of the THUNDER trial demonstrated no benefit.4

### Future Directions

The recent benefits reported with local paclitaxel delivery in femoropopliteal disease are welcome advances, though progress is needed in understanding how to deliver patient-centered, lesion-specific therapy. Optimal application of local drug delivery for PAD probably will hinge on a host of variables including patient characteristics, lesion characteristics, and vascular bed involved (Figure).

Evidence to date favors paclitaxel for femoropopliteal disease, though no trials comparing paclitaxel with sirolimus have been conducted, and only sirolimus on a DES platform has been tested in this distribution.4,5,47 In contrast, sirolimus-eluting-stents may be more efficacious than PES in the infrapopliteal distribution.35,36,40 The utility of newer antiproliferatives, such as the sirolimus analogs, remains to be determined.48

Patient and lesion characteristics are important considerations as well. Though no consensus exists regarding dual antiplatelet therapy after peripheral intervention, patients not suitable for prolonged dual antiplatelets may be poor candidates for DES. Similarly, stentless drug delivery may be desirable in locations vulnerable to compression, lesions involving in-stent restenosis, and with interventions jeopardy...
izing major side branches. There is emerging evidence that antiproliferative drug uptake is influenced by the degree of vascular disease present. Not only does the degree of disease influence how a single drug is absorbed, these differences are not uniform and differ between antiproliferatives. How plaque morphology influences drug uptake and how these differences affect drug efficacy remains to be determined. As such, one can portend the need for better “lesion stratification,” either with advanced imaging modalities or with molecular techniques to identify the ideal antiproliferative for a specific lesion.

Conclusions

The antirestenotic properties of paclitaxel continue to make this agent important in the treatment of peripheral vascular disease. Multiple methods of local paclitaxel delivery are available, and more probably will become available in the near future. Rather than competitors, these methods may be complementary. The ideal application of this technology will be based on a complex number of factors that need clarification with future research. It is unclear if alternative antiproliferatives will replace paclitaxel, but it is certain that future advances in this field of local drug delivery will have been aided by the knowledge gained with its use in the peripheral vasculature.

Disclosures

Dr Hennebry is the principal investigator of IRRITAX. Atrium Medical Corporation is supplying irrigating catheters and a grant to Hawkins and Hennebry Paclitaxel and PAD 301

References


Local Paclitaxel Delivery for Treatment of Peripheral Arterial Disease
Beau M. Hawkins and Thomas A. Hennebry

_Circ Cardiovasc Interv._ 2011;4:297-302; originally published online May 3, 2011;
doi: 10.1161/CIRCINTERVENTIONS.110.961052
_Circulation: Cardiovascular Interventions_ is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
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Print ISSN: 1941-7640. Online ISSN: 1941-7632

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