Animal Models of Retinal Vein Occlusion

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PURPOSE. To provide a comprehensive and current review on the available experimental animal models of retinal vein occlusion (RVO) and to identify their strengths and limitations with the purpose of helping researchers to plan preclinical studies on RVO.

METHODS. A systematic review of the literature on experimental animal models of RVO was undertaken. Medline, SCOPUS, and Web of Science databases were searched. Studies published between January 1, 1965, and March 31, 2017, and that met the inclusion criteria were reviewed. The data extracted included animal species used, methods of inducing RVO, and the clinical and histopathologic features of the models, especially in relation to strengths, limitations, and faithfulness to clinical sequelae.

RESULTS. A total of 128 articles fulfilling the inclusion criteria were included. Several species were used to model human branch and central RVO (BRVO; CRVO) with nonhuman primates being the most common, followed by rodents and pigs. BRVO and CRVO were most commonly induced by laser photocoagulation and all models showed early features of clinical disease, including retinal hemorrhages and retinal edema. These features made many of the models adequate for studying the acute phase of BRVO and CRVO, although macular edema, retinal ischemia, and neovascular complications were observed in only a few experimental animal models (laser-induced model in rodents, pigs, and nonhuman primates, diathermy-induced model in pigs, and following intravitreal injection of PD0325901 in rabbits for BRVO; and in the laser-induced model in rodents, rabbits, and nonhuman primates, diathermy-induced model in nonhuman primates, following permanent ligation of the central retinal vein in nonhuman primates, and with intravitreal injection of thrombin in rabbits for CRVO).

CONCLUSIONS. Experimental animal models of RVO are available to study the pathogenesis of this disease and to evaluate diagnostic/prognostic biomarkers and to develop new therapeutics. Data available suggest laser-induced RVO in pigs and rodents to be overall the best models of BRVO and the laser-induced RVO rodents the best model for CRVO.

Keywords: retinal vein occlusion, retinal vein thrombosis, ischemia, experimental models, animal models, in vivo models

Retinal vein occlusion (RVO) is the second most common vascular cause of visual loss, surpassed only by diabetic retinopathy.1–5 Obstruction of the retinal venous system is commonly caused by thrombus formation, which may result in devastating consequences, including macular edema and neovascular complications, leading to visual impairment and blindness.6–14 RVO has been typically classified into central (CRVO), branch (BRVO), hemispheric and hemicentral types based on the site of the occlusion.1,2,4,5,15–17 Each of these RVO types has been further subclassified into ischemic and nonischemic forms based on the severity of the disease and the likelihood of developing neovascular complications. Ischemic RVO (iRVO) is the most severe form, associated with higher risk of complications and having a poorer prognosis than non-iRVO.1,2,4,5,17,18

Current treatments of RVO, including laser photocoagulation, intravitreal anti-VEGF therapies, intravitreal steroids, and pars plana vitrectomy, target the complications of RVO, namely macular edema and neovascularization and its consequences,1,2,5,7,10,16,17,19–24 and may not fully reverse the functional and structural damage result of the disease.10,25–59 Furthermore, each of these treatments carries a risk to patients, such as destruction of the retina following laser photocoagulation, endophthalmitis following intravitreal injections, and cataract and glaucoma as a result of steroid administration. Treatments for macular edema that are a result of RVO have been predominantly investigated for the nonischemic form, with most randomized clinical trials excluding or including only few with the iRVO.55–59,40,45,47,52–55,60 In trials in which they have been included, only approximately 50% or less of patients with iRVO show a meaningful improvement in visual acuity following these therapies,54,57,58,45,40–51,57 with often poor final visual acuity (< 20/100) despite treatment.10,34,36–38,41,43,51,57

Further research is still needed to improve current understanding of the pathogenesis of RVO as well as to identify more clinically effective and cost-effective therapeutic options. This is especially true for patients with iRVO.

Experimental animal models often can be useful to study disease mechanisms and to test the efficacy and potential...
toxicity of new treatments. Such animal approaches have been successful in ophthalmic research, allowing advancement in our understanding of pathogenesis and development of improved novel therapies. Experimental animal models of RVO also are available, which variably develop functional and structural features resembling those present in people with this disorder. Herein, we aim at providing a comprehensive up-to-date review on experimental animal models of RVO including species, methods of vessel occlusion, their clinicohistopathologic features, and the limits of their translational value. Taken together, this focused and in-depth review ought to help researchers design future studies and appreciate the strengths and weaknesses of the animal models they use.

METHODS

A systematic review of the literature was conducted, and data sources were Medline, SCOPUS, and Web of Science databases. Keywords including "retinal vein occlusion," "retinal vein thrombosis," and "retinal vein obstruction" were combined with "experimental models" or "animal models." The search covered published articles from January 1, 1965, to March 31, 2017, and was filtered to include articles in English only. The included articles of studies describing methods of creating animal models of RVO and their findings were analyzed, and data contained in these articles were used to inform species-specific model systems, the range of methods for inducing vein occlusion, pathologic and clinical features developed in these models, and strengths and limitations of available models. The information extracted was used to populate Tables 1 through 8 of this review. In addition, their clinical value and potential translational implications for the management of patients with this disorder was considered. Changes on levels of cytokines/chemokines/growth factors and other biochemical and molecular events occurring as a result of the induction or RVO in these models, as well as effects of treatments tested in these models, are not summarized herein.

RESULTS

Studies Included

After removal of duplicates, a total of 320 titles were identified and their abstracts obtained and evaluated for potential inclusion in the review. Of the 320 abstracts, 193 were found to relate to studies outside the scope of this review and, thus, were excluded. Full articles of the remaining 128 studies were obtained, found to be directly related to the topic of this review, and used to extract pertinent data.

Species

Several animal species have been used to study RVO, including rodents, rabbits, cats, dogs, pigs, and nonhuman primates (Tables 1, 2). Each of these species has its own size and anatomic advantages, but also ethical challenges and cost implications; these have been summarized in Table 3. Although the retina and retinal vessels of these animals share many anatomic features with humans, differences still exist and are more pronounced in some species (Table 4). None of the animal models, with the exception of the nonhuman primate, have an anatomic macula or fovea centralis. Pigs, cats, and dogs have a central retinal area with high density of ganglion cells and cone photoreceptors known as area centralis, which would correspond to the fovea centralis in humans but is less specialized and cannot be identified by gross fundus examina-

<table>
<thead>
<tr>
<th>Species</th>
<th>Laser Photoablation</th>
<th>Photodynamic Therapy</th>
<th>Diathermy</th>
<th>Photosensitizer</th>
<th>Total, n</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rodents, n</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>Total, n</td>
</tr>
<tr>
<td>Rabbits, n</td>
<td>1</td>
<td>5</td>
<td>0</td>
<td>1</td>
<td>7</td>
</tr>
<tr>
<td>Cats, n</td>
<td>1</td>
<td>2</td>
<td>0</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>Dogs, n</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Pigs, n</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Nonhuman primates, n</td>
<td>1</td>
<td>2</td>
<td>0</td>
<td>1</td>
<td>4</td>
</tr>
</tbody>
</table>

**Bolded values represent models that addressed macular edema or ischemic features.** Ischemia defined by one or more of the following criteria: development of neovascularization, extensive areas of retinal capillary nonperfusion, or areas capillary nonperfusion associated with atrophy/cell loss of the inner retinal layers (MO, macular edema; n, number of articles).
Animal Species and Techniques Used to Induce CRVO

<table>
<thead>
<tr>
<th>Laser Photocoagulation</th>
<th>Intravitreal Photosensitizer</th>
<th>Intravitreal Thrombin, n</th>
<th>Intravitreal NPe6, n</th>
<th>Total, n</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rodents, n</td>
<td>9</td>
<td>0</td>
<td>0</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>Rabbits, n</td>
<td>1 (ischemia = 4)</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Cats, n</td>
<td>1 (ischemia = 1)</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Pigs, n</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Nonhuman primates, n</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>12</td>
<td>6</td>
</tr>
<tr>
<td>Total, n</td>
<td>15</td>
<td>1</td>
<td>1</td>
<td>17</td>
<td>17</td>
</tr>
</tbody>
</table>

Bolded values represent models that addressed macular edema or ischemic features. Ischemia defined by one or more of the following criteria: development of neovascularization, extensive areas of retinal capillary nonperfusion, or areas of capillary nonperfusion associated with atrophy/cell loss of the inner retinal layers (i.e., outer retinal layers).

Methods of Inducing RVO

Several techniques have been used to induce an RVO in experimental animals. These have been summarized, including their advantages and disadvantages, in Table 5. In most cases, experimental RVO has been induced by traumatizing one or more retinal veins using laser photocoagulation. Branch Retinal Vein Occlusion. Experimentally, BRVO has been produced by using laser photocoagulation, photodynamic coagulation, or intravitreal injection of PD032590.

Laser Photocoagulation. In this method, laser irradiation is performed on selected retinal veins to produce BRVO. Laser photocoagulation is typically done on the slit-lamp using a contact lens. Some studies have combined laser photocoagulation with vitrectomy. Different types of laser and wavelengths have been used, commonly 514-nm Argon, and their parameters varied depending on the type of laser used, type of animal, and use or not of adjuvants (Table 6). Photosensitizers, such as Rose Bengal, erythrosin B, sodium fluorescein, chloroaluminium sulfonated phthalocyanine, PAD-S31, and mono-L-aspartyl chlorin e6 (NPe6) have been commonly used with the laser photocoagulation to minimize the amount of the laser energy required to produce the RVO. Rose Bengal has been the most commonly used photosensitizer.

Combination of intravitreal injec-
tion of thrombin (50 units) and laser photocoagulation has also been reported. Endophotocoagulation has also been used to achieve a vein occlusion; for this technique, an endolaser probe is inserted into the eye through a sclerostomy (without removing the vitreous) and retinal veins are then photocoagulated until evidence of occlusion is seen.146,147

Photodynamic Therapy. Photodynamic coagulation is another method that has been used to induce BRVO. 93–95,112,119,148,149 This method involves light illumination using a slit-lamp and a contact lens, or an endo illuminator in combination with vitrectomy aiming at selected retinal vein or veins, with care not to damage retinal arteries, for a duration ranging between 6 and 20 minutes until evidence of venous occlusion is observed.93–95,112,119,148,149 Photosensitizers, such as Rose Bengal,93–95,112,119,148,149 sodium fluorescein,119 and NP60,82 have been used in different doses depending on the species used to facilitate thrombus formation.

Diathermic Cauterization. An alternative way to produce experimental BRVO is by using diathermy, which has been undertaken via a pars plana sclerotomy.75,120–124,150–152 In cats, BRVO has been induced with indirect ophthalmoscopy and 20-gauge bipolar diathermy that is applied to the targeted vein/veins for 5 seconds.120–124 In pigs, a technique has been described that produces a BRVO following a temporal canthotomy, conjunctival incision, and performance of three sclerotomies at 10, 2, and 5 o'clock, 2 mm posterior to the corneal limbus.150–153 In this method, a light source and a blunt bipolar diathermy probe are inserted into the vitreous and one or two major retinal veins are coagulated approximately 1 disc diameter away from the optic disc for 5 to 7 seconds after 5 seconds of compression and under direct view.
through an operating microscope and with the aid of a fundus contact lens. This procedure does not involve vitrectomy.

**Intravitreal Injection of Substances.** PD0325901 (N-[2,3-dihydroxy-propoxy]-3,4-difluoro-2-[fluoro-4-ido-phenylamino]-benzamide) is a mitogen-activated protein kinase inhibitor that has been used in clinical trials for the treatment of solid tumors and has been found to be associated with development of BRVO. Based on this, one study established a rabbit model of BRVO by a single intravitreal injection of PD0325901 (0.5 or 1.0 mg per eye) using a 27-gauge needle inserted approximately 3 mm posterior to the limbus at the superior temporal quadrant and advanced until into the midvitreous cavity. 

**Central Retinal Vein Occlusion.** CRVO has been produced by laser photocoagulation, diathermic cautery, and intravitreal injection of thrombin.

**Laser Photocoagulation.** In this method, all major branches are irradiated with laser to produce CRVO, classically 0.5 to 2.0 disc areas from the optic disc, avoiding damaging the retinal arteries. Similar to BRVO, laser photocoagulation is typically done on the slit-lamp using a contact lens.

**Diathermic Cauterization.** Diathermic cauterization of the central retinal vein has been achieved through a lateral orbitotomy approach in nonhuman primates to produce CRVO. In this method, diathermy is applied at the central retinal vein on the inferiomedial aspect of the optic nerve as it exits the optic nerve sheath, avoiding injury to the ciliary vessels.

**Mechanical Ligation.**

- Permanent ligation of central retinal vein: Mechanical ligation of the central retinal vein was used in nonhuman primates to produce CRVO in one study. Through a lateral orbital approach and using the operating microscope to aid visualization and achieve adequate magnification, the central retinal vein was identified and ligated using an 8-0 silk suture. Two approaches were then used to achieve a CRVO: (1) a small incision was made proximal to the suture and neovane was introduced through a cannula into the central retinal vein where it solidified, or (2) the central retinal vein was cut after ligation.
- Transient ligation or clamping of the optic nerve: Transient ligation/clamping (60–120 minutes) of the optic nerve using a lateral orbital approach has been used also to produce CRVO in rats and in pigs. This method, however, included the ciliary vessels and the central retinal artery and, thus, not reproducing an isolated CRVO.

**Clinical and Histopathologic Features of RVO Models**

Clinical and/or histopathologic features observed in animal models of BRVO and CRVO were described in 89 and 38 articles, respectively, identified in our search. Macular edema has been addressed in only 4 of 21 studies on nonhuman primate models of BRVO, all laser-induced, and in only 2 of 21 studies on nonhuman primate models of CRVO.
Table 5. Advantages and Disadvantages of the Different Methods Used to Induce RVO

<table>
<thead>
<tr>
<th>Method</th>
<th>Advantages</th>
<th>Disadvantages</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photodynamic therapy ± photosensitive dye</td>
<td>• Produces BRVO</td>
<td>• Potential phototoxicity with photosensitizers and sun/light exposure</td>
<td>93–95, 112, 119, 148, 149</td>
</tr>
<tr>
<td>Diathermic cauterization</td>
<td>• Produces CRVO and BRVO</td>
<td>• Invasive</td>
<td>120–124, 150–153, 168–169, 170, 172, 173, 195</td>
</tr>
<tr>
<td>Permanent ligation of the central retinal vein</td>
<td>• Produces CRVO</td>
<td>• Invasive</td>
<td>174</td>
</tr>
<tr>
<td>Transient ligation/clamping of optic nerve</td>
<td>• Produces CRVO</td>
<td>• Invasive</td>
<td>76–79, 128</td>
</tr>
<tr>
<td>Intravitrebral thrombin injection</td>
<td>• Produces CRVO</td>
<td>• Successful in only 43% of cases</td>
<td>102</td>
</tr>
<tr>
<td>Intravitrebral ET-1 injection</td>
<td>• Produces BRVO</td>
<td>• Only 1 reported study</td>
<td>115</td>
</tr>
<tr>
<td>Intravitrebral NPe6 injection</td>
<td>• Produces BRVO</td>
<td>• Only 1 reported study</td>
<td>105</td>
</tr>
<tr>
<td>Intravitrebral PD0325901 injection</td>
<td>• Produces BRVO</td>
<td>• Only 1 reported study</td>
<td>114</td>
</tr>
</tbody>
</table>

BRVO, branch retinal vein occlusion; CRVO, central retinal vein occlusion; RVO, retinal vein occlusion; ET-1, endothelin-1; NPe6, mono-L-aspartyl chlorin e6.

Both diathermy-induced, 170,195 ischemia, defined by development of neovascular complications, extensive areas of capillary nonperfusion (capillary dropout), or both, or capillary nonperfusion associated with atrophy/cell loss of the inner retinal layers, has been reported in 28 of 89 studies in laser-induced BRVO models of rodents (n = 8), 80,83,85,89,90,92–96,97 pigs (n = 6) 130–134,154 and nonhuman primates (n = 13). 175,176,178–181,184,187–190,192,193,197 PD0325901-induced BRVO models of rabbits (n = 1) 114; and in 16 of 38 studies in laser-induced CRVO models in rodents (n = 4), 67–69,74 rabbits (n = 1), 101 and nonhuman primates (n = 9), 157–160,162–166 in permanent ligation of central retinal vein CRVO models in nonhuman primates (n = 1). 174 And in thrombin-induced CRVO models in rabbits (n = 1). 102 The features described in this section, unless otherwise specified, do not refer to the changes observed at the site of the occlusion and caused by the procedure used to create the RVO itself, but rather those result of the vein occlusion.

All models showed early features classically observed in human BRVO and CRVO, including cessation of blood flow and venous dilation, engorgement, and tortuosity distal to the
### Table 6. Parameters of Laser Photocoagulation Used in the Different Animal Models

<table>
<thead>
<tr>
<th>Animal</th>
<th>Type of Laser</th>
<th>Wavelength, nm</th>
<th>Adjuvant</th>
<th>Power</th>
<th>Duration, s</th>
<th>Size</th>
<th>No. of Shots</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mice</td>
<td>Krypton</td>
<td>530.9</td>
<td>IV Rose Bengal (40 mg/kg)</td>
<td>50 mW</td>
<td>3</td>
<td>50 μm</td>
<td>2–3</td>
<td>89</td>
</tr>
<tr>
<td>Yag</td>
<td>552</td>
<td></td>
<td>1 mL 1% fluorescein</td>
<td>200 mW</td>
<td>0.5</td>
<td>50 μm</td>
<td>7–12</td>
<td>90</td>
</tr>
<tr>
<td>N/A</td>
<td>552</td>
<td>0.15 mL Rose Bengal</td>
<td>160 mW</td>
<td>0.8–2.5</td>
<td>50 μm</td>
<td>2–5</td>
<td>91, 92</td>
<td></td>
</tr>
<tr>
<td>Rats</td>
<td>Argon</td>
<td>514</td>
<td>IV Rose Bengal (40 mg/kg)</td>
<td>80–150 mW</td>
<td>0.1–0.2</td>
<td>50–100 μm</td>
<td>6–20</td>
<td>68, 69, 73, 81, 83, 96, 217, 220</td>
</tr>
<tr>
<td>Argon</td>
<td>490</td>
<td></td>
<td>IV PAD-S31 (10 mg/kg)</td>
<td>3 mW</td>
<td>N/A</td>
<td>300 μm</td>
<td>N/A</td>
<td>84</td>
</tr>
<tr>
<td>Argon</td>
<td>N/A</td>
<td></td>
<td>IP 0.3 mL 10% sodium fluorescein</td>
<td>100–200 mW</td>
<td>0.2</td>
<td>50 μm</td>
<td>3–5</td>
<td>124</td>
</tr>
<tr>
<td>Argon</td>
<td>N/A</td>
<td></td>
<td>IV 0.2 mL 10% sodium fluorescein</td>
<td>50–100 mW</td>
<td>0.5–1</td>
<td>50 μm</td>
<td>1–12</td>
<td>71, 72, 86, 88</td>
</tr>
<tr>
<td>Diode</td>
<td>552</td>
<td></td>
<td>IV Rose Bengal (20 mg/kg)</td>
<td>100 mW</td>
<td>0.4</td>
<td>75 μm</td>
<td>N/A</td>
<td>70</td>
</tr>
<tr>
<td>Diode</td>
<td>552</td>
<td></td>
<td>180–240 mW</td>
<td>0.4</td>
<td>100 μm</td>
<td>5–7</td>
<td>80</td>
<td></td>
</tr>
<tr>
<td>Diode</td>
<td>675</td>
<td></td>
<td>IV PAD-S31 (10 mg/kg)</td>
<td>3 mW</td>
<td>N/A</td>
<td>300 μm</td>
<td>N/A</td>
<td>84</td>
</tr>
<tr>
<td>N/A</td>
<td>552</td>
<td></td>
<td>IV 2% Erythrosin B (20 mg/kg)</td>
<td>100 mW</td>
<td>0.2</td>
<td>100 μm</td>
<td>5–10</td>
<td>74</td>
</tr>
<tr>
<td>Rats</td>
<td>Argon</td>
<td>N/A</td>
<td>IV Rose Bengal (40 mg/kg)</td>
<td>90–120 mW50–300 mW</td>
<td>0.2–0.5</td>
<td>50–125 μm</td>
<td>5–20</td>
<td>101, 104, 107</td>
</tr>
<tr>
<td>Argon</td>
<td>552</td>
<td></td>
<td>IV Rose Bengal (40 mg/kg)</td>
<td>150–300 mW</td>
<td>0.5</td>
<td>125 μm</td>
<td>10–30</td>
<td>109, 110</td>
</tr>
<tr>
<td>Argon</td>
<td>N/A</td>
<td></td>
<td>IV Rose Bengal (50 mg/kg)</td>
<td>0.14 mW</td>
<td>0.3</td>
<td>100 μm</td>
<td>5–20</td>
<td>106</td>
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<tr>
<td>Diode</td>
<td>670</td>
<td></td>
<td>IV CASPc (5 mg/kg)</td>
<td>2 mW</td>
<td>N/A</td>
<td>0.5 mm²</td>
<td></td>
<td>105</td>
</tr>
<tr>
<td>Rabbits</td>
<td>Argon</td>
<td>N/A</td>
<td>IV Rose Bengal (40 mg/kg)</td>
<td>300–500 mV</td>
<td>0.2</td>
<td>200 μm</td>
<td>20–25</td>
<td>116–118</td>
</tr>
<tr>
<td>Dogs</td>
<td>Argon</td>
<td>514</td>
<td>IV Rose Bengal (50 mg/kg)</td>
<td>100–150 mW</td>
<td>0.2</td>
<td>100 μm</td>
<td>15–20</td>
<td>126</td>
</tr>
<tr>
<td>Dogs</td>
<td>Green</td>
<td>514</td>
<td>IV Rose Bengal (40 mg/kg)</td>
<td>100–150 mW</td>
<td>0.2</td>
<td>100 μm</td>
<td>15–20</td>
<td>127</td>
</tr>
<tr>
<td>Pigs</td>
<td>Argon</td>
<td>514</td>
<td>IV Rose Bengal (10–15 mg/kg)</td>
<td>100–180 mW</td>
<td>1</td>
<td>100–125 μm</td>
<td>4–6</td>
<td>132, 134, 137, 139, 141, 151, 155</td>
</tr>
<tr>
<td>Argon</td>
<td>514</td>
<td></td>
<td>IV Rose Bengal (10–15 mg/kg)</td>
<td>250 mW</td>
<td>0.2–0.5</td>
<td>500 μm</td>
<td>N/A</td>
<td>136, 140</td>
</tr>
<tr>
<td>Argon</td>
<td>552</td>
<td></td>
<td>IV Rose Bengal (10 mg/kg)</td>
<td>400 mW</td>
<td>0.5</td>
<td>N/A</td>
<td>20–40</td>
<td>144, 145, 156</td>
</tr>
<tr>
<td>Argon (endo-</td>
<td>552</td>
<td></td>
<td>IV Rose Bengal (10 mg/kg)</td>
<td>140 mW</td>
<td>N/A</td>
<td>N/A</td>
<td></td>
<td>146, 147</td>
</tr>
<tr>
<td>photocoagulation)</td>
<td></td>
<td></td>
<td>IV 1 mL 10% sodium fluorescein</td>
<td>100–20 mW</td>
<td>0.2</td>
<td>200 μm</td>
<td>N/A</td>
<td>142</td>
</tr>
<tr>
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<tr>
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<td>100 μm</td>
<td>5–7</td>
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<tr>
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<td>IV CASPc</td>
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<td>100 μm</td>
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<td>100 μm</td>
<td>5–7</td>
<td>166</td>
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CASPc, chloraluminium sulfonated phthalocyanine; IP, intraperitoneal; IV, intravenous; N/A, no data available.
occlusion site. Moreover, all models, except the ET-1-induced CRVO, showed retinal hemorrhages and various degrees of retinal edema, which were commonly observed within the first 48 hours of RVO induction.170,174,176,187,189,190,192,221 Retinal hemorrhages were reported in all eyes 14 days following induction.170,174,176,187,189,190,192,221 peaked at day 4.70,74,84,98 and resolved 7 to 28 days following occlusion.70,74,75,89,96,97,102,108,129,156,169,170,172,192,199,221 various degrees of exudative retinal detachment developed in many eyes of laser-induced and diathermy-induced CRVO.67,74,80,85,89,96,97,105,115,121,124,126,132,186 and laser-induced CRVO eyes.67,70,174 Bullous retinal detachment also was observed in many models that resolved spontaneously during follow-up.67,70,74,75,79,85 Changes in the thickness of the overall retina and individual retinal layers as a result of the edema (thickening) or ischemia (thinning) were evaluated mainly by histopathology70,74,76,89–92,94,95,114,121,129,131–133,151,154,169,174,179,180,189,190,192,199,221, in five studies, optical coherence tomography (OCT) was used also for this purpose.75,80,90,91,100–105 Both CRVO and BRVO models showed significant increase in the thickness of the inner retinal layers 1 to 4 days postinduction, followed by gradual reduction over time, with follow-up periods ranging between 7 and 28 days. In many models, retinal thickness was reduced during the follow-up to values below those detected at baseline (atrophic thinning); this was observed at 7 to 14 days from RVO induction.75,80,90,91,100

Branch Retinal Vein Occlusion. Macular Edema. Macular edema in the nonhuman primate models was observed as early as 1 to 6 hours following venous occlusion180,193 and became prominent at 7 to 9 days postocclusion.180,193 It was found in up to 100% of treated eyes in one of the four studies on nonhuman primate models that described macular edema in induced BRVO (see above).180,193 Both intraretinal cellular and extracellular edema were reported.180,189,195 The edema was mainly observed in the nerve fiber layer and outer plexiform layer.190,193 Adjacent to the extracellular edema often appeared shrunken or compressed.190 In addition, macular edema was often associated with photoreceptor cell loss, which persisted after resolution of macular edema.180,186,193 Spontaneous resolution of macular edema occurred in all occluded eyes between 14 days and 2 years after laser photocoagulation clinically.180,186,190,193 In one study, histopathologic examination of six eyes at 48 months showed cystic spaces in the outer plexiform layer in four of six eyes.180

Retinal Capillary Nonperfusion and Reperfusion. Various degrees of capillary nonperfusion in laser-induced, diathermy-induced, and PD325901-induced models of BRVO were reported.170,174,176,180,186,189,190,192,221 Areas of capillary nonperfusion were observed as early as 3 days following venous occlusion189,189 and found to progress with time.170,192 Extensive or severe areas of capillary nonperfusion were prominent 1 to 4 weeks following vein occlusion172,187,192,222 and were observed in up to 75% of eyes.193,153,221 The areas of capillary nonperfusion persisted during the follow-up, which ranged between 1 and 20 weeks, despite reperfusion.70,80,85,89,92,96,97,132,153,159,175,179,189,191–193,221,222. Reperfusion in these models was either by recanalization/reopening of the occluded vessels in some or all eyes,170,174,176,180,90,92,93,95,97,104,105,110,112,115,120,126,129,152,153,157,168,187,189,192,195 or development of collateral vessels.185,89,92,96,104,105,120,121,124,129,133,135,157,175,179,180,183,187,189,192,221,222. Recanalization was observed in 0% to 100% of eyes of BRVO models 1 to 14 days following induction.70,80,85,89,92,93,95,97,104,105,110,112,126,129,132,153,186,221. Collateral vessels were observed in up to 14 days following establishment of the RVO.79,129,179,180,192 (Tables 7, 8).

Neovascular Complications. Posterior segment neovascularization occurred in some laser-induced BRVO models in rodents,185,89,96 pigs,132,154,154,221,222 and nonhuman pri- mates,175,188,189,192 but not in the other BRVO models. Retinal and/or disc neovascularization was observed in 8.3% of eyes as early as 7 days postocclusion,89 and in 60% to 70% of eyes 14 days following laser induction in rodent models.89 In laser-induced pig models, retinal and/or disc neovascularization were described in approximately 50% to 93% of eyes 3 to 4 weeks following RVO induction152,153,221,222 and up to 100% of eyes at 6 weeks.134,193 In laser-induced nonhuman primate models, 9% of eyes developed retinal neovascularization at 4 weeks.192 Anterior segment neovascularization was observed in laser-induced nonhuman primate models when three major branches were targeted.176,178,181,184 In this model, up to 100% of eyes developed iris neovascularization within the first 6 days of occlusion176,178,181,184 and 17% to 20% developed neovascular glaucoma within 25 days of follow-up.176,178 There was no spontaneous regression during follow-up of 28 to 84 days.193,90

Vascular Endothelial and Pericyte Cell Loss. Damage and loss of the vascular endothelial cells and pericytes was detected by histopathologic examination in experimental animal models of BRVO.80,100,105,120,127,180,190,193 which resulted in high acellular vessels with glial invasion.170,189,193 observed as early as 1 to 48 hours postocclusion.170,190,193 Endothelial cell apoptosis was detected as early as 1 day postocclusion.190 Edema loss was observed 3 days following occlusion and significantly worsened at 7 days with 40% pericyte cell loss detected.90

Retinal Atrophy. Atrophy (thinning/loss) of the inner retinal layers5,70,84,89,91,92,94,95,121,124,179,189,190,192,195,222 and replacement with glia151,187 has been reported. The loss of the inner retinal layers was first observed 3 days postocclusion89 and was marked at 7 to 28 days of follow-up.70,84,89,91,92,94,95,121,124,179,189,190,192. Damage of the outer retinal layers and loss of the photoreceptors was observed distal to the site of the occlusion in some eyes with laser-induced BRVO and ischemia at 3 to 6 weeks postocclusion.132,153,222 Photoreceptor cell loss was observed in 67% of eyes at 3 months following the occlusion.180 Damage to the photoreceptors was reported in photodynamic-induced thrombosis in rats within 2 days of the occlusion, which was most likely related to the photodynamic therapy itself rather than the result of ischemia.112 Unspecified RPE changes were reported 4 to 3 months following occlusion in laser-induced BRVO nonhuman primate models.132,180,192,195

Functional Changes. When conducted, ERG studies showed reduction of the “a” and “b” wave amplitudes of both scotopic and photopic ERG at 1, 2, 3, 4, 6, and 7 days following laser-induced BRVO in rat models.80,190. In multifocal ERG, a significant decrease in the P1 and N1 amplitudes and prolonged implicit times in the affected retina were observed 4 weeks following thrombus formation in diathermy-induced BRVO in pig models.151,152

Other Features. Other features also were observed in some eyes with experimental animal BRVO, such as cotton wool spots, detected at 3 days to 6 weeks in laser-induced nonhuman primate models.180,192 venous sheathing between 7 days and 3 months,125,127,129,152,192 microaneurysms 1 to 8 months,190,125 and reduction of preretinal oxygen saturation measured at different time points between 60 minutes and 3 weeks following occlusion,150,121,124,131,150,222.

Central Retinal Vein Occlusion. Macular Edema. Macular edema was observed as early as 48 hours following venous thrombosis in 14% to 66% of CRVO nonhuman primate models induced by diathermy.170,193 This had resolved spontaneously in all eyes 14 days following induction.70,195. Capillary Nonperfusion and Reperfusion. Various degrees of capillary nonperfusion were reported in laser-induced,
<table>
<thead>
<tr>
<th>Animal Models of RVO</th>
<th>Success, %</th>
<th>Retinal Hemorrhage</th>
<th>Retinal Edema</th>
<th>MO</th>
<th>CNP</th>
<th>Recanalization</th>
<th>Collaterals</th>
<th>Posterior Segment NV</th>
<th>Anterior Segment NV</th>
<th>Loss of EC/Pericytes</th>
<th>Loss of IRL</th>
<th>Loss of ORL</th>
<th>RPE Changes</th>
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CNP, capillary nonperfusion; EC, endothelial cells; IRL, inner retinal layers; MO, macular edema; N, not developed; N/A, not assessed/no data available; NV, neovascularization; ORL, outer retinal layers; Y, developed.
<table>
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</table>
permanent ligation of the central retinal vein, and thrombin-induced CRVO models. In one of these studies, it was found to become extensive 2 to 4 weeks following the induction of CRVO and progressed to involve up to 75% of the retinal area 7 weeks postinduction of RVO by laser photocoagulation in 67% of eyes. In thrombin-induced CRVO in rabbits, extensive areas of retinal capillary nonperfusion were observed at 3 months following the occlusion. Recanalization or reopening of the occluded vessels was reported in many studies of laser-induced CRVO, 108, 111, 157–159 This was observed 1 to 21 days postocclusion 70, 74, 108, 111, 159 in 6% to 80% of eyes. 108, 111, 157, 158 Collateral vessels were also reported in some eyes at 2 weeks to 2 months of follow-up following laser-induced and thrombin-induced CRVO. 102, 108, 157

**Neovascular Complications.** Neovascular complications were observed in laser-induced and thrombin-induced CRVO. 68, 69, 74, 102, 157–160, 162–166 Preretinal neovascularization was observed 1 to 3 weeks following laser photocoagulation in 17% to 90% of rats, with no spontaneous regression described. 74 In nonprimate models, however, posterior segment neovascularization was described in only one study, in which disc neovascularization was detected in 17% of eyes day 15 to 26 days postocclusion that resolved spontaneously at day 87, but not in other studies with follow-up periods ranging between 1 and 24 weeks. 111, 158, 160–167 Thrombin-induced CRVO in rabbits showed retinal neovascularization in 60% of eyes at 3 months following injection. 102 Spontaneous regression of neovascularization in this model was not reported. Iris neovascularization was observed only in laser-induced nonprimate models. 157–160, 162–166 This was detected 4 to 22 days postocclusion 159, 160, 162–166 in up to 100% of eyes, 157, 165, 166 with some having spontaneous regression 13 to 60 days following laser photocoagulation. 157 Fluorescein leakage from iris new vessels was observed at 5 days of follow-up in 50% of eyes. 157 Neovascular glaucoma developed in 18% to 53% of eyes in the laser-induced nonprimate model 12 to 21 days following occlusion. 158

**Vascular Endothelial and Pericyte Cell Loss.** Vascular endothelial and pericyte cell loss has not been described in experimental models of CRVO. Retinal Atrophy. Atrophy thinning of the remaining retina was found 7 to 21 days in rodents and rabbit models following laser photocoagulation 70, 74, 75, 101, 3 to 10 days in diathermy-induced nonprimate models, which was in this model associated with gliosis 169, 3 to 7 days in nonprimate models of permanent ligation of the central retinal vein; and 4 days in temporary (60 minutes) ligation of the optic nerve. 76 These changes were not reversible in any of the models during the follow-up, which ranged from 1 to 6 weeks. 70, 74–76, 169, 177 The ganglion cell loss in overall retina (central, midperipheral, and peripheral retinal regions) was reported to be approximately 11% at 7 days, 74, 30% to 51% at 14 days 70, 74 and 40% at 21 days following laser-induced RVO in rodents. 74 Atrophy of the outer nuclear layers distal to the site of laser photocoagulation was reported as early as 4 days following vein occlusion using laser photocoagulation in rodent models. 76, 101, 103, 157, 170 (Tables 7, 8). Functional Changes. Loss of retinal function in these models was confirmed with ERG studies that showed significant reduction of amplitudes in both scotopic and photopic ERG in laser-induced CRVO in rodents and temporary ligation of optic nerve in rodents. Other Features. Disc hyperemia was observed within 48 hours in up to 100% of diathermy-induced CRVO in nonhuman primate models, which was secondary to the procedure rather than to the CRVO. 168, 195

**Strengths and Limitations of Available Animal Models.** Although none of the animal RVO models described above develop all features occurring in human RVO, almost all models demonstrate the early characteristics of this disease, including retinal hemorrhages and edema, which may make them adequate models to study the acute phase of both BRVO and CRVO. Only a few models, however, developed macular edema (i.e., laser photocoagulation in BRVO nonhuman primate models and diathermy in CRVO nonhuman primate models) (Tables 7, 8), 170, 180, 186, 190, 193, 195 which makes the study of this particular feature difficult.

Most animal models of RVO demonstrated spontaneous reperfusion and/or vascular remodeling, which seemed to occur more rapidly and effectively than in humans with RVO. As a result, persistent ischemic features failed to develop in most models, and iris neovascularization was not observed, except in laser-induced nonhuman primate models, 157–160, 162–166, 176, 178, 181, 183 making the study of the ischemic form of RVO more challenging. This might be attributed, even if partly, to the fact that the animals used for these studies were young and healthy, whereas patients with BRVO and CRVO are often older and many have underlying systemic risk factors, such as hypertension, dyslipidemia, dysfunctional thrombotic responses, or impaired glucose tolerance/diabetes, among others. The ischemic form of RVO, however, is the one that requires further research more urgently, given its very limited treatment options and often poorer outcomes.

The laser-induced models of BRVO in rodents, pigs, and nonhuman primates and of CRVO in rodents and nonhuman primates were found to be the most successful at achieving nonperfusion and posterior segment neovascularization (see Tables 7, 8). The lack of ischemic features (i.e., extensive areas of retinal nonperfusion and/or neovascularization) being observed in other models may be attributed to the inadequate follow-up time in some of the studies or may be due to other factors such as the nature of the occlusion induced by the various techniques, including duration of the occlusion, and the timing and characteristics of the reperfusion that followed. There are still limitations of the models available that reproduce best retinal ischemia and neovascularization. For example, the laser-induced rodent model of BRVO and CRVO may pose difficulties due to the small size of the eye (Fig.), the large crystalline lens, and the thin and delicate sclera, which may make the undertaking of functional and imaging studies as well as therapeutic interventions challenging. The lack of a macula in many nonprimate models makes it impossible to study macular edema and, although as stated above the occlusion can be produced with high success (92%–100%, see Table 8), neovascularization occurs variably (60%–70%) and 17%–90% in models of BRVO and CRVO, respectively. The laser-induced pig model of BRVO appears to be ideal due to anatomic similarities (see Table 4), including the presence of an area centralis, and the high success at achieving vein occlusion (93%–100%) and development of neovascularization (100%) in a relatively short period (6 weeks). Furthermore, the larger size of the eye in this model facilitates functional, structural, and interventional studies. Pigs are larger animals, posing other difficulties (see Tables 3, 5). Nonhuman primate models of laser-induced ischemic CRVO and BRVO best mimic the clinical and histopathologic features observed in humans; however, the use of this species carries major ethical considerations and other inconveniences, such as high cost (see Tables 3, 5) and are not available to most researchers.
CONCLUSIONS

Several experimental animal models of RVO are available to study the pathogenesis and to test new diagnostic/prognostic/therapeutic interventions for this disease. Selecting the most appropriate ones, based on the information provided in this review, will allow researchers to better adhere to two of the three “Rs” of “reduction” and “refinement,” as “replacement” is not an option when understanding the complex events that take place in RVO. It will also help researchers in the development of new treatment modalities by allowing them to select those that mimic more closely the human disease, that develop its features more consistently and in shorter periods of time. This will subsequently reduce testing times and costs and will improve the planning and design of future, more successful studies as well as the potential for translation to clinical practice.

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References

Animal Models of RVO


