PULSED ELECTRON AVALANCHE KNIFE IN VITREORETINAL SURGERY

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Purpose: To evaluate the advantages, disadvantages, safety, and surgical applicability of the pulsed electron avalanche knife (PEAK-fc), a new electrosurgical knife for "cold" and tractionless cutting, in vitreoretinal surgery. PEAK-fc is equipped with an integrated fiber-optic that makes bimanual procedures in intraocular surgery possible.

Methods: A prospective consecutive trial of 18 eyes in 18 patients who underwent vitreoretinal surgery for proliferative diabetic retinopathy, proliferative vitreoretinopathy, subretinal macular hemorrhage, or macular pucker was performed. The following specific maneuvers were performed with PEAK-fc: transection of epiretinal membranes, retinotomies, retinal vessel coagulation, and posterior membranectomy.

Results: Detached and attached retina could be dissected successfully in eight cases. Intraoperatively, incision edges were sharply demarcated, showing no visible collateral damage. Deeper layers than the neurosensory retina were not affected. With the bimanual approach, epiretinal avascular and vascular membranes could be removed in 10 cases. Hemorrhages occurring during transection of vascularized membranes could be stopped immediately using the coagulation mode of PEAK-fc. Posterior capsule fibrosis was successfully excised in one patient. No complications were observed.

Conclusion: PEAK-fc offers precise and tractionless tissue cutting during ocular surgery. Using different waveform parameters, the same device performs cold cutting and/or "hot" coagulation, thus improving the precision, safety, and ergonomics of vitreoretinal surgery.

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The pulsed electron avalanche knife (PEAK-fc; Carl Zeiss Meditec, Jena, Germany), an electrosurgical device, has recently been introduced as an improved precise cutting instrument for "cold" and traction-free dissection of tissue in liquid medium.[1–4] A thin layer of pulsed plasma is formed around an elongated microelectrode in physiologic medium or tissue. PEAK-fc operates with voltages between 300 V and 600 V and pulses of $\approx$100 microseconds in duration, each of them consisting of a burst of several tens of "minipulses" (Fig. 1). Pulsed plasma-mediated discharges rapidly vaporize and ionize liquid and tissue in close proximity to the probe. Duration of the pulsed waveform is chosen to minimize both cavitation-related and heat diffusion–related damage.[1–4] A protruding wire of 0.3 mm or 0.6 mm in length and 50 μm in diameter offers convenient cutting and coagulation under visual control.

Applicability of the intraocular laser systems based on CO_2 and Ho:YAG lasers has been limited due to strong variability in the ablation depth and low reproducibility[5] as well as to deep collateral damage produced

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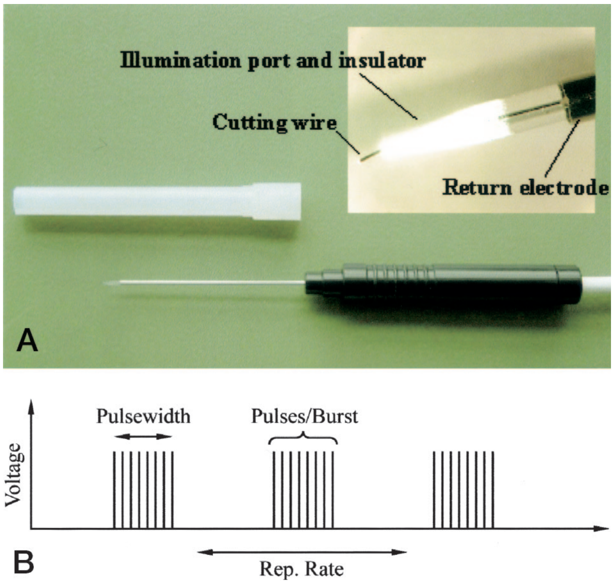

Fig. 1. Diagram of pulsed electron avalanche knife (PEAK-fc) probe and pulse mode. The cutting part of the PEAK-fc probe is a protruding tungsten wire with a diameter of 50 μm (**A**). The wire used in this study extends from the glass insulator 0.6 mm in length. The glass insulator also serves as a light pipe providing integrated intraocular illumination. This facilitates bimanual procedures in vitreoretinal surgery. In addition, a coagulation mode has been integrated. The PEAK-fc operates at voltages from 300 V to 600 V and ≈100 μs, consisting of a burst of several tens of minipulses (**B**). Rep., repetition.

in the surrounding tissue.[6,7] Although Er:YAG[8–12] and ArF excimer lasers[13,14] are capable of precise dissection of ocular tissue, they have failed to achieve widespread acceptance in clinical practice due to their prohibitively high cost, large size, and relatively slow pace. In contrast, the electrosurgical instrument PEAK-fc allows for reproducible and reliable retinal dissection with induction of only minimal collateral damage at the edges of the cut.[15] In vitro human and in vivo animal studies have demonstrated that the penetration depth and the extent of collateral damage with PEAK-fc mainly depend on voltage, probe length, and its distance from the retina.[15]

The purpose of the current study was to further evaluate the safety and effectiveness of this new cutting device in clinical settings. The efficacy of PEAK-fc in various surgical maneuvers for patients undergoing vitreoretinal surgery for proliferative diabetic retinopathy, proliferative vitreoretinopathy, and subretinal hemorrhages in age-related macular degeneration was tested.

Materials and Methods

PEAK—2nd Version (PEAK-fc; Carl Zeiss Meditec, Jena, Germany)

In contrast to the first version of PEAK, which operated with submicrosecond pulses of 3 kV to 6 kV,[1–3] advanced PEAK-fc operates at much lower voltages (300–600 V) and much longer pulses (≈100 microseconds) consisting of a burst of several tens of minipulses (Fig. 1B). The cutting part of the PEAK-fc probe is a protruding tungsten wire with a diameter of 50 μm (Fig. 1A). The wire used in this study extends from the glass insulator 0.6 mm in length. The glass insulator itself has an outer diameter of 0.6 mm and is enclosed in a 20-gauge stainless steel return electrode. The glass insulator in PEAK-fc also serves as a light pipe providing integrated intraocular illumination (Fig. 1). This facilitates bimanual procedures in vitreoretinal surgery with a lower risk of unintended tissue damage due to improved ergonomics. In addition, a coagulation mode has been integrated.

In the present study, PEAK-fc parameters varied as follows: pulse repetition rate, 30–100 Hz; number of minipulses per pulse, 25–60; and pulse duration, 100 microseconds. Voltage ranged from 350 V to 600 V. The parameters selected for the particular maneuvers are listed in Table 1.

Patients and Surgical Approach

Eighteen patients were consecutively enrolled in this study. Patients were chosen with regard to the preoperative situation potentially suitable for the surgical maneuvers that could be performed with PEAK-fc. Surgery was performed after obtaining written informed consent concerning the intraoperative use of PEAK-fc, and follow-up visits occurred at 1 week and 4 weeks and at 3-month intervals thereafter. An external review board monitored the study. Exclusion criteria were history of glaucoma, visual acuity of less than 20/800 in the fellow eye, or a medical history requiring systemic anticoagulation.

One eye of each patient (Table 2) was included in the study. There were 10 men and 8 women (mean age, 64 years; range, 53–79 years). Preoperative diagnoses included tractional retinal detachment involving the fovea in eyes with diabetic retinopathy (6 eyes), proliferative vitreoretinopathy (5 eyes), age-related macular degeneration with subretinal hemorrhage (5 eyes), tractive epiretinal membrane (macular pucker) with a history of central retinal vein occlusion (1 eye), and posterior capsule fibrosis with prolonged proliferative diabetic retinopathy (1 eye). All patients underwent complete ophthalmologic examinations including visual acuity testing, slit-lamp examination, intraocular pressure determination, and fundus biomicroscopy using a 78-diopter lens (Volk, Mentor, OH).

Surgery consisted of standard three port pars plana vitrectomy using a commonly available vitrectomy machine (Megatron, Geuder, Germany). The study

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Table 1. Pulsed Electron Avalanche Knife Parameters for Each Performed Maneuver

Maneuver	Probe Length (μm)	Energy Level (V)	Repetition Rate (Hz)	Minipulses per Pulse	Pulse Duration (μs)
Incision/transection of PVR membrane (avascular)	600	350–400	30	25	100
Incision/transection of PVR membrane (vascular)	600	450	40	30	100
Drainage retinotomy (retina attached)	600	350	30	30	100
Drainage retinotomy (retina detached)	600	350–450	40	30	100
Relaxing retinotomy/retinectomy	600	350–400	40	30	100
Dissection of retinal vessels (after coagulation)	600	450	35	35	100
Transection of retrolental fibrovascular membrane	600	600	100	60	100
Coagulation of retinal vessel	600	coagulation mode, 5			

PVR, proliferative vitreoretinopathy.

design provided the optional use of PEAK-fc within a surgical procedure for one or more maneuvers at the discretion of the surgeon. The following specific maneuvers were tested during surgery (Table 1): drainage retinotomy for patients with subretinal hemorrhages; relaxing retinotomy for patients with prolonged retinal detachment; transection and incision of epiretinal membranes in proliferative diabetic retinopathy, proliferative vitreoretinopathy, or macular pucker; surgical posterior membranectomy with posterior capsule fibrosis in prolonged proliferative diabetic retinopathy; and retinal vessel coagulation to stop intraoperative bleeding from vascularized epiretinal membranes in proliferative diabetic retinopathy. All maneuvers were recorded on videotape, permitting documentation of the efficacy and possible complications.

Results

A total of 18 consecutive patients were treated with PEAK-fc. In each maneuver, PEAK-fc parameters were initially set at the values determined by animal and in vitro studies as safe and efficient for dissection of neurosensory retinal layers without damaging the underlying retinal pigment epithelium[15]: voltage, 350 V; pulse repetition rate, 30 Hz; pulse duration, 100 microseconds; and 30 minipulses per pulse. Parameters were increased until the desired tissue effect was observed. Typical effective settings for each maneuver performed are presented in Table 1.

Transection and incision of epiretinal membranes, both vascular (4 cases) and avascular (6 cases), were rapidly and consistently accomplished without complications in 10 patients (Fig. 2; Table 2). One to three membranes were peeled in each of the 10 patients who had traction retinal detachment with proliferative diabetic retinopathy, proliferative vitreoretinopathy, or macular pucker (Table 2). A bimanual approach (fixating the proliferative vitreoretinopathy membrane with an intraocular forceps or vitrector and simultaneously illuminating the vitreous and cutting with PEAK-fc) obviously facilitated precise cutting with minimal or no traction and avoided potential complications of inadvertent retinal tears, bleeding, or collateral injury (Fig. 2). Except for strong adherent membranes and intraretinal proliferative vitreoretinopathy, membranes could be removed in all cases.

Removal of vascular membranes required higher energy levels (up to 450 V) for successful vessel dissection. Intraoperative hemorrhages from perfused nonfibrotic vessels occurred in two maneuvers and were easily stopped using the coagulation mode of PEAK-fc (level 5).

Drainage and relaxing retinotomies on attached and detached retina were easily performed without complications (Figs. 3 and 4). PEAK-fc cuts showed sharp edges with hardly visible whitening, indicating little collateral damage. Minor self-limited bleeding was observed at the margin of one retinotomy. Drainage retinotomy was performed on five patients who had submacular bleeding associated with age-related macular degeneration (Table 2). Although extensive bleeding in 3 of these patients required 180° retinotomy after induction of an iatrogenic retinal detachment (Fig. 3), the other 2 retinotomies were performed extrafoveolarly on attached retina (Fig. 4). In the latter cases, PEAK-fc parameters previously determined as safe for dissection of the neurosensory retina[15] were used, and no damage of the retinal pigment epithelium

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Table 2. Clinical Characteristics of Patients

Case No.	Sex/ Age (y)	Eye	Diagnosis	VA, Preop	Peak Procedure	Tamponade	VA, 4 wk	VA, 3 mo	Postoperative Finding(s)
1	M/57	L	Traction detachment with PDR, history of CRVO	20/200	Incision/transection of PVR membrane (avascular)	C_2F_6	HM	HM	7 wk postop, vitreous hemorrhage treated with vitrectomy
2	M/68	L	Traction detachment with PDR	20/200	Incision/transection of PVR membrane (avascular)	C_2F_6	20/200	20/200	Retina reattached
3	M/45	L	Epiretinal membrane with history of CRVO	HM	Incision/transection of epiretinal membrane (avascular)	Silicon-oil	LP	LP	Recurrent vitreous hemorrhages and optic atrophy
4	M/57	L	Traction detachment with PDR	CF	Incision/transection of PVR membrane (vascular)	Silicon-oil	20/200	20/400	Retina reattached
5	F/79	L	Subretinal hemorrhage with AMD	HM	180° Retinotomy after iatrogenic retinal detachment	C_2F_6	20/400	20/300	Postop retinal detachment, revitrectomy + C_2F_6
6	F/72	R	Subretinal hemorrhage with AMD	HM	Extrafoveolar retinotomy	C_2F_6	20/800	20/700	Subretinal hemorrhage and choroidal neovascularization removed
7	M/73	L	Retinal detachment with PDR	20/400	Incision/transection of PVR membrane (vascular)	C_2F_6	20/200	20/100	Retina reattached, subretinal hemorrhage removed
8	F/71	R	Subretinal hemorrhage with AMD	20/200	180° Retinotomy after iatrogenic retinal detachment	C_2F_6	20/200	20/125	Retina reattached, subretinal hemorrhage removed
9	F/65	L	Traction detachment with PDR, vitreous hemorrhage	CF	Incision/transection of PVR membrane (vascular)	C_2F_6	20/400	20/200	Retina reattached
10	M/54	R	Traction detachment with PDR	20/200	Incision/transection of PVR membrane (vascular)	C_2F_6	20/200	20/125	Retina reattached
11	F/67	L	Retinal detachment with PVR after PPV	HM	Incision/transection of PVR membrane (avascular)	C_2F_6	20/400	20/200	Retina reattached
12	M/53	L	Retrolental fibrosis with prolonged PDR	HM	Surgical posterior membranectomy	Silicon-oil	HM	HM	Posterior capsule removed, irreversible PVR retinal detachment
13	M/70	R	Retinal detachment with PVR after PPV	HM	Incision/transection of PVR membrane (avascular)	C_2F_6	20/400	20/200	Retina reattached

(*Table continues*)

VA, visual acuity; PDR, proliferative diabetic retinopathy; CRVO, central retinal vein occlusion; PVR, proliferative vitreoretinopathy; HM, hand movement; LP, light perception; CF, counting fingers; AMD, age-related macular degeneration; PPV, pars plana vitrectomy.

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Table 2. Continued

Case No.	Sex/Age (y)	Eye	Diagnosis	VA, Preop	Peak Procedure	Tamponade	VA, 4 wk	VA, 3 mo	Postoperative Finding(s)
14	F/62	R	Retinal detachment with PVR after PPV + silicon-oil	HM	240° Relaxing retinotomy	C_2F_6	CF	20 /700	Retina reattached
15	M/55	L	Retinal detachment with PVR after buckling surgery	CF	Relaxing retinotomy, incision of PVR membrane (avascular)	Silicon-oil	20/400	20 /400	Retina reattached
16	F/77	R	Subretinal hemorrhage with AMD	20/400	Extrafoveolar retinotomy	C_2F_6	20/200	20 /200	Subretinal hemorrhage and choroidal neovascularization removed
17	M/56	R	Peripheral retinal detachment after PPV + silicon-oil	20/400	180° Relaxing retinotomy	Silicon-oil	20/400	20 /200	Retina reattached
18	F/75	R	Subretinal hemorrhage with AMD	HM	180° Retinotomy after iatrogenic retinal detachment	C_2F_6	20/800	20 /400	Subretinal hemorrhage and choroidal neovascularization removed

or choroid occurred. Subretinal bleeding and choroidal neovascularizations could be successfully removed. For retinotomies on attached retina, the PEAK-fc probe was slowly moved along the surface of the retina with a velocity of ≈1 mm/s. Retinotomies on detached retina allowed cutting laterally by deeper tracking of the PEAK-fc probe, while velocity reached up to ≈2 mm/s.

Relaxing retinotomy was performed on three patients who had prolonged retinal detachment with tense and contracted retina (Table 2). In comparison to dissection of attached retina, we used slightly increased PEAK-fc parameters (Table 1). Before dissection, retinal vessels were coagulated using the PEAK-fc coagulation mode (level 5) to avoid intraoperative bleeding (Fig. 5). These coagulated vessels required increased PEAK-fc parameters for successful dissection (Table 1).

For one patient who had massive capsule fibrosis after vitrectomy and silicone oil tamponade for treatment of proliferative retinopathy, we decided to perform posterior membranectomy using PEAK-fc for transection of the thickened and partially vascularized membrane (Table 2). Although maximal power of PEAK-fc was used (voltage, 600 V; pulse repetition rate, 100 Hz; pulse duration, 100 microseconds; and 60 minipulses per pulse), ablation of the posterior capsule membrane was difficult. However, it finally could be removed, allowing inspection of the posterior segment.

Complications included minor bleeding during one retinotomy, which stopped spontaneously, and bleeding from vascularized epiretinal membranes in proliferative diabetic retinopathy. Intraoperative bleeding from these vessels was successfully stopped using the coagulation mode (level 5) of PEAK-fc. Formation of gas bubbles similar to those seen during conventional diathermy has been observed. However, for the PEAK-fc parameters used, the amount of bubbles could be reduced to a minimum, and controlled cuts could be performed despite the generation of gas bubbles in all surgical procedures.

Discussion

Along with improved understanding of vitreoretinal diseases, ongoing development of microsurgical techniques in vitreoretinal surgery has occurred. Special miniaturized instruments have been developed to perform tissue transection, removal, and coagulation within the vitreous cavity. Although blades, scissors, forceps, cautery systems, and other devices have been

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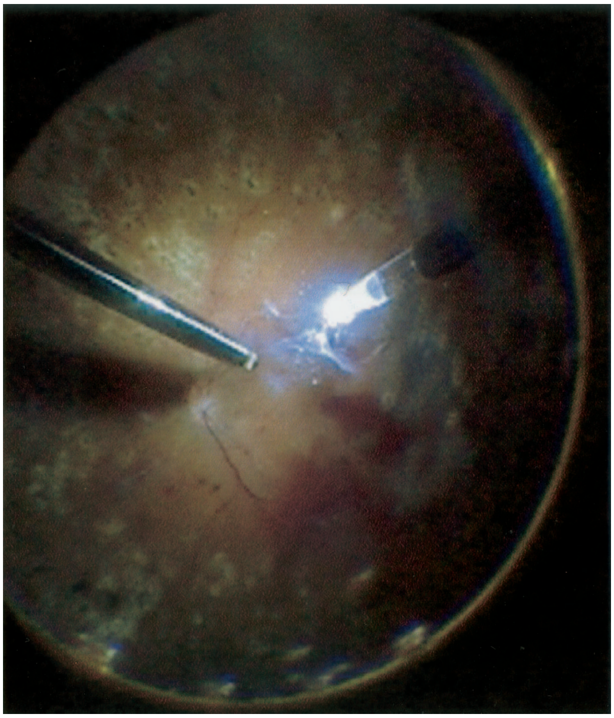

Fig. 2. Transection of an epiretinal proliferative vitreoretinal membrane. Patient 2 presented with traction detachment with proliferative diabetic retinopathy. With the bimanual approach, the proliferative vitreoretinopathy membranes can be successfully removed by fixating them with the vitrector, simultaneously illuminating the vitreous and cutting with the pulsed electron avalanche knife (PEAK-fc). Precise cutting with minimal or no traction avoids potential complications. PEAK-fc parameters: voltage, 350 V; pulse repetition rate, 30 Hz; pulse duration, 100 microseconds; and 25 minipulses per pulse.

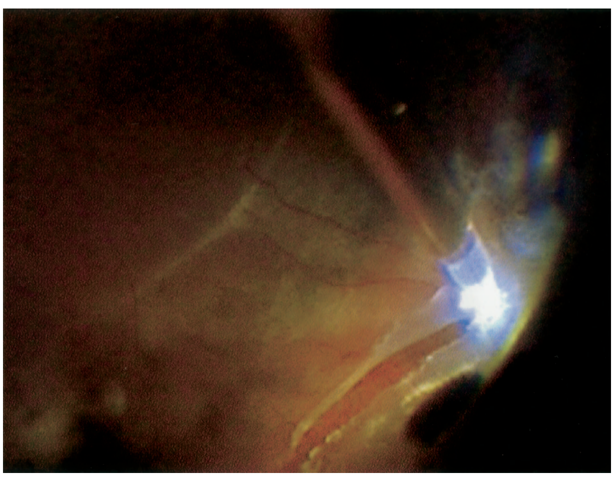

Fig. 3. Drainage retinotomy on detached retina. Patient 5 had extensive subretinal bleeding with age-related macular degeneration. After iatrogenic retinal detachment, 180° retinotomy was performed to remove the macular bleeding. A pulsed electron avalanche knife (PEAK-fc) cut shows sharp edges and little collateral damage. PEAK-fc parameters: voltage, 380 V; pulse repetition rate, 40 Hz; pulse duration, 100 microseconds; and 30 minipulses per pulse.

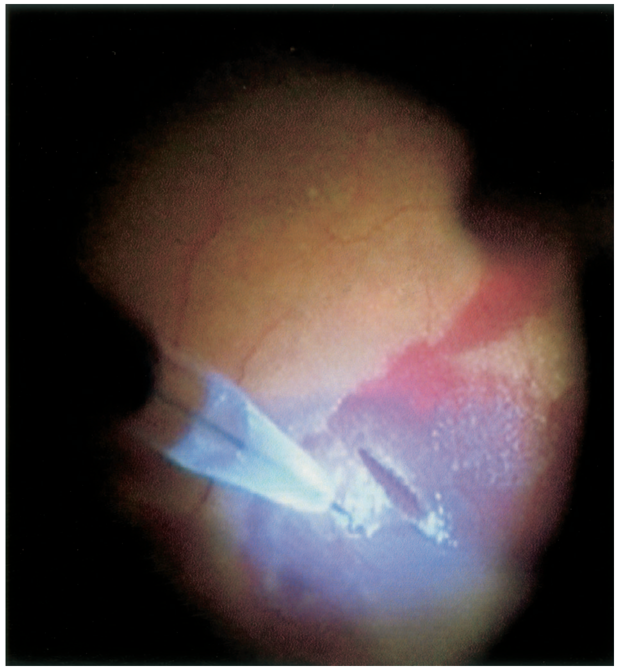

Fig. 4. Drainage retinotomy on attached retina. Patient 6 had minor subretinal bleeding with age-related macular degeneration. Extrafoveolar retinotomy on attached retina was performed, and subretinal bleeding and choroidal neovascularizations were removed successfully. Pulsed electron avalanche knife parameters (determined for safe dissection of the neurosensory retina[15]): voltage, 350 V; pulse repetition rate, 30 Hz; pulse duration, 100 microseconds; and 30 minipulses per pulse.

continually refined, difficulties and limitations are still encountered, particularly as increasingly finer surgical maneuvers are attempted. We report our initial clinical experience with the new cold cutting device PEAK-fc for maneuvers in vitreoretinal surgery.

Removal of contractile fibrocellular and fibrovascular epiretinal membranes (e.g., in proliferative vitreoretinopathy and proliferative diabetic retinopathy) requires surgical cutting in the most precise way and with the least amount of traction. When removing epiretinal membranes, especially the less experienced surgeon might cause iatrogenic breaks or retinal injury using standard forceps or scissors.[16] The delicacy of the retina, the sharpness of the instruments, and the challenges of visualizing the posterior pole of the eye all contribute to potentially harmful unintended results. Although current procedures for the removal of proliferative vitreoretinopathy membranes usually exert a certain degree of traction on the tissue that can potentially damage retinal structures and cause iatrogenic tears or hemorrhages, PEAK-fc dissects tissue with minimal traction, thus preventing unintended tears and hemorrhages. In addition, the integrated light source of PEAK-fc facilitates intraocular procedures and makes vitreoretinal surgery safer. The PEAK-fc

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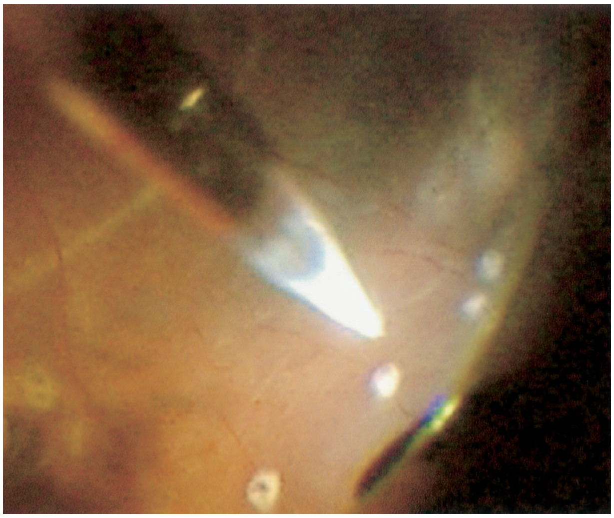

Fig. 5. Vessel coagulation before retinotomy. Patient 14 presented with retinal detachment with proliferative vitreoretinopathy after pars plana vitrectomy with silicone oil tamponade. Coagulation of retinal vessels prevented hemorrhage during subsequent 240° retinotomy. Pulsed electron avalanche knife parameter: coagulation mode of level 5.

probe allows a bimanual approach for the surgeon by using the free hand to prepare the region of interest with maximum safety, simultaneously facilitating illumination and dissection of ocular tissue with the other hand.

In a safe and quick way, we demonstrated that PEAK-fc allows the surgeon to perform large retinotomies that are required for the removal of extensive subretinal hemorrhages or for macular translocation. Retinal cuts with PEAK-fc showed almost no thermal damage in the cutting zone, thus confirming observations made in preclinical postmortem and animal studies.[15] One further advantage of PEAK-fc is the possibility of power adjustment for different tissue structures, which allows cuts through soft tissue without affecting harder tissues such as vascular walls. Thus, when working adjacent to vessels, potential damage to these vessels can be minimized.[15] However, even in the case of intraoperative bleeding, it can be immediately stopped using the coagulation mode of PEAK-fc without having to remove the instrument, as required during conventional surgery. Maximal power of PEAK-fc dissection of a thick fibrotic posterior capsule membrane turned out to be relatively difficult. Increasing the absolute voltage power available might be an option to solve similar problems in future applications of PEAK-fc.

One side effect of PEAK-fc application is the formation of gas bubbles potentially impairing the surgeon's view on the retina or other operating site. The amount of gas bubbles generated by PEAK-fc can be compared with the gas development in conventional intraocular diathermy. However, in the present study, the development of gas did not reduce visibility to a degree that would have made surgery unsafe in any of the performed procedures.

In summary, PEAK-fc was successfully used for a variety of surgical maneuvers commonly encountered in patients undergoing vitreoretinal and anterior segment surgery. Advantages of this new technology include sharply defined transection and incision of epiretinal membranes, fine coagulation of vascularized epiretinal tissue during surgery for diabetic traction detachment, and traction-free dissection of attached or elevated retina. PEAK-fc appears to be a promising cutting device for intraocular surgery, potentially allowing a higher level of microsurgical precision in vitreoretinal surgery. However, due to the preliminary nature of the present investigation, additional studies incorporating larger patient series will be required to accurately determine the role of this new instrument in vitreoretinal surgery.

Key words: pulsed electron avalanche knife (PEAK), retina, microsurgery, vitreoretinal surgery.

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