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Research Article

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iOCT with surgical microscopes: a new imaging during microsurgery

Abstract: The optical coherence tomography (OCT) is a non-invasive imaging technique, which recently has found important clinical micrometer applications. It allows noncontact and non-invasive cross-section imaging of the tissues with a depth resolution of about 10 µm. Similar to high-frequency ultrasound, the OCT shows real-time cross-sectional images of the tissue structures and tissue layers in a depth of a few millimeters. The OCT has evolved to an indispensable tool in ophthalmic diagnosis. An emerging application is the intraoperative use of OCT (iOCT). We developed the first commercially available device for the OCT, a universal OCT-Camera, which can be attached to the camera port of the different surgical microscopes. The OCT-Camera is completely integrated into the surgical procedure by enabling the OCT imaging before, during, and after microsurgery without interruption. The individual steps and the outcome of the surgical procedures, such as transplantation of the thin membranes or micro implants, are visualized in real time. The easy handling and first clinical applications of the iOCT were successfully demonstrated.

Keywords: intraoperative imaging; intraoperative OCT; iOCT; microsurgery; OCT-Camera.

OCIS codes: 170.4500; 170.4460; 170.4940; 170.4470.

1 Introduction

Since its introduction in 1991, the optical coherence tomography (OCT) [1, 2] has evolved into an important clinical diagnostic modality in ophthalmology [3]. The emerging diagnostic applications for the OCT are found in otolaryngology [4–12], neurosurgery [13–15], dermatology [16, 17], and the other fields. The OCT visualizes the small structures and layers at a depth of a few millimeters with a resolution of about 10 µm. The main application, so far, is the diagnosis of the different pathologies of the eye.

Besides the diagnostics, the OCT may also be used during surgical interventions. Today, the intraoperative OCT (iOCT) becomes more and more interesting [6, 15, 18–24]. There are different prototypes described in [25]. Here, we describe a new device for the iOCT imaging, which provides the live cross-section imaging of the tissue, which gives additional information to the conventional view onto the tissue surface during microsurgery.

The OCT devices for the ophthalmic diagnosis are available by a number of companies. Here, the imaging situation is quite simple. The patient sits in front of the OCT device. The measurement of the distance and field of view are exactly defined, and the physician can actively influence the OCT measurements. In the iOCT, the patient is lying down, sometimes completely anaesthetized, and the requirements for the OCT device are more challenging as the working distance and field of view are variable. The space requirements and the stringent intraoperative workflow in the operating room have to be obeyed. The OCT-Camera was specially developed according to these requirements and is completely integrated into the surgical microscope and its floor stand or ceiling unit.

2 Material and methods

To enable the iOCT, the OCT-Camera (Figure 1) is to be attached to the camera port of the surgical microscopes

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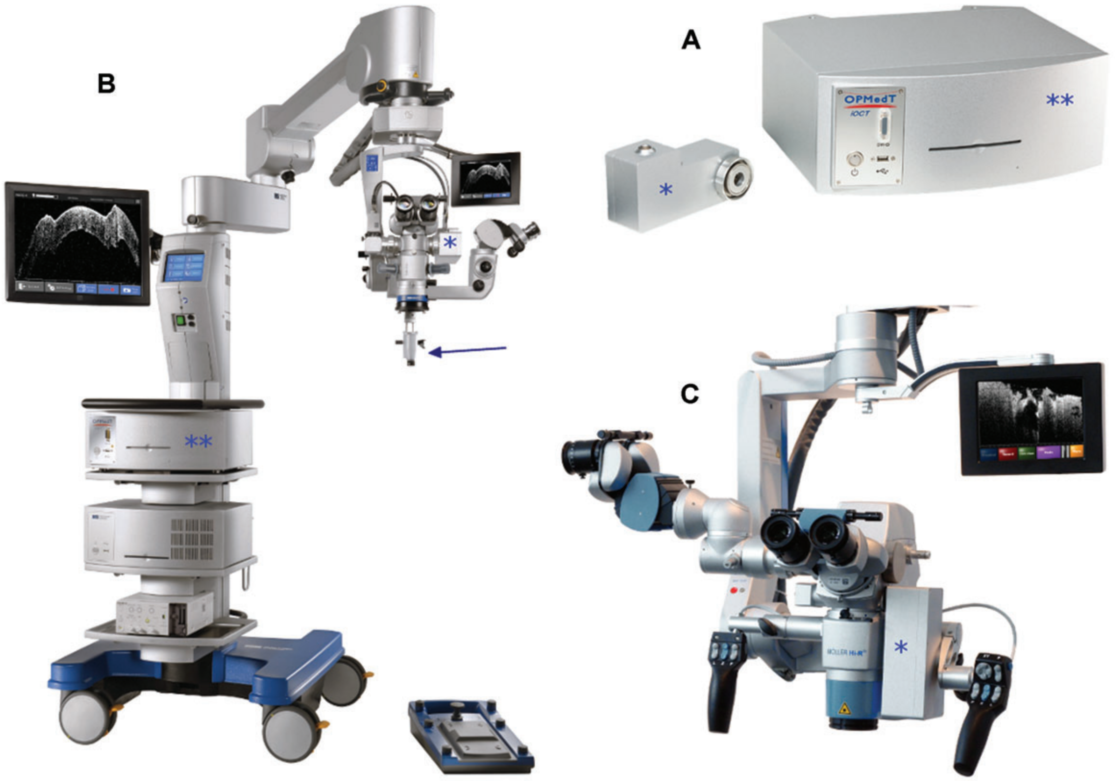

Figure 1 The OCT-Camera consists of a scan head (*) and a base unit (**) with light source and detector (A). It is easily coupled to the surgical microscope Hi-R Neo 900 (B) (Haag-Streit Surgical GmbH) and Hi-R 1000 NIR (C) (Moeller-Wedel GmbH).

like the Hi-R Neo 900 (Haag-Streit Surgical GmbH, Wedel, Germany) or the Hi-R 1000 NIR (Moeller-Wedel GmbH, Wedel, Germany). These microscopes are especially optimized for a good transmission in the near-infrared (NIR) spectral range. The OCT-Camera can be easily handled by the surgeon, himself, via a small touch screen monitor; no additional staffs are needed.

The OCT-Camera head, marked by * in Figure 1A, uses a two-axis scanner and a scanning optics, which is optimized for performance at the camera port of the operating microscopes. Via the optical fiber and electric cable, the OCT-Camera head is connected to the OCT-Camera base device (** in Figure 1A), which consists of an 840-nm broadband light source, a spectral domain OCT detector, and a motorized OCT reference optics. The reference optics enables the use of the iOCT at different working distances of the microscope, e.g., a full OCT functionality is provided for the Hi-R 1000 over a range from 220 to 500 mm. The working distance of the Hi-R Neo 900 is fixed to 175 mm. When the surgeon focuses onto the sample, he will always see a real-time iOCT video of the same field of view he sees through the microscope. The field of view changes with the continuously adjustable magnification (zoom parameter) of the microscope ranging between 5 and 30 mm (Figure 2A). The lateral resolution of the iOCT depends on the central wavelength λ_c and the numerical aperture (NA), which changes with the magnification and working distance:

$$d=0.61\cdot\frac{\lambda_c}{NA}$$

Figure 2 illustrates the dependency of the lateral iOCT scan width (A) and resolution (B) on the selected microscope zoom parameter. The best lateral resolution reaches 10.6 µm (line in Figure 2B). With the focus size, the depth of the optimal lateral resolution, which is defined by twice the Rayleigh length, z_r also changes

$$z_r=\frac{\pi\cdot d^2}{\lambda_c}$$

During microsurgery, the tissue position may vary within some millimeters. Accordingly, we designed the spectral radar detector for a depth of the measurement window of 4.2 mm in air (red line in Figure 2C). The iOCT can be performed in the complete range of microscope magnifications (Figure 2A). The best iOCT quality is expected within the blue shaded area of Figure 2A–C, where the lateral resolution is between 10.3 and 20.8 µm, and the confocal range is between 1.7 and 7 mm.

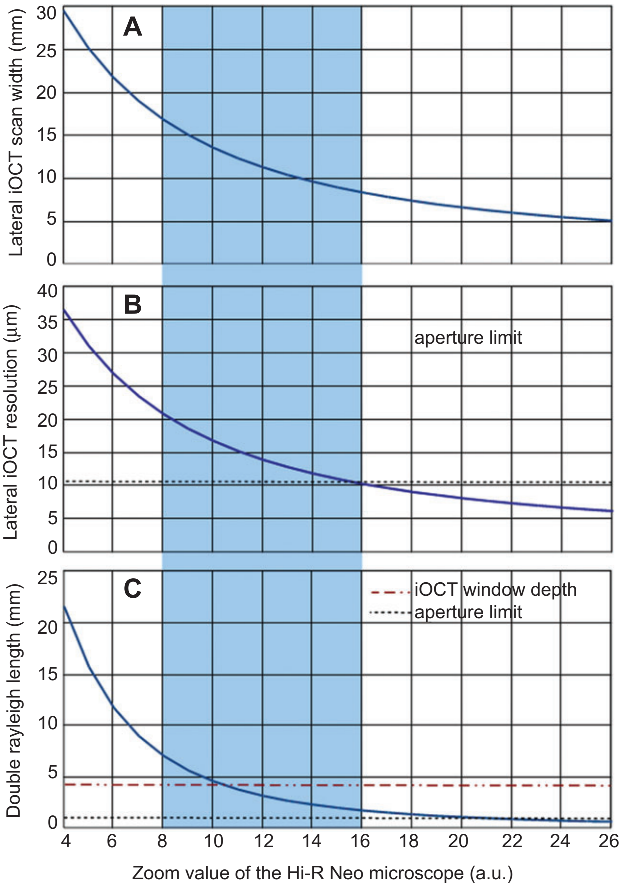

Figure 2 The lateral iOCT scan width and resolution depend on the magnification (zoom) of the surgical microscope Hi-R Neo (Haag-Streit Surgical GmbH) with the front lens f=175 mm.

The light source and OCT spectrometer were designed to provide a depth resolution of 10 µm in air, respectively, 7.5 µm inside the tissue, which is in the range of the achievable lateral resolutions. The group velocity dispersion (GVD) of the microscope optics and of the OCT reference optics has to be matched in order to achieve the optimal depth resolution supported by the OCT light source [26]. The motorized OCT reference optics varies with the GVD of the reference beam path by inserting the glass material of the different thicknesses. This enables the use of the additional optics with the operating microscope, like the EIBOS (arrow in Figure 1B), to image the posterior segment of the eye or a gonioscope prism to image the chamber angle of the eye.

3 Results

With this new OCT-Camera, the iOCT enables the view inside the tissue during surgery.

Figure 3 illustrates the iOCT imaging of the anterior segment of a healthy eye at the typically used microscope zoom positions. At a low magnification, the cornea, iris, and sclera can be visualized in an overview image (Figure 3A). At high magnification, the details become visible (Figure 3B). During surgery, the OCT-Camera records videos, snapshots, or volume scans. One cross-sectional OCT image consists of 1000 pixels in the lateral direction and 1024 pixels in the axial direction. Ten OCT images per second are measured and displayed, which is sufficient for real-time *in vivo* imaging.

In ophthalmology, several surgical applications were already identified in which the iOCT helps to visualize the architecture of the eye.

For example (Figure 4), the iOCT was able to visualize the thickness of an opaque cornea, the position of the iris, and the relative depth of a surgical instrument inside the cornea (D), which was not possible by the conventional microscopic view (C). Especially in the opaque corneas after eye burns and severe alterations of the anterior segment, this diagnostic instrument is of great help to define the surgical plains to prevent complications and to achieve good results in these extremely difficult surgical situations.

The main advantage of this intraoperative imaging tool is that the retro-corneal structures are visible even if the cornea is cloudy (Figure 4B, D). The perfect pupillary centration for visualizing the damage of the Descemet's membrane, anterior synechia, and openings of the angle was achieved. The status and location of the intraocular lens was detectable without any direct view through the cornea.

The further applications of the iOCT are found in the otorhinolaryngology [4–12]. During panendoscopy, the iOCT showed the layers and structures inside the vocal cords (Figure 5). The dimensions of the edema, the epithelium, or the lamina propria layer can be seen. It has been shown that the OCT can describe the microanatomy of the healthy and of the benign lesions [4, 11].

However, most OCT studies of the larynx have been conducted using a rigid or flexible probe [5]. This approach is not always acceptable because of the difficulty in handling the OCT probe while using the surgical instruments.

4 Discussion and conclusions

Although the first clinical OCT device was introduced more than 15 years ago, it was only recently made available to the microsurgeon. The high axial imaging resolution

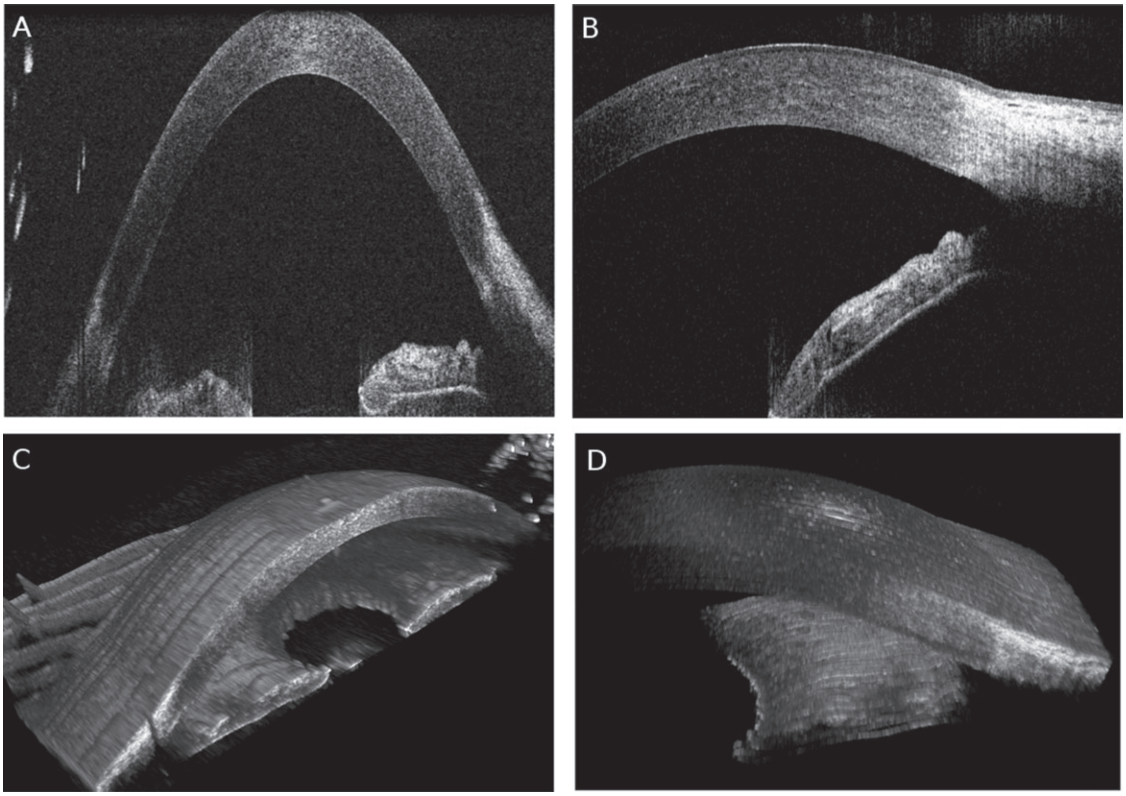

Figure 3 The iOCT of the anterior segment of the eye with the microscope zoom 8 (A) and zoom 16 (B). The iOCT volume scans are shown in (C) for zoom 8 and (D) for zoom 16.

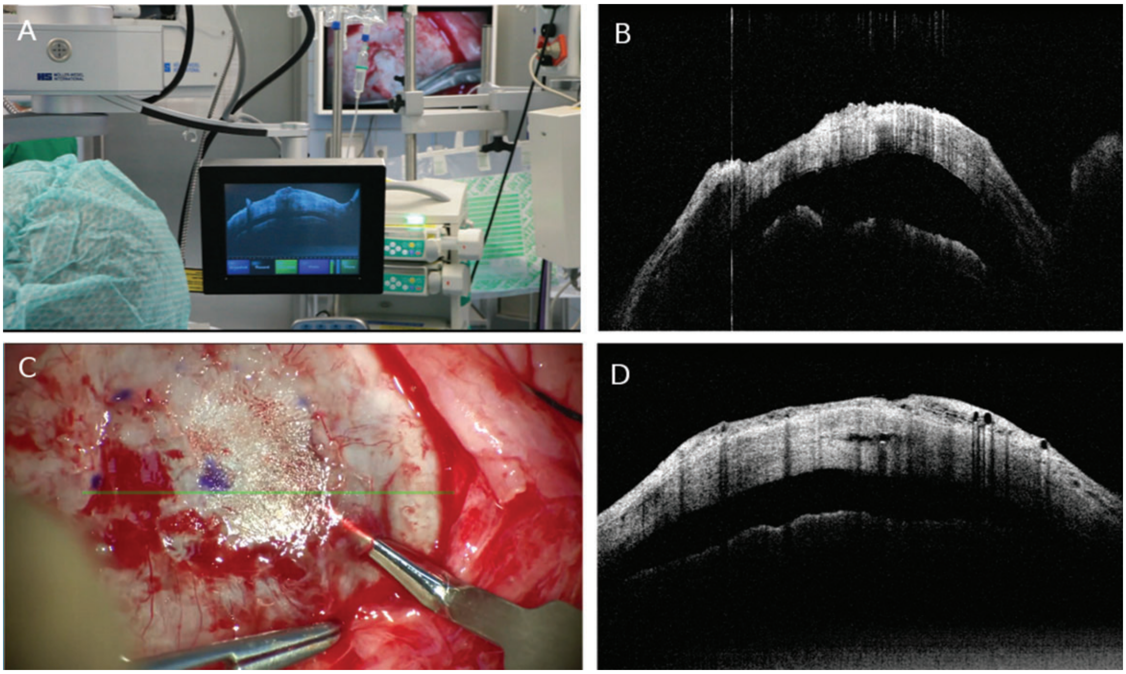

Figure 4 The iOCT of an acid burned eye (B). (A) The iOCT in the operating theater. The microscope view of an acid burned eye with its opaque cornea (C) with the corresponding OCT image (D). The green line in (C) shows the position of the OCT image.

of the OCT provides additional online information on the tissue structures. In contrast to the clinical OCT diagnosis outside the operation theatre, the iOCT quantitative measurements of the tissue morphology are less important. Although it could be interesting to measure the thickness of a tissue layer, an angle between the tissue

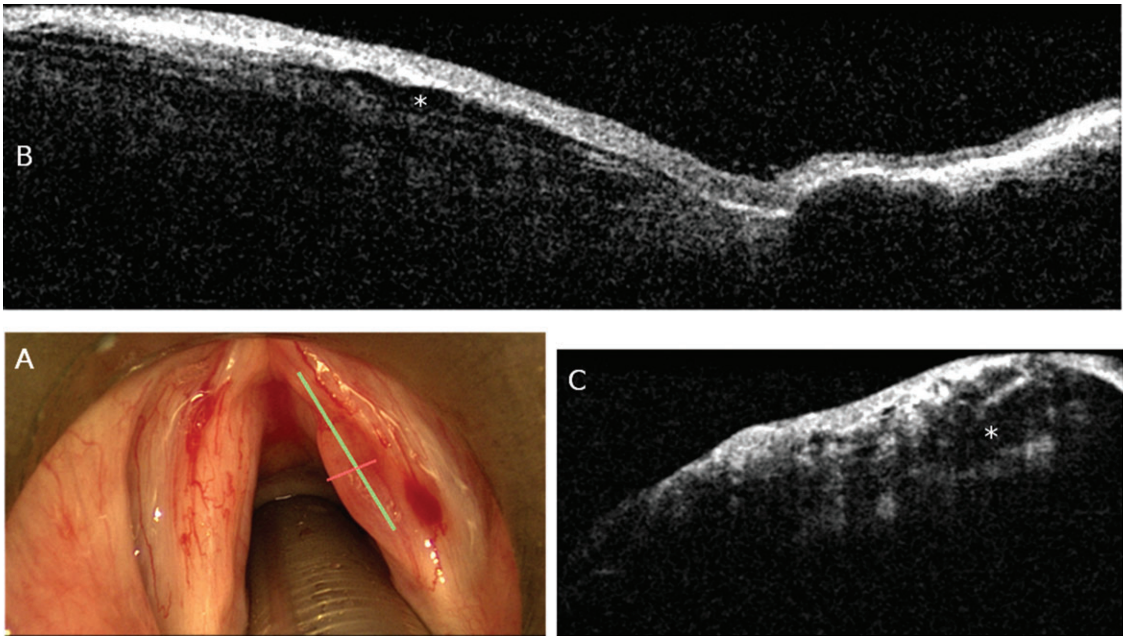

Figure 5 The OCT image of a Reinke's edema at the right vocal cord. (A) The top view with a green and red line at the scan position of the iOCT (B and C). The low signal area under the basal membrane, within the lamina propria (*), is caused by the edema.

surfaces, or the distances between the different tissue structures, all the surgical procedures will influence the light path and may lead to distortions in the images. Especially the air bubbles, special oils, or surgical instruments inside the tissue would obscure the quantitative measurement. Therefore, there is a less need for the intraoperative measurement functions but a high need of imaging information of the relative position orientation, which is easily provided by the iOCT.

In the field of corneal surgery, the iOCT visualizes the single cornea layers and helps to find the right orientation of the membrane transplants like the Descemet's membrane [20, 24]. In contrast to the direct microscopic view, the iOCT easily visualizes the correct alignment of the thin membrane. Especially, a nonperfect attachment of the graft to the patient's cornea can be detected. This is expected to improve the surgery.

The OCT technology is rapidly evolving. The different central wavelengths are being used for the different applications. The wavelength range of 800 to 900 nm offers high contrast and resolution and is compatible with the optics of the modern surgical microscopes. The good penetration of the eye allows for the high-quality retinal imaging at this wavelength. In general, the longer wavelength provides a better penetration in the scattering tissues, e.g., a full visualization of the anterior chamber angle was demonstrated at a wavelength of 1300 nm. This wavelength would also be the wavelength of choice for the applications in ENT and neurosurgery if the maximal imaging depth is desired. However, the clinical benefit does not only depend on the imaging depth. Good clinical results were achieved with an 830-nm OCT compared to a 1300-nm device when imaging the laryngeal epithelial dysplasia [27]. A good visualization of the brain tumors with 840 nm was also demonstrated [28]. As the iOCT matures, we will probably see the use of the longer wavelength even if further modifications of the microscope optics are necessary.

The functional OCT, the use of Doppler or polarization information, may also be used during surgery. The iOCT could enhance the visualizations of the vessels, quantify the blood flow, and show the pigmented structures with high quality.

As an add-on to the surgical microscopes, the OCT enables the non-invasive cross-sectional images of the microstructures inside the tissue during surgery in the complete range of the microscopes' magnification and working distances without interrupting the microsurgical workflow. With the OCT as a new imaging addition to the microscope top view, the surgeon obtains more confidence during the microsurgical procedures even if the small structures and layers inside the tissue are not exactly known.

Up to now, the clinical research and experience with the iOCT are still in the early stage. For the clinical procedures like the lamellar cornea transplants and the opaque corneas after severe acid eye burns, the clinical benefit of this new intraoperative imaging technique is already obvious.

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Marc Krug studied Physics at the University of Kassel. In his Diploma, he set up a velocity map imaging (VMI) spectrometer for investigations on the interaction of the ultrashort polarization-shaped femtosecond laser pulses with the alkali metal atoms. At the University of Kassel, he received his PhD for the measurements of the three-dimensional photoelectron angular distributions employing a novel tomographic reconstruction technique. In 2009, he joined the group of Dr. Eva Lankenau for preparing the foundation of the OptoMedical Technologies GmbH (OpMedT). Today, he is the Chief Operating Officer and Head of the R&D of OpMedT (Lübeck, Germany).

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Norbert Schrage received his medical PhD in 1990 for the investigations of the severest acid burns of the corneas with scanning electron microscopy and X-ray structure analysis. In 1996, he received the board certification in Ophthalmology. With his habilitation in the field of chemical elements inside the cornea, he received his venia legendi in 1997. He is the chairman of the ACTO e.V. After he was Deputy Director of the Department of Ophthalmology in Aachen, he is now the Head of the Department of Ophthalmology in Cologne Merheim since 2004.

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