ophthalmic imaging

James Wolffsohn
Dedicated to my ever supportive family, in particular my wife
Rachel and son Peter
Eye Essentials is a series of books intended to cover the core skills required by the eye care practitioner in general and/or specialized practice. It consists of books covering a wide range of topics, ranging from: routine eye examination to assessment and management of low vision; assessment and investigative techniques to digital imaging; case reports and law to contact lenses.

Authors known for their interest and expertise in their particular subject have contributed books to this series. The reader will know many of them, as they have published widely within their respective fields. Each author has addressed key topics in their subject in a practical rather than theoretical approach, hence each book has a particular relevance to everyday practice.

Each book in the series follows a similar format and has been designed to enable the reader to ascertain information easily and quickly. Each chapter has been produced in a user-friendly format, thus providing the reader with a rapid-reference book that is easy to use in the consulting room or in the practitioner’s free time.

Optometry and dispensing optics are continually developing professions, with the emphasis in each being redefined as we learn more from research and as technology stamps its mark. The Eye Essentials series is particularly relevant to the practitioner’s requirements and as such will appeal to students,
graduates sitting professional examinations and qualified practitioners alike. We hope you enjoy reading these books as much as we have enjoyed producing them.

Sandip Doshi
Bill Harvey
Preface

Enhanced imaging is one of the most exciting developments in healthcare of the eyes. It enables a better understanding of the differences between individuals (physiological variation) and how this may affect choices in laser refractive surgery and intraocular lens choice, for example. Perhaps more importantly, it allows the detection of changes in the structure of the eye, such as in the macular region, improving the ability to detect disease, to establish the best treatment strategy, and to monitor the subsequent changes that occur. The technology is already reaching the level of photoreceptor resolution which will help in our understanding of eye disease and enable new treatments to be developed. Further advances in imaging may allow us to better understand the individual’s ocular physiology rather than just anatomical structure.

Ocular imaging is a rapidly advancing field and some of the technology explained in this book will be superseded in a short period of time. However, the book purposely explains and demonstrates the complete technology involved with imaging, from imaging chip and colour information capture to high-end instrumentation as this is critical to a full understanding of the potential and limitations of ocular imaging. I hope you find this book as interesting and enjoyable as I have in writing it.

James Wolffsohn
The author gratefully acknowledges Rachael Peterson for her support, data collection and superb images. Also collaborative work with Clare O’Donnell on corneal transparency, Christine Purslow with digital imaging, Peter Hurcomb with imaging in systemic hypertension, Leon Davies and Shehzad Naroo with anterior eye imaging, and Krish Singh and Hannah Bartlett on MRI.

Clinical and Experimental Optometry kindly allowed use of some material in the anterior eye imaging chapter (Chapter 4) which has previously been published (Wolffsohn J S, Peterson R C (2006) Anterior ophthalmic imaging. Clinical and Experimental Optometry 89:205–214). Jon Gibson kindly provided the figure on angiography in Chapter 5 (Fig. 5.6).

The author does not have any commercial or proprietary interest in any of the techniques mentioned in this review.
1

Importance of ophthalmic imaging
Importance of ophthalmic imaging

Computer imaging is becoming more common in our everyday lives. Whether it is having your holiday snaps on CD, digital cameras, e-mail attachments or work presentations, the advantages of electronic imaging and storage are attracting much attention and usage. Not surprisingly, ophthalmic documentation is not far behind. Medical and allied professions have always emphasized the need for recording what clinicians have observed, but the time needed to sketch interesting features and the accuracy of the finished result have not been ideal. The use of film-based photography in optometric documentation has long been advocated as a better alternative, but it is expensive and the delay between taking the photographs and observing the results makes poor images difficult to replace and rapid monitoring awkward to achieve (Cox 1995). Computer imaging (often referred to as ‘digital imagery’) can offer increased flexibility and improved storage, comparison facilities, image enhancement and analysis.

However, the use of imaging in ophthalmic practice goes beyond just recording what clinicians have observed. For example, imaging sensors are used in videotopographers, some autorefractors, aberrometers, visual field analysers (for eye fixation monitoring) and low-vision electronic vision enhancement systems (often referred to as closed-circuit televisions). Other technologies such as scanning laser ophthalmoscopy, confocal microscopy, magnetic resonance imaging (MRI) and ultrasonography can also build an image of ocular structures. This book aims to highlight the issues involved with ocular imaging and how such techniques can be best utilized in enhancing ocular diagnosis, monitoring and treatment.

Chapter 2 examines the hardware used in ophthalmic imaging. Imaging chips have developed greatly, particularly with the commercial demand for digital cameras to replace film cameras. This was accelerated by the camera function built into many mobile phones and has resulted in the investment in this technology required for rapid development and a reduction in price. The two main forms of chip are discussed, namely charge-coupled devices (CCDs) and complementary metal oxide semiconductors (CMOS). A newer technology, foveon chips,
is also mentioned as a way to achieve 100% spectral and spatial resolution without the expense, light loss and fragility of three-chip cameras. Image transfer from the light capture medium to a computer is one of the main limiting factors to real-time imaging of megapixel images, with ‘live’ video being of low resolution or jerky. Knowledge of digital image interfaces is of interest not just to video capture, but also to the ability to capture optimized static images of the ocular surfaces. Much emphasis is placed on camera resolution, but higher resolution requires larger and more efficient storage options. Optical and lighting hardware considerations are often overlooked when purchasing imaging devices in favour of camera characteristics, but are critical for optimal imaging. Image illumination is controlled by shutter speed (at the expense of image blur for fast moving objects) and aperture size (at the expense of depth of focus). Flash units can overcome these disadvantages, but make the captured image less predictable. Finally, no matter how good your captured image, if a hard copy is required printing issues need to be considered.

Once an image has been captured, it needs to be stored and manipulated. Imaging software is discussed in Chapter 3. Software also has an increasingly important role in controlling imaging hardware, allowing more user-friendly and ‘intelligent’ user interfaces. Because of the commercial availability of cameras, beam splitters and slit-lamp biomicroscopes, many attempts have been made to design simple imaging solutions, but they often fail due to a poor interface with computer software. Easy access to the images of a patient, following progression, objective grading, image analysing, enhancing and labelling are all essential to good ophthalmic imaging. Image compression algorithms are widely used to make complex images more usable, but care must be taken not to compromise the quality of the image captured. With improvements in image technology, more importance has been placed on the capture and editing of movies to allow more realistic presentation of techniques, ocular devices and ocular conditions.

For ophthalmic imaging, considerations can be neatly broken down into anterior eye and posterior eye regions. Few
importance of ophthalmic imaging instruments can image both regions, without major changes in hardware, although more general instrumentation is attracting much interest. The slit-lamp biomicroscope is a key and diverse instrument in eye care. Beam splitters have long been integrated to split the eye-piece view to a second observer or image capture device. Newer systems have integrated the camera into the body of the slit-lamp to produce a more compact, stylish device than many bolt-on systems. Illumination techniques and their uses are reviewed in Chapter 4, along with the imaging of the essential vital dye, fluorescein. Other anterior eye imaging techniques include: corneal topography, to assess the curvature of the corneal surfaces through reflection or scanning slit techniques; confocal microscopy, to produce high resolution images of the corneal structure; optical coherence tomography, a well-established macular assessment technique which has now been applied to anterior segment imaging; ultrasonography, previously the main technique for assessing corneal and crystalline lens thickness, but now being used more when light-based non-invasive techniques fail; and more expensive body imaging techniques such as computerized tomography and magnetic resonance imaging.

Posterior eye imaging is covered in Chapter 5. Fundus cameras are becoming more commonplace in eye care practice, with systems allowing advanced imaging techniques such as ‘stitching’ of mosaic composites and stereoscopic viewing. Hardware and software considerations discussed in Chapters 2 and 3 are important to the optimization of image capture. Newer instruments combine basic fundus imaging with visual field light sensitivity information (retinal microperimeter) and achieve a wider field of view and reduced light scatter with scanning techniques (scanning laser ophthalmoscopes, optical coherence tomography and scanning laser polarimetry). Other techniques such as ultrasonography, computerized tomography and magnetic resonance imaging take advantage of non-light techniques to penetrate deeper into the eye and avoid optical distortion effects.

The imaging considerations of different surfaces of the eye are considered in Chapter 6. This provides clinicians with different
options to consider when changes are suspected or detected, to improve diagnosis and monitoring of the condition. Finally Chapter 7 is dedicated to the evolving area of telemedicine, where the limitations of geographical location are minimized by the transmission of images to allow quicker and more expert interpretations of changes, to improve treatment of complex conditions.

Whether you are in an ophthalmic clinical practice, research or manufacture, you cannot ignore the advances in ophthalmic imaging. Few advanced instruments do not involve some element of imaging. Living in a more litigious society demands that proof is available regarding past reality. Imaging offers us improved visualization and grading of conditions, and the ability to refer to the past without relying on having seen the patient on previous visits, or on intensive record keeping or a fantastic memory. Even if we don’t have the instrumentation ourselves, knowledge of what new techniques are capable of and which are appropriate, as well as being able to communicate what the patient will experience are critical. So with the falling cost of basic ophthalmic imaging devices, can you afford to remain ignorant?
2 Hardware

Light capture medium  8
Capture technology    11
Image transfer        14
  Analogue transfer   14
  Digital transfer    15
  Television video standards  16
Image storage         18
Resolution            18
Optical considerations 18
Lighting considerations 20
  Shutter speed        20
  Aperture size        20
  Additional lighting  22
Printing               25
Whenever one mentions an electronic imaging system, resolution seems to be the key feature that is emphasized. However, a full understanding of the mechanism of imaging technology and the optical system as a whole is necessary to optimize ocular imaging.

**Light capture medium**

A traditional analogue camera is a basic device, exposing a piece of film through a lens and shutter. Photographic films are coated with crystals of a silver halide, usually silver bromide. The crystal atoms are electrically charged, with positively charged silver ions and negatively charged bromide ions. These are maintained in an evenly spaced cubic grid by their electrical attraction. When the film is exposed to light energy, the photons of light release electrons from bromide ions, which collect at defects in the crystal (sensitivity specks), which in turn attract an equal number of free silver ions. The combination is silver atoms (black deposits), which in the processing stage are amplified by chemicals to a negative image.

Usually 24 or 36 images are recorded on one film and processing takes some time, interrupting the continuity of care of a patient and adding to administration of patient files, and whether the images were good enough quality cannot be assessed immediately with the patient present. Polaroid™ film had the advantage of almost instant development, but the image quality and durability was inferior to 35 mm colour transparencies. The complexity is in the design of the film and the processing stage. In comparison, digital cameras are more complex, with the image processing undertaken internally by the cameras’ electronics. Few ‘digital’ photo-sensors are as large as a piece of 35 mm film, so camera lenses have to be longer (typically 1.4–1.6×). Digital images can be viewed instantaneously on a monitor, enhanced or magnified and stored on a computer or memory stick. It should also be noted that if dirt or dust enters a camera on changing a lens or fitting to an optical system, whereas for a film camera this normally only damages a
single picture, with a digital camera it will continue to affect images until it is removed.

Digital images are a made up of a matrix of light intensity points called pixels (picture elements). Digital cameras typically have one of three types of light detection chip (Fig. 2.1):

1. **CCD** (charge-coupled device – a description of the technology used to move and store the electron charge). CCDs consist of etched pixelated metal oxide semiconductors made from silicon, sensitive in the visible and near infrared spectrum. They convert light that falls onto them into electrons, sensing the level/amount of light rather than colour. Only the photon-to-electron conversion is conducted on the pixel, allowing the maximum amount of space to remain within each pixel for capturing light information. They therefore have a low signal-to-noise ratio. The electron-to-voltage conversion is done on the chip, leaving the supporting camera circuitry (three to eight additional chips) to digitize this analogue data.

2. **CMOS** (complementary metal oxide semiconductor – technology used to make a transistor on a silicon wafer). CMOS chips are similar to CCDs, but both the photon-to-electron and electron-to-voltage conversion are conducted within the pixel together with digitization of the signal, leaving less room for the light-sensitive part of the sensor. Normally a micro-lens is used to capture more light within the pixel area and bend it towards the light-sensitive part (the fill factor) of the pixel. CMOS have the advantage of being cheaper and less power hungry than CCDs, because they have fewer components, making them more reliable.

3. **Foveon X3** (a chip of transparent quartz containing three layers of CMOS). This newer sensor uses three layers of CMOS imagers embedded in silicon, positioned to take advantage of the fact that silicon absorbs different wavelengths (and hence colour) of light at different depths. This enables each pixel to record individual and independent values of green, red and blue, providing full and accurate colour data from each pixel.
Figure 2.1 CCD, CMOS and Foveon light capture and processing (reproduced with permission from TASi).
Image processing creates heat, which can lead to image noise from erroneous charges within the sensor. Therefore, methods such as heat sinks or active cooling are employed in digital cameras. In an over-humid environment, over-cooling can lead to condensation causing chip damage. As noted previously, CMOS technology is less power-demanding than CCDs and therefore requires less cooling. Although most pixels are square or rectangular, more hexagonal style designs are being created to allow tighter arrangement and hence more efficient imagers.

Capture technology

Most optometric imaging needs the versatility of capturing both dynamic and static objects and therefore uses a matrix or grid of CCD/CMOS elements (area array). Progressive scanning cameras (such as those used in flatbed scanners) do exist, with a sensor consisting of three parallel lines of CCD pixels (coated with red, green or blue filters) that are gradually moved across an image by a stepper motor and lead screw, building up a complete colour image with accurate colour data at every pixel position. However, exposure times are long, requiring continuous light and a very stable image. Area array imaging only allows each pixel to capture one colour in a single exposure (shot; Fig. 2.2), so to create full colour information the camera can be:

1. **Single matrix, one shot** – each pixel coated in a different colour, spatially arranged in a mosaic pattern (providing twice as many green as red or blue pixels, based upon the Bayer pattern; Fig. 2.2). The image is then processed (interpolation of colour data from the surrounding pixels) to an image with the full resolution of the chip, with 100% spatial, but only 90–95% spectral fidelity. This can result in colour fringing around sharp edges, although more modern interpolation algorithms have reduced this effect. Interpolation requires a significant amount of processing, which takes both time and power to accomplish (Fig. 2.3a).

2. **Single matrix, three shot** – instead of individually coating pixels, three shots are taken through a red, green and blue
Hardware

3. **Single matrix, one/three shot** – this works as a single-matrix, one-shot camera for action shots, but for static imagery can be switched so that the pixel matrix is shifted by one pixel between shots to allow the same pixel position to take consecutive readings in red, green and blue (Fig. 2.3c).

4. **Single matrix, macroshift** – the limitation for all area array cameras is the physical pixel dimensions of currently available CCD and CMOS sensors, so these cameras take multiple exposures, moving the sensor between shots, and use ‘stitching’ software to create the final image. They work best for stationary, constantly lit targets and have a relatively slow capture process (Fig. 2.3d).

5. **Triple matrix, one shot (often called three-chip cameras)** – each chip captures an image of the scene at its

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**Figure 2.2** Single-chip, one-shot cameras use an area array matrix of red, green and blue typically based upon the Bayer pattern. The colour of each pixel location is established from a balance of the intensity of light passing through its colour filter and the colour of all the surrounding pixels (reproduced with permission from TASi).