General Principles of Endoscopic Imaging

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Introduction

The easy and safe access to image acquisition of the bronchial tract has been a long-standing desire of many physicians. Yet, the technical challenges faced while delivering images of the bronchi are much tougher than in many other endoluminal disciplines like gastroenterology. The anatomical structures of the bronchi require a thin, flexible endoscope shaft to reach desired deep structures in the periphery as well, while the wish to obtain biopsy specimen supporting the diagnosis or the need for retrieval of a foreign body demands a working channel and thus a wider diameter.

Retrospectively, it was a windy and stony road. Gustav Killian's first successful removal of a foreign body under direct visualisation using a rigid instrument in 1897 marked a very important milestone. Shigeto Ikeda's vision of the design of a flexible fibre bronchoscope in the late 1960s of the twentieth century was another major breakthrough for bronchoscopy procedures globally. Today's flexible bronchoscope technology utilising video chip technology and special light for better differentiation and contrast of pathological changes builds the actual cutting edge of this development. The story continues. This chapter will give an overview of the evolution of the first idea of a flexible bronchoscope to current state-of-the-art video bronchoscopy design, technology highlights in endoscopic imaging and design to finally providing an outlook to further improvements arising at the horizon.

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The Idea of a Flexible Bronchoscope

It was Shigeto Ikeda's visionary approach to hand over technical specification sheets in parallel to two Japanese endoscope manufacturers, requesting the development of a flexible bronchoscope. In spring of the year 1964, Ikeda handed over the idea with specifications of his flexible bronchoscope (see Table 2.1) to Machida Endoscopic Company Ltd. and Olympus Optical Company Ltd. in Japan.

The companies started to work on the implementation resulting in two slightly differing realisations as outcome of this competition. The first prototype of Machida was shown to the public in summer 1966 – without working channel and limited angulation. The seventh version was finally the one to become commercially available under the name Machida One in 1967. Olympus worked in parallel and manufactured a first prototype in August 1966 under the model name Olympus No 1. During the year 1967–1968, several design modifications improved the handling and specifications remarkably. These years can be considered as the starting point of flexible fibre bronchoscopes finding their way into the pulmonary departments worldwide.

Evolution of Flexible Bronchoscope Design

A fast penetration contributed to a swift gathering of valuable early adopters' feedback. The experience from specialised respiratory centres proved to be a solid basis for advice on how to further enhance the bronchoscope. In the following years, bronchoscopes were already available in a variation of different models (see Fig. 2.1), targeting different applications.

The first bronchoscopes were based on fundamental technology available for gastroenterologists for examination of the GI tract (see Fig. 2.2). The major technical challenge was the required thinner flexible shaft of the bronchoscope.

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It had to accommodate a sufficient number of glass fibres to transport the light into the lumen, a high precision fibre bundle to transport the image from the distal end of the scope to the eyepiece. Via the ocular piece at the proximal end, the physician can observe the area of interest. The proximal tip of the bronchoscope can be angulated by a lever which is located at the control section – the central part of the scope the user is holding and manoeuvring the scope with. Different to GI scopes which usually allow deflection of the distal tip in all four directions (up/down, left/right), the bronchoscope can be bent only in two directions 180°and 130°, respectively. A measure to safe space, as such a strategy requires only two wires to run inside the shaft. By clockwise or counterclockwise shaft rotation, the bronchoscope tip can reach all areas of interest. A working channel, sometimes called instrument channel, provides aspiration possibilities and guides thin long instruments, so-called endotherapy devices, to, e.g. acquire specimen during the procedure, allowing subsequent histopathological examination.

Imaging Fibre Bundle

The imaging fibre bundle is a key component of a flexible fibre bronchoscope and determines the image quality. The clearer and more well defined the image quality, the more support it delivers to the diagnosis of the lesion and suggests options for further treatment planning. The challenge is that each single fibre has exactly the same dimension and is positioned at the identical position at both ends of the fibre bundle. If this is not achieved, the image quality is impaired and artefacts disturb the image (see Fig. 2.3).

Table 2.1 Requested specifications of the first flexible bronchoscope

Outer diameter	<6 mm
Imaging fibre bundle	
Single fibre diameter	<15 μm
Number of fibres	>15,000
Focus	5–30 mm
Angulation of distal end	60 ° at 30 mm from distal end
Length of the rigid part of distal end	<10 mm
Total length	~1 m
Field of view	80 °, prograde

Channel System Inside the Fibre Bronchoscope

For various purposes, channels are running through the bronchoscope. The first one is starting at the control section down to the distal tip. It is used for aspiration of mucous – and consequently called suction channel. A suction valve at the control section is connected via a tube to an external suction pump. By pushing this valve, the bronchoscopist can activate the suction function. Slightly deeper at the lower part of the control section, a second port is available, the so-called instrument channel port. Through a different valve at this port, endotherapy instruments can be inserted into the bronchoscope to reach the lesion of interest inside the bronchial tract. Thus allowing, e.g. to guide biopsy forceps and to retrieve specimen for further investigation. Sometimes, it is therefore also called biopsy channel. As a space-saving measure, the instrument channel joins the suction channel at the lower part of the control section.

Light Source

In addition to the bronchoscope, the user needs a light source which delivers the light along the glass fibre bundles down to the lumen of interest. The bronchoscope is connected to the device while the examiner is observing the illuminated lumen through the eyepiece (see Fig. 2.4).

Fig. 2.1 Three early bronchoscope models with different outer diameter (Olympus)

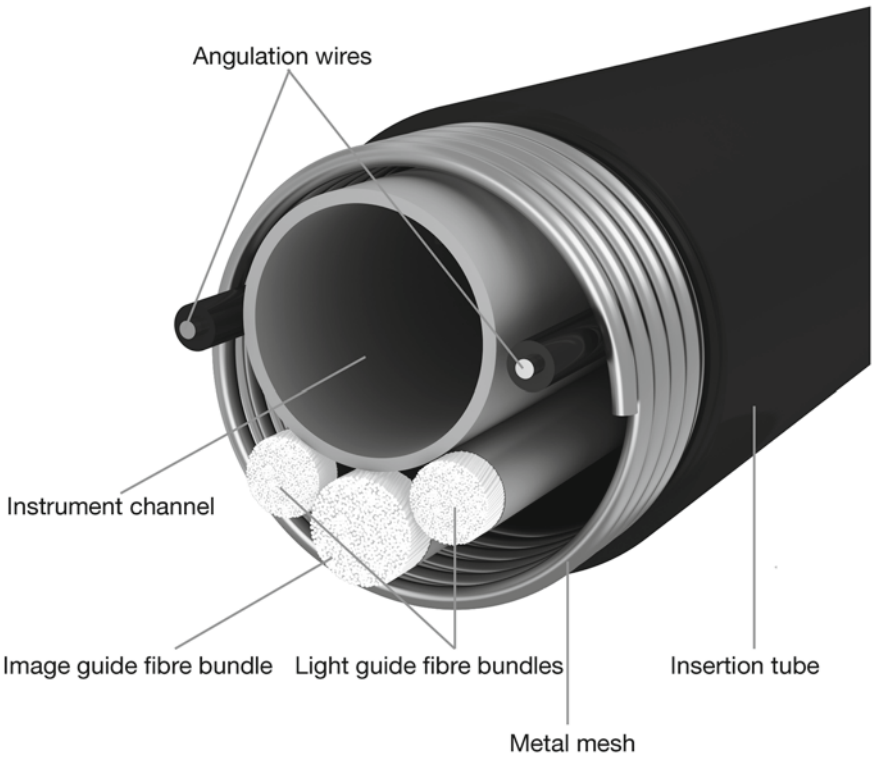

Fig. 2.2 Details of the internal arrangement of components

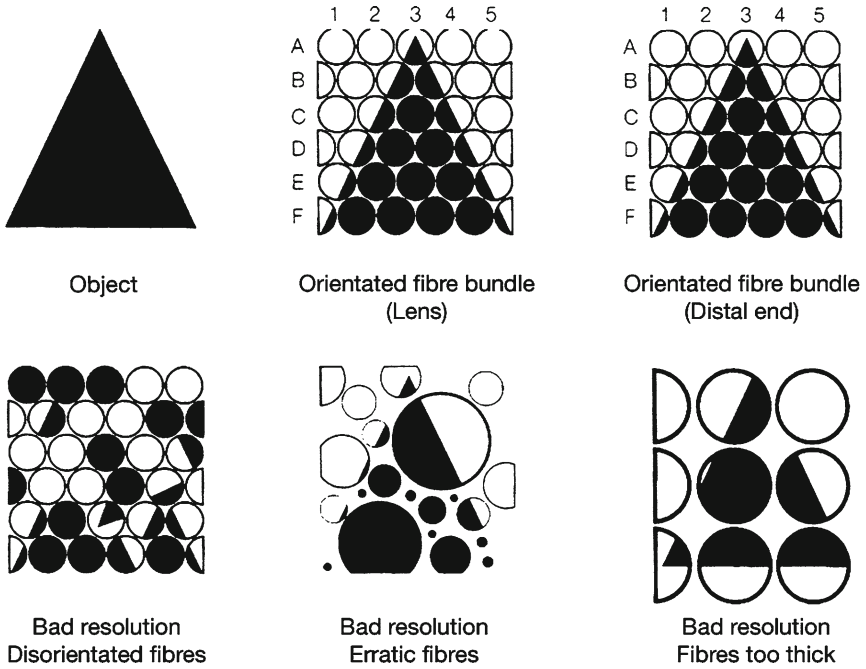

Fig. 2.3 Importance of fibre bundle arrangements

Suction Pump

Finally, to complete the system, a pump is required which is connected to the suction channel connector. In case the examiner is activating the valve at the control section, visibility interfering mucous can be aspirated through the channel system to clear the view.

Principles of Airway Image Acquisition

Over decades, a wide range of fibre bronchoscopes have been in use in daily routine. The continuous advances in endoscopy design and especially the introduction of video technology – a key breakthrough and a quantum leap for the image quality – influenced the bronchoscope evolution (see Fig. 2.5).

Fig. 2.4 Principle design of a fibre bronchoscope

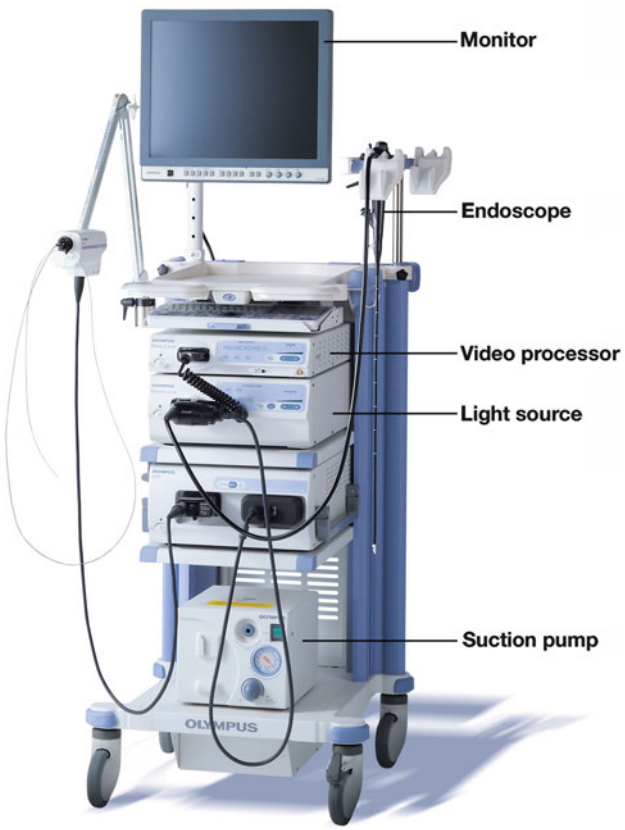

Fig. 2.5 Example of a complete modern endoscopic system

The core component needed is the CCD chip (charged coupled device) which delivers as a light-sensitive analogue device the image as a electrical signal and is mounted at the distal tip just behind a lens system (see Fig. 2.6).

The major technical challenge was the miniaturisation of the CCD chip enough that the human anatomy can accommodate the outer shaft dimension of such a video bronchoscope. In comparison to a fibre scope, the image glass fibre bundle requires less space compared to the CCD sensor. The eyepiece though is no longer necessary. Wires deliver the electrical video signal to the light guide connector (see Fig. 2.7).

In addition to the light source, a video processing unit is now mandatory. After looping the signal through a connection to the video processor with relevant signal processing measures, the user observes the endoluminal image on a monitor linked to the video processor (see Fig. 2.8).

Two Fundamentally Different Acquisition Technologies

Since the very first design concepts of video bronchoscopes, there existed two different principles of image acquisition by video signal. The key difference is the way how the CCD sensor at the distal tip of the endoscope is working and acquiring the image contents information in detail.

One principle is using pure white light and the CCD sensor is converting the reflected white light from the bronchus

Fig. 2.6 Internal arrangements of lenses and CCD in the scope distal section

Fig. 2.7 Handle and light guide/image connector of a modern video bronchoscope

into video signal components. Active image sensor areas, called pixels, produce the signal for red (R), green (G) and blue (B) portion. One pixel for each colour simultaneously. It is therefore called colour chip system. The other principle follows a different methodology in how to compose the RGB colour information. Instead of simultaneous image detection, the light produced in the light source is transmitted through a rotary RGB filter wheel, resulting in short revolving sequences of R, G and B light. The difference is that 1 pixel is responding on the colour sequences and delivering the R-G-B components of the image sequentially. The system is therefore called R-G-B sequential or sometimes (misleadingly) black and white system (see Fig. 2.9).

Both systems have advantages (see Table 2.2). R-G-B sequential CCDs can be designed in smaller dimensions, and this was the first system utilised for video bronchoscopes. Later, when the technology advancement allowed further miniaturisation, colour chip CCDs found their way into the tip of video bronchoscopes. The advantage of this technology is that even fast movements do not disturb the image by the so-called rainbow effect, an effect resulting from the fact that while the scope is moving fast the system does not have "enough time" to collect all three-colour signals. The consequence is a small band of false colours. The latest technology is reducing this effect, but the principle itself might hardly allow a complete elimination. The colour chip system established itself well in USA and continental Europe. Japan and UK in contrast focus on the RGB sequential system.

Autofluorescence Imaging (AFI)

While the step from fibre scopes to video scopes realised an unprecedented advancement in endoscopic imaging quality, the desire to facilitate improved detection possibilities, especially the detection of early lesion, still leaves room for improvement. An approach to use special light is autofluorescence imaging. White light endoscopy is utilising visible light of differing wave lengths between 380 (purple) and 720 nm (red) (see Fig. 2.10). AFI utilises the inherent properties of short wavelength blue light (390–470 nm) to assess mucosal tissue (see Fig. 2.11).

When the blue excitation light reaches the subepithelial layer, healthy tissue will fluoresce green. However, if there is any subtle mucosal change in the surface layer, potentially consistent with early malignant change, such as increased vasculature or thickening of the mucosa, tissue fluorescence will decrease. Therefore, by enabling changes in florescence to be observed, AFI can assist the early detection of suspicious lesions, displaying normal tissue in green and abnormal in magenta (see Figs. 2.12 and 2.13).

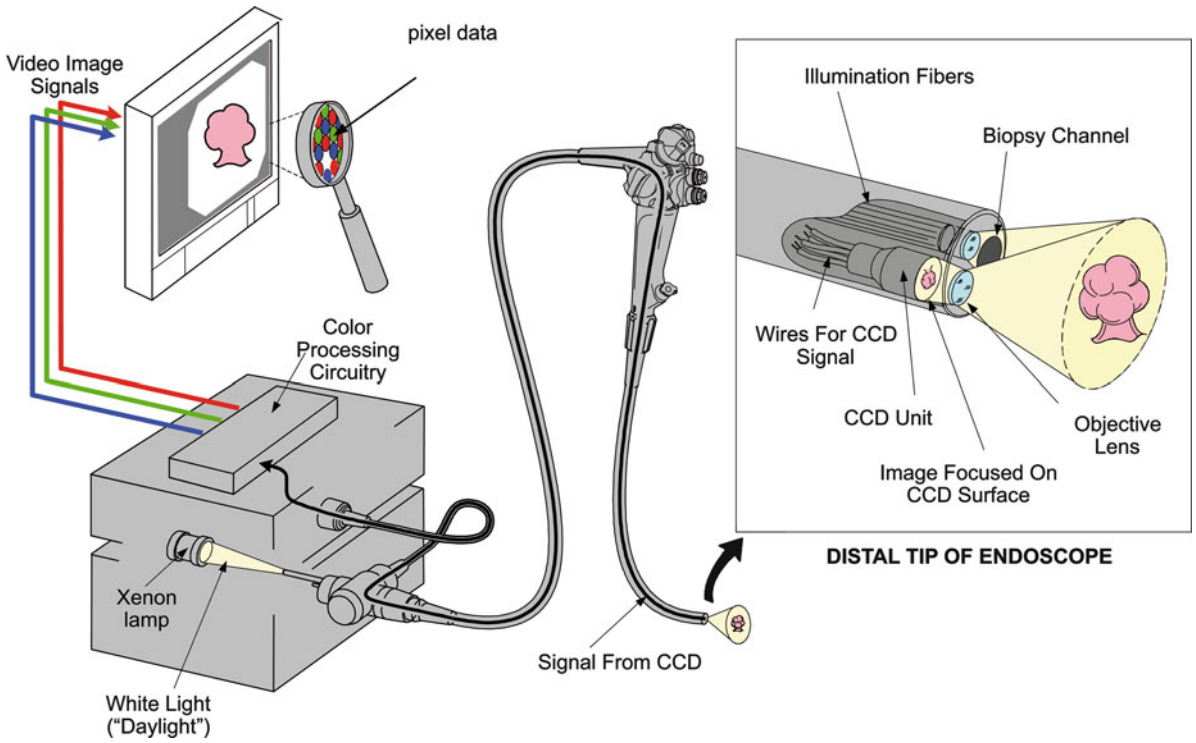

Fig. 2.8 System design of modern video endoscopy

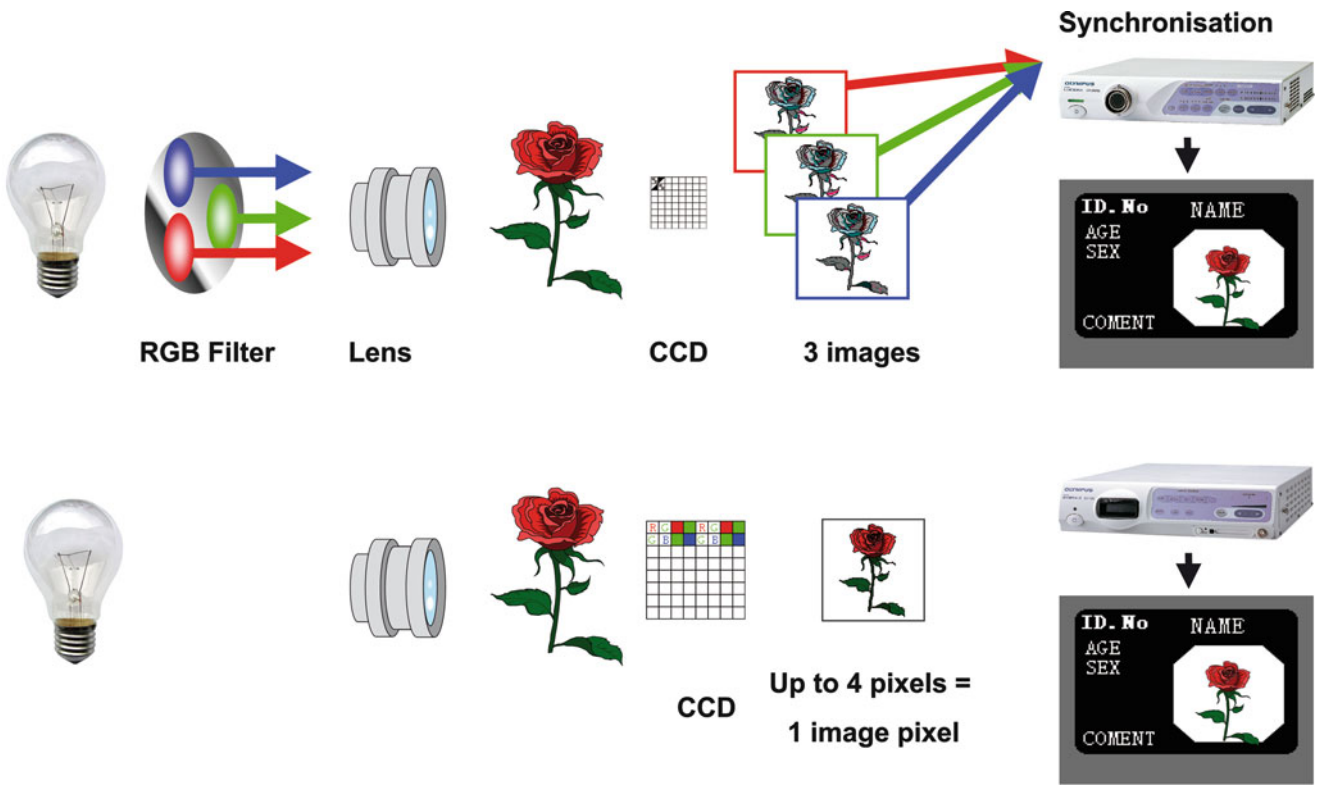

Fig. 2.9 Principles of RGB sequential (top) and colour chip (bottom) image generation

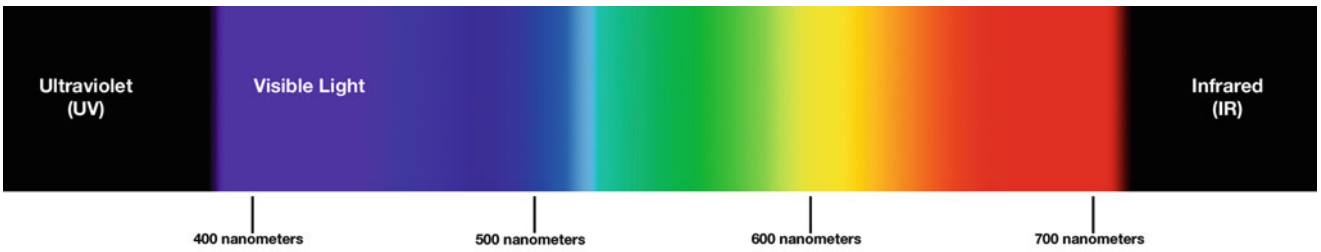

Fig. 2.10 Spectrum of light

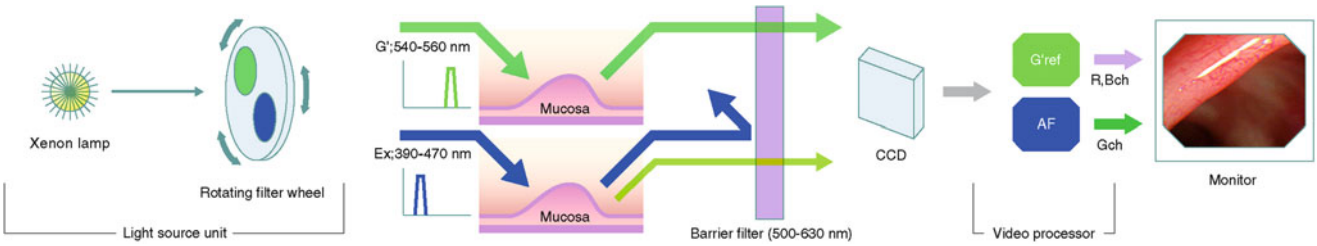

Fig. 2.11 Principle of autofluorescence imaging technology

Table 2.2 Key advantages of RGB sequential and colour chip technologies

RGB sequential	Colour chip
Small outer dimensions	Easier design of light source
Natural colour (no colour filters)	Easier image processing
Higher resolution (at given dimensions)	No rainbow effect

The technical challenge is, compared to white light endoscopy, the need for the special CCD to detect the extremely low intensity autofluorescence light signal.

AFI bronchoscopes therefore utilise two different CCD chip sensors: One used for standard white light endoscopy imaging and the other hypersensitive one whenever the AFI image mode is selected (see Fig. 2.14).

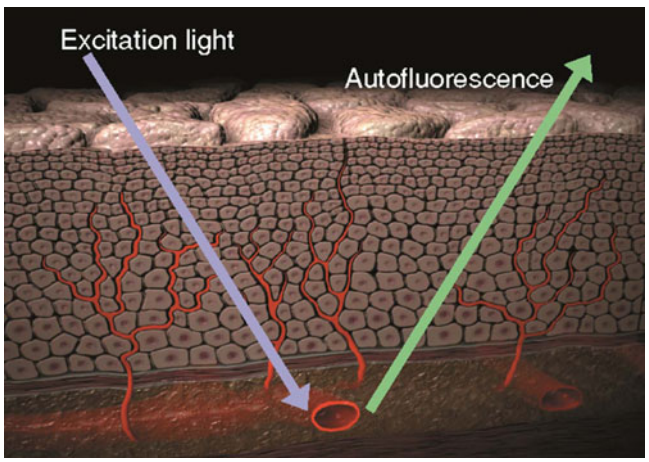

Fig. 2.12 Autofluorescence and the mucosa

Narrow Band Imaging (NBI)

Another approach of special light observation is making use of scattering and absorption properties of human tissue. The penetration depth before being scattered (partly absorbed) depends on the wavelength (colour) of the light. The shorter the wavelength (e.g. blue), the earlier it is reflected. Longer wavelengths (e.g. green) penetrate deeper. In other words, the image obtained through white light is a composition of slightly different tissue layers (see Fig. 2.15). A bright but partially blurred image is the result.

Narrow band imaging (NBI) enhances the visualisation of the capillary network and mucosal morphology during endoscopic observation of the gastrointestinal tract.

Via a button at the control section, the NBI mode is activated. A rotary filter moved into the light beam and alters the

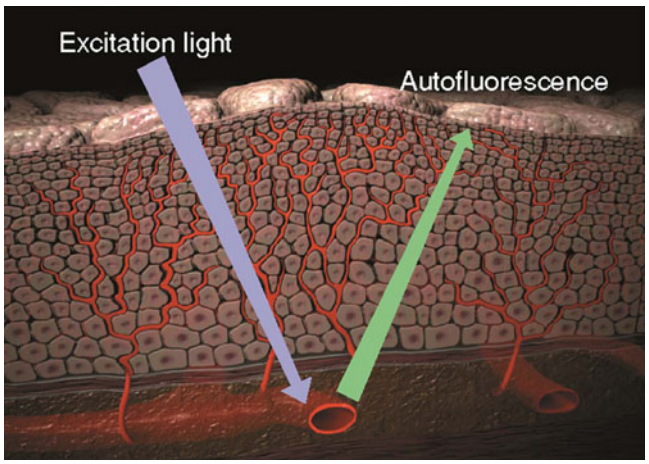

Fig. 2.13 Autofluorescence and the mucosa

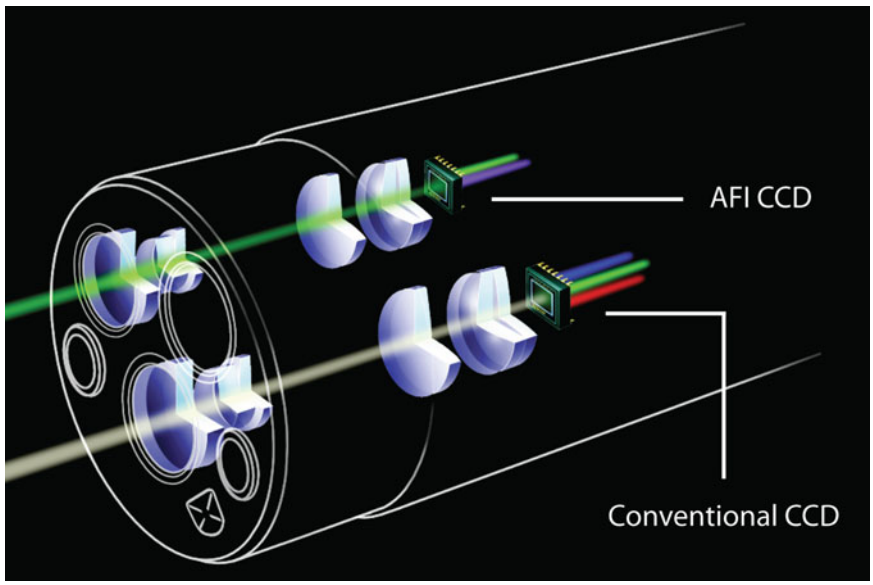

Fig. 2.14 Internal design of AFI scopes

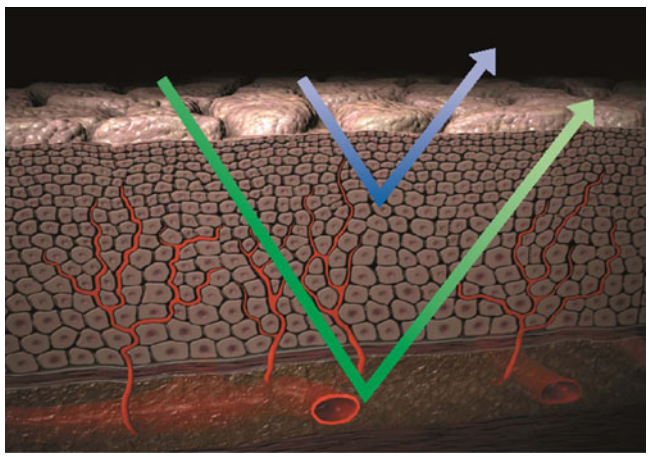

Fig. 2.15 Different wavelength light and the mucosa

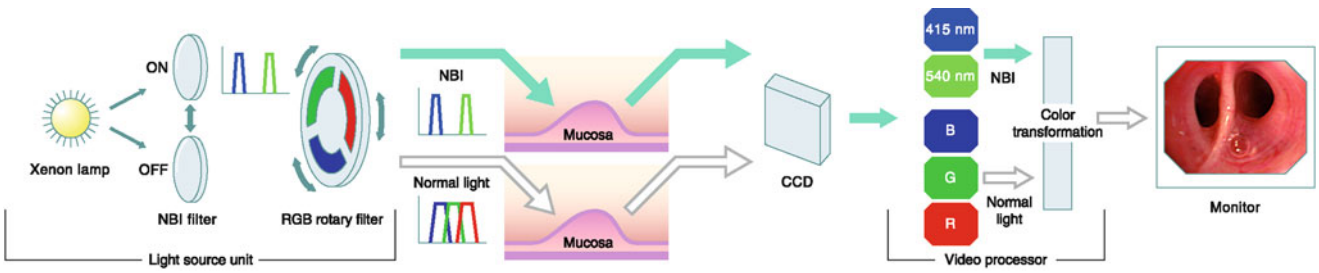

Fig. 2.16 Principle of narrow band imaging technology

white light to consist of specific wavelength bands (blue 415 nm and green 540 nm). The endoluminal observation is now done with this special light composition (see Fig. 2.16).

The result is an image with focus on superficial mucous layers (blue) and the capillary network of the deeper submucosal layer (green). This provides improved visual contrast of the surface structure and fine capillary patterns of the mucous membranes. The fact that only selected bandwidths are emitted results in a lower brightness which requires special high-sensitive dual mode CCDs. Recent systems try to achieve such high contrast image depiction from post-processing using special software algorithms. In any case, the user can select the mode by a switch on the control section of the bronchoscope.

Hybrid Fibre-Video Bronchoscopes

The pursuit to reach more peripheral lesions requires extremely thin insertion tube diameter of bronchoscopes. A new concept incorporates a modified endoscope design strategy. It unifies the advantages of thin calibre fibre scopes and the better image quality and easier image recording features of video scopes. The CCD is removed from the distal tip and placed in the control section. A thin glass fibre bundle is delivering the image from the distal tip to the CCD. The control section offers enough space to accommodate the image fibre bundle – CCD interface link (see Fig. 2.17).

The result is, e.g., a 4-mm-outer-diameter bronchoscope featuring a 2-mm working channel. The design combines the ergonomic handling of a video scope with a small outer diameter but still providing a wide working channel. The image quality is superior to pure fibre scopes image; furthermore, the video signal can be visualised on a monitor and also be recorded. The limitation from the fibre bundle as original starting point of the image acquisition remains. Another phenomenon which can occur over time is that single fibres can break. A broken fibre loses its capability to transport the light from one end to the other. This wear-and-tear effect can affect light guide bundles and image bundles over years. While the light intensity is impacted in the first case, for the latter case, little black dots in the image are the result.

Mobile Fibre Bronchoscopes

Technical advancement in the field of light-emitting diodes (LED) led recently to the availability of super bright miniaturised LEDs which can be incorporated in the distal tip of an endoscope. The low power consumption allows operating LEDs with batteries over hours. In combination with a small monitor attached (e.g. a display known from digital consumer cameras), a design of a lightweight mobile bronchoscopes is possible (see Fig. 2.18). Instead of the traditional eyepiece, the tilt- and rotatable monitor can be used to observe the surface of the bronchi or alternatively to review recorded images or video clips (see Table 2.3). The flexible usability during emergency cases or in the ICU is now easier possible with such scopes, requiring a charged battery pack and an optional memory card which can record the medical findings during the procedure.

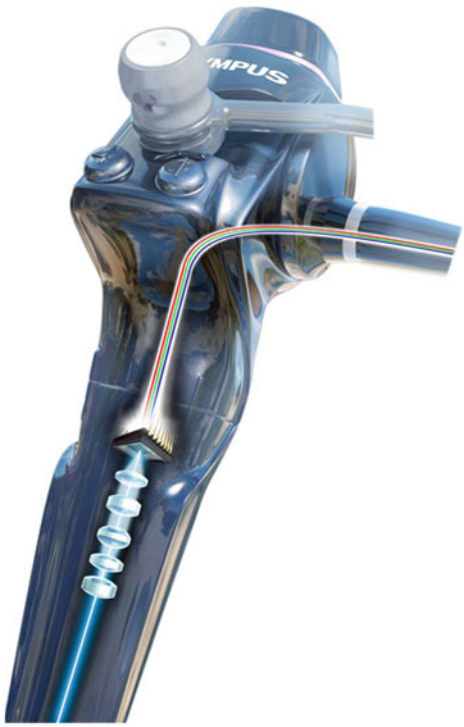

Fig. 2.17 Placement of the CCD inside the control section of a hybrid scope

Fig. 2.18 Mobile fibre bronchoscope

Table 2.3 Specifications of a mobile bronchoscope

Mobile scope specifications	
Supply voltage	3.7 V
Current consumption	350 mA
Maximum battery life	60 min (rechargeable)
Frames/images per second	15 (video mode)
	30 (still images)
Still image max. size	1,600 × 1,200 pixels
Movie max. size	640 × 480 pixels

Outlook

Future technology advancements in miniaturising CCD chip technology will open up the chance to integrate high-definition, so-called HDTV, CCD image sensors in the distal tip. While current standard definition video signals deliver 475 or 575 vertical lines (NTSC/PAL standard) as active image resolution, the recently introduced HDTV standard is composed of 1,080 lines in vertical direction. The overall image will contain more minute details for a potentially better diagnosis of the mucosa.

Reprocessing of Bronchoscopes and Autoclaving

The very first bronchoscopes were not at all watertight. Which means reprocessing of these first models needed special attention and lots of manual work. Hygiene awareness and standards were getting stricter over the years, so the bronchoscope design needed to be consequently enhanced in this respect as well. A breakthrough in this endeavour was the first completely watertight bronchoscope. Since then, it is possible to completely immerse the scope in cleaning and disinfection solution during the manual, semi-automatic or nowadays automatic reprocessing procedure. The disinfection chemicals base either on glutaraldehyde or recently more and more on peracetic acid.

Considerations to further enhance the safety of cross-contamination between patients have resulted in the request to design a flexible bronchoscope which can be autoclaved, e.g., in the central sterilisation department of a hospital. Autoclaving is a routine procedure in hospitals to prepare, e.g., OR instruments for the next patient with temperatures of 134 °C and in France even 138 °C. The thermal stress to a flexible endoscope is huge. Various components consisting of different material undergo different expansion processes during the autoclaving procedure. A standard scope undergoing autoclave cycles shows deterioration at the universal cord, the insertion tube and at the light guide connector (see Figs. 2.19 and 2.20).

Fig. 2.19 Wearing and erosion through autoclaving of normal endoscopes

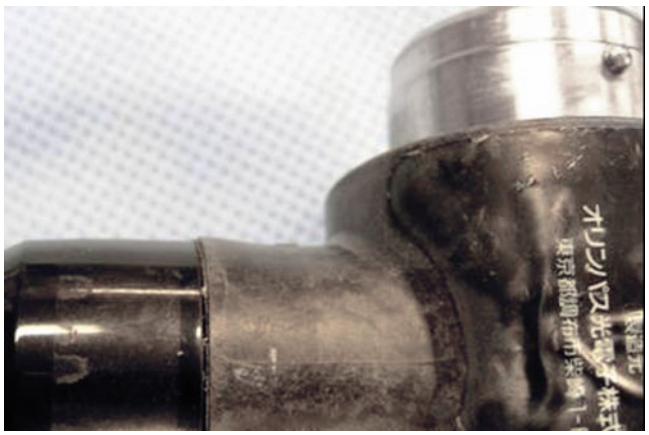

Fig. 2.20 Wearing and erosion through autoclaving of normal endoscopes

Typical sensitive areas and problems which are affected the most after several reprocessing cycles of a non-autoclavable endoscope are fog of the endoscopic view due to invasion of water creating humidity, cracks of the bending rubber, breaking of the top coating of the insertion tube, transformation and breaking of the control body. Without special preparation and careful material selection of those components, the endoscope will not withstand the reprocessing cycles and the endoscope will be damaged. Consequently, components formerly being glued together like the objective lens and the light guide lens had to be re-engineered. The revised design needs to allow different parts to be soldered together; thus, a high-tech metal coating of the lenses is necessary. Other components needed to be exchanged with biocompatible and heat-resistant material, which is repeatedly withstanding the thermal stress. Keeping the various components and materials used in a flexible bronchoscope in mind, only a solution for all challenges guaranteed the final autoclaving compatibility.

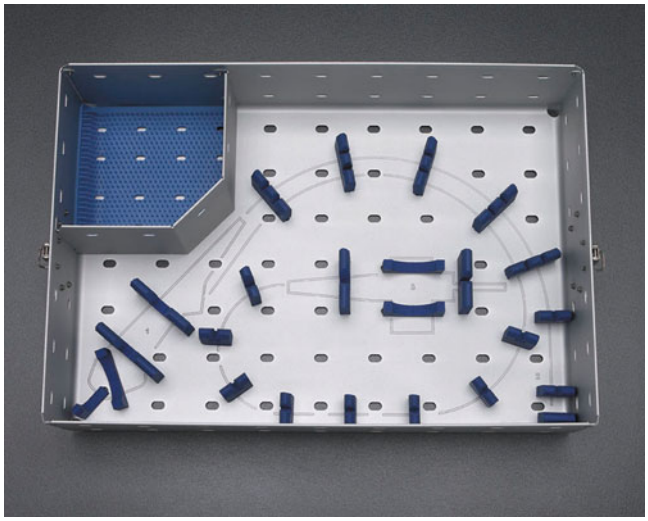

Fig. 2.21 Autoclave reprocessing tray

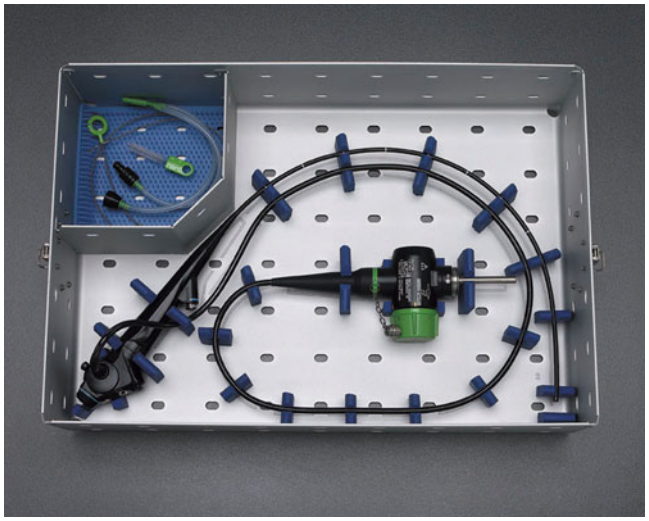

Fig. 2.22 Autoclave reprocessing tray

In order to ensure a standardised reprocessing result and to reduce the deformation of the flexible endoscope during autoclaving, a special reprocessing tray has been developed (see Figs. 2.21 and 2.22).

Acknowledgement All pictures used in this chapter courtesy and copyright of Olympus Medical Systems Corp., Tokyo.

Suggested Reading

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