Chapter 14: Nuclear Medicine Image Display

Set of 102 slides based on the chapter authored by H. Bergmann of the IAEA publication (ISBN 78–92–0–143810–2):
Nuclear Medicine Physics: A Handbook for Teachers and Students

Objective:

To familiarize the student with the principles of image display for nuclear medicine imaging, 3D visualisation, dual modality display and quality assurance procedures for nuclear medicine displays.

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International Atomic Energy Agency

Slide set prepared in 2015
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14.1 INTRODUCTION

- Following a medical imaging procedure, a display system is used to present the final image(s) to the medical specialist for interpretation and diagnosis.
- Nowadays, hard copy images on x-ray film or photographic film have been replaced by soft copy display systems with cathode ray tube (CRT) or liquid crystal display (LCD) monitors.
- Display monitors:
  - Primary (‘diagnostic’) devices – quality suitable for diagnostic reading.
  - Secondary (‘clinical’) devices – lower quality, but good enough for positioning, image display in wards, and data processing.

14.1 INTRODUCTION

- Nuclear medicine images can be adequately displayed, even for diagnostic purposes, on secondary devices.
- However the display of high resolution x-ray images from dual-modality studies (SPECT/CT and PET/CT) requires devices capable of displaying such images at diagnostic quality, i.e. primary devices.
- The wide adoption of picture archiving and communication systems (PACSs) has led to images being displayed at multiple locations, and on disparate devices, often far from the image source. This has led to the need for a standard specifying the requirements for image display on different devices [1].

[1] NATIONAL ELECTRICAL MANUFACTURERS ASSOCIATION, Digital Imaging and Communications in Medicine (DICOM), Part 14: Grayscale Standard Display Function, Rosslyn, VA (2003).

14.1 INTRODUCTION

- For colour displays, similarity in visual appearance is achieved by using an industry standard colour management system (CMS) [1]. The requirements for inclusion of a CMS into a PACS are addressed in [2].
- Display hardware needs to operate at maximum performance and to deliver consistent and reproducible results.
- Quality assurance of a display device, at the time of installation and during its lifespan, ensures stability and optimum performance, and is an important component of the quality system in nuclear medicine.

[1] INTERNATIONAL COLOR CONSORTIUM, Color Management, UK (2003), http://www.color.org/slidepres2003.pdf

[2] NATIONAL ELECTRICAL MANUFACTURERS ASSOCIATION, Digital Imaging and Communications in Medicine (DICOM), Supplement 100: Color Softcopy Presentation State Storage SOP Classes, DICOM Standards Committee WG1DNEMA, Rosslyn, VA (2005).

14.2 DIGITAL IMAGE DISPLAY AND VISUAL PERCEPTION

- The digital image to be displayed is represented as a rectangular matrix of integer values (8 or 16 bits). Each matrix element corresponds to a pixel of the image.
- These digital intensity values are transferred to the memory of the display controller, also known as a graphics card or video card, and converted to the analogue signals which control the electronics of the display device.
- Inherently, there is no colour in the image, but pseudo-colours are routinely used in nuclear medicine images to improve the visibility or to emphasize special features within an image.

14.2 DIGITAL IMAGE DISPLAY AND VISUAL PERCEPTION

- Another common use of colour is with overlay display techniques of pairs of registered images, e.g. originating from dual modality acquisitions such as PET/CT or SPECT/CT.
- Colour display devices, therefore, play an increasingly important role in the visualization of medical images.

14.2 DIGITAL IMAGE DISPLAY AND VISUAL PERCEPTION

14.2.1 Display resolution

- The resolution of a digital display device is commonly described in terms of the number of distinct pixels in each dimension that can be displayed.
- How many pixels are needed for adequate visualization?
- The desirable lower limit of pixel size would be reached if the human eye would not be able to distinguish individual pixels on the screen.
- Assuming a spatial resolution of the human eye of 1 arc minute and a reading distance of 65 cm, a human observer would not be able to discern two adjacent pixels smaller than about 0.18 mm as separate.

14.2 DIGITAL IMAGE DISPLAY AND VISUAL PERCEPTION

14.2.1 Display resolution

- A modern LCD monitor with a screen diagonal of 540 mm and pixel matrix dimensions of 1536x2048 has a pixel size of 0.21 mm. This is close to the resolution limit of the eye, so individual pixels are almost indistinguishable.
- Monitors of this quality are used routinely as primary display devices in radiology, except for mammography.
- For digital mammography images, an accepted primary reading device with a monitor of the same screen size would have pixel matrix dimensions of 2048x2560 and linear pixel dimensions of 0.17 mm.

14.2 DIGITAL IMAGE DISPLAY AND VISUAL PERCEPTION

14.2.1 Display resolution

- LCD monitors are composed of a large number of liquid crystals. This number represents the ‘native’ resolution of the display device since each pixel can be addressed individually to change brightness and colour.
- The display of an image is best if each pixel of the image maps to a pixel of the screen.
- If the mapping requires interpolation of the image pixels to the screen pixels, the image loses sharpness.

14.2 DIGITAL IMAGE DISPLAY AND VISUAL PERCEPTION

14.2.1 Display resolution

- A CRT display, in contrast, can change screen pixel size without loss of image sharpness by changing deflection and modulation frequencies.
- Several display resolution values can, therefore, be used with equal sharpness.

14.2 DIGITAL IMAGE DISPLAY AND VISUAL PERCEPTION

14.2.1 Display resolution

- The matrix dimensions of acquired and reconstructed nuclear medicine images (e.g. 128x128) are much smaller than the capabilities of the display (e.g. up to 1536x2048).
- This is due to both the poor spatial resolution of a nuclear medicine imaging device and its noise characteristics.
- Displaying the original image matrix at native pixel resolution would result in an image too small for visual interpretation. Therefore the image is magnified to occupy a reasonable proportion of the display area.
- Various interpolation schemes are provided by the display system software for this purpose.

14.2 DIGITAL IMAGE DISPLAY AND VISUAL PERCEPTION

14.2.2 Contrast resolution

- Contrast resolution is the number of intensity levels which an observer can perceive for a given display (perceived dynamic range (PDE)).
- Brightness refers to the emitted luminance on screen and is measured in candelas per square metre (cd/m^2).
- The maximum brightness of a monitor is an important quality parameter.

14.2 DIGITAL IMAGE DISPLAY AND VISUAL PERCEPTION

14.2.2 Contrast resolution

- Specifications of medical display devices also include the calibrated maximum brightness which is lower but is recommended for primary devices to ensure that the maximum luminance can be kept constant during the lifespan of the display device.
- Typical values for a primary device LCD monitor are 700 and 500 cd/m^2 for the maximum and the calibrated maximum luminance, respectively.

14.2 DIGITAL IMAGE DISPLAY AND VISUAL PERCEPTION

14.2.2 Contrast resolution

- The dynamic range of a display monitor is defined as the ratio between the highest and the lowest luminance (brightness) a monitor is capable of displaying.
- The dynamic range is highest if measured in the absence of ambient light. It is then called contrast ratio (CR = L_H/L_L) and is the figure usually quoted by vendors in the specifications.
- A typical CR of a grey scale primary LCD monitor is 700:1, measured in a dark reading room.

14.2 DIGITAL IMAGE DISPLAY AND VISUAL PERCEPTION

14.2.2 Contrast resolution

- If luminance values are measured with ambient light present, which is the scenario in practice, CR is replaced by the luminance ratio (LR = L'_H/L'_L), which is the ratio of the highest and the lowest luminance values including the effect of ambient light.
- It can be considerably smaller than the CR, since the effect of ambient lighting is added as a luminance L_{amb} to both the minimum and the maximum luminances.
- CR is related to PDR, but it is of limited use as a predictor of monitor performance as there are no standardized measurement procedures and it is affected by ambient light.

14.2 DIGITAL IMAGE DISPLAY AND VISUAL PERCEPTION

14.2.2 Contrast resolution

- The PDR is the number of intensity levels an observer can actually distinguish on a display.
- It can be estimated based on the concept of just noticeable differences (JNDs). The JND is the luminance difference of a given target under given viewing conditions that the average human observer can just perceive.
- The measured JND depends strongly on the conditions under which the experiment is performed, for example, on the size, shape and position of the target.

14.2 DIGITAL IMAGE DISPLAY AND VISUAL PERCEPTION

14.2.2 Contrast resolution

- PDR = the number of JNDs across the dynamic range of a display.
- The PDR for grey scale displays is ~ 100 [1].
- The number of intensity values which a pixel of the digital image can hold is much higher. It is an integer number between 256 and 65 536, and is given by the pixel depth of the image matrix.
- The use of 256 intensity values is common as it produces a sequence of brightness levels that appear continuous to the human observer.

[1] PIZER, S.M., CHAN, F.H., Evaluation of the number of discernible levels produced by a display, INSERM 88 (1979) 561–580.

14.2 DIGITAL IMAGE DISPLAY AND VISUAL PERCEPTION

14.2.2 Contrast resolution

- Colour displays using pseudo-colour scales can extend the PDR to about 1.5 times that of a grey scale display.
- This has been demonstrated for a heated-object scale which has the additional advantage to produce a ‘natural’ image [1].
- Owing to the enormous number of possible colour scales and the fact that the majority of them produce ‘unnatural’ images, the concept of JNDs while valid in principle cannot be transferred directly to colour displays.

[1] PIZER, S.M., CHAN, F.H., Evaluation of the number of discernible levels produced by a display, INSERM 88 (1979) 561–580.

14.3 DISPLAY DEVICE HARDWARE

14.3.1 Display controller

- The interface between the computer and the display is called the display controller (also termed video card, or graphics card).
- Components:
  - Graphical processing unit (GPU) – a fast, specialized processor for graphics operations.
  - Video memory – holds the data to be displayed. Capacity 128 MB to 4 GB, sufficient to store and switch rapidly between, multiple images, e.g. for cine display.
  - Random access memory digital to analogue converter (RAMDAC) - comprises three fast DACs with a small SRAM used to store the colour palette. Generates the analogue signals used to drive a colour CRT, or the digital signals needed to drive an LCD display.

14.3 DISPLAY DEVICE HARDWARE

14.3.1 Display controller

- Lookup tables (LUTs) contain the digital values (called ‘digital driving values’ or DDLs) that are converted by the RAMDAC to intensity values for display.
- DDLs are typically 8-bit, ranging from 0 to 255, although for some medical imaging displays they can be up to 12-bit. The maximum DDL corresponds to the maximum brightness the screen can display.
- The luminance values generated by the sequence of available DDLs (e.g. 0…255) produce the characteristic curve of the display device.

14.3 DISPLAY DEVICE HARDWARE

14.3.1 Display controller

- In displaying an image, the pixel values of the image stored in video memory are mapped to the values in an LUT.
- The mapping transformation associates each intensity with an LUT index.
- In the case of a colour display, a triple of DDLs, one each for the three primary colours red, green and blue, is used for a pixel. The LUT consisting of triples of primary DDL values is referred to as a colour lookup table (CLUT).

14.3 DISPLAY DEVICE HARDWARE

14.3.2 Cathode ray tube

- The CRT is a vacuum tube containing an electron gun and a phosphor screen.

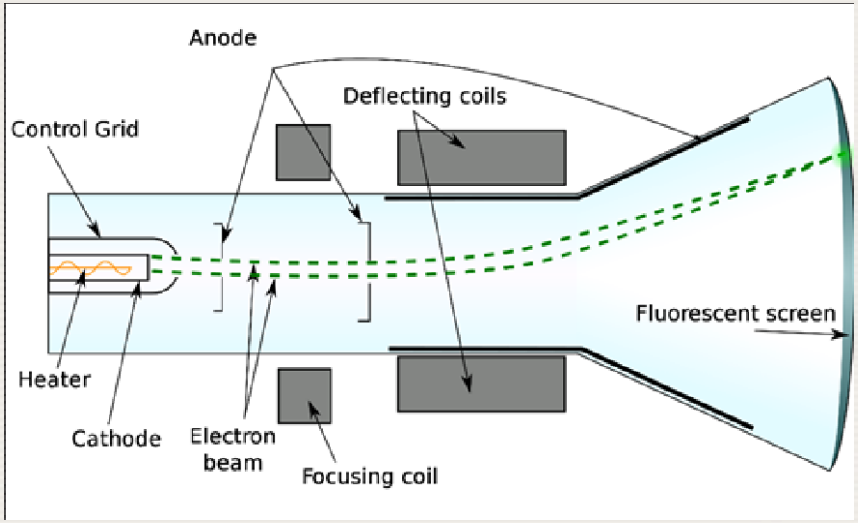


FIG 1. The cathode ray tube.

- The electron beam is accelerated by a positive high voltage applied to the anode towards the fluorescent screen.

14.3 DISPLAY DEVICE HARDWARE

14.3.2 Cathode ray tube

- The screen is covered with a phosphor coating that produces a visible light spot when hit by the electron beam.
- Voltages applied to the deflecting coils cause the beam to scan the screen area in a rectangular (raster) pattern. At the same time, the intensity of the electron beam is controlled by the control grid, thereby producing different light intensities.
- An image is produced on the screen by changing the beam intensity in accordance with the LUT value at each image pixel location during the raster scan.

14.3 DISPLAY DEVICE HARDWARE

14.3.2 Cathode ray tube

- Colour CRTs use three different phosphors which emit red, green and blue light, respectively.
- The phosphors are packed together in clusters called ‘triads’ or in stripes.
- Colour CRTs have three electron guns, one for each primary colour. Each gun’s beam reaches the dots of exactly one type of phosphor.
- A mask close to the screen absorbs electrons that would otherwise hit the wrong phosphor. The triads or stripes are so small that the intensities of the primary colours merge in the eye to produce the desired colour.

14.3 DISPLAY DEVICE HARDWARE

14.3.3 Liquid crystal display panel

- An LCD display panel consists of a rectangular array of liquid crystal cells in front of a light source, the backlight.

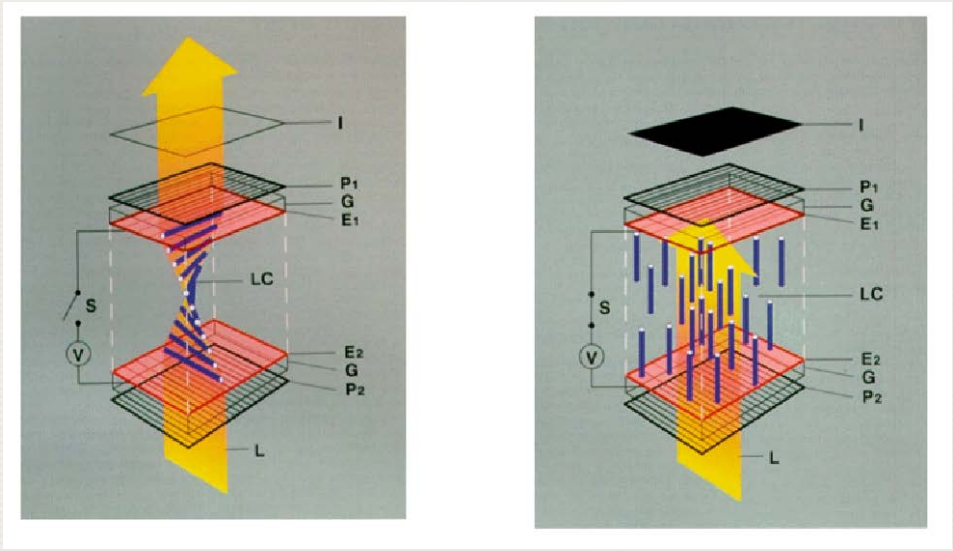


FIG. 14.2. Illustration of construction and operation of a single pixel of a twisted nematic liquid crystal cell. No voltage applied = OFF state (left diagram); voltage applied = ON state (right diagram). Two glass plates, G, coated with alignment layers (not shown) precisely twist the liquid crystal by 90° when no external field is present (left diagram). Light from the backside is polarized by polarizer P2 and rotated by the crystal structure. The second polarizer P1, set at 90° to P2, then permits the light to pass. If a voltage is applied to the two transparent electrodes, E1 and E2, the nematics re-align themselves (right diagram) and the polarized light is blocked by P1. Partial re-alignment is achieved by varying the voltage and permits the transmitted intensity to vary. (courtesy of M. Schadt).

14.3 DISPLAY DEVICE HARDWARE

14.3.3 Liquid crystal display panel

- Each cell acts as a tiny light valve which transmits the backlight to an extent determined by a voltage applied to the liquid crystal.
- The image on the screen is formed by applying voltages to each cell separately, thereby modulating the light intensity into the desired intensity pattern.
- In colour LCDs, each individual pixel is divided into three cells, or subpixels, which are coloured red, green and blue, respectively, by additional filters. Each subpixel can be controlled independently, so that thousands or millions of possible colours can be obtained for each pixel.

14.3 DISPLAY DEVICE HARDWARE

14.3.3 Liquid crystal display panel

- Active matrix LCD - the predominant type of flat panel display, used as general computer displays, in notebooks and increasingly as high quality displays for medical imaging.
- Each pixel has an individually switchable transistor (Fig. 14.3).

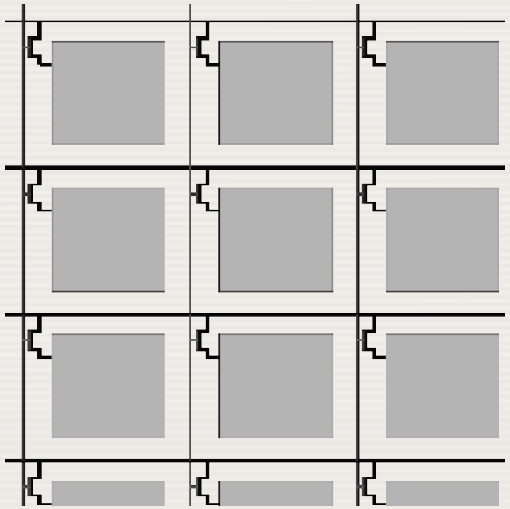


FIG. 14.3. The pixel layout in an active matrix LCD panel. Each liquid crystal pixel is connected to a transistor which provides the voltage that controls the brightness. The pixel is addressed by a row–column scheme.

14.3 DISPLAY DEVICE HARDWARE

14.3.4 Hard copy devices

- Although most reporting is now done using soft copy displays and PACS, hard copies of images are still used in operating theatres and sent to referring physicians.
- In nuclear medicine, acceptable output devices include dry laser film, thermal printers, colour laser printers and inkjet printers.
- The spatial resolution of a printer is given in dots per inch (DPI), defined as the number of individual dots that can be placed within the span of 1 in (2.54 cm).

14.3 DISPLAY DEVICE HARDWARE

14.3.4 Hard copy devices

Film laser imager

- Prints X ray images on transparent film with the same quality as available with conventional X ray film. Spatial resolution is up to 650 DPI, adequate for diagnostic quality output for all imaging procedures, including mammography.
- Contrast resolution depends on film quality and can reach a D_{max} of up to 4.0.

14.3 DISPLAY DEVICE HARDWARE

14.3.4 Hard copy devices

Colour printers

- Mainstream colour laser printers - produce cheap grey scale and colour output of images with a spatial resolution of typically 600–1200 DPI. For normal paper, the CR is low. Image quality can be improved by using special paper with a smooth surface for improved toner gloss and sharpness.
- Inkjet printers - spatial resolution of up to 4800×1200 DPI, which translates in practice to spatial resolutions of higher than 300 DPI. With special photo paper, excellent image quality equivalent to colour photographs can be achieved.

14.4 GREY SCALE DISPLAY

- In contrast to X ray imaging, the use of colour display has long been recognized as useful in nuclear medicine as an aid to diagnostic reading of the image, as well as for display of curves and functional images. Off the shelf colour displays have sufficed for this purpose.
- However the advent of routine hybrid imaging with CT and increasing use of PACS has brought the need for grey scale displays of diagnostic quality (primary devices) in nuclear medicine.

14.4 GREY SCALE DISPLAY

- LCD displays are rapidly replacing CRT displays as primary devices. LCDs :
  - Are twice as bright as CRTs
  - Have no geometric distortion
  - Are about 1/3 of the weight of a CRT display
  - Are less prone to detrimental aging effects
  - Less expensive.
- Furthermore, high quality colour LCD devices can be used as grey scale primary devices, which is not feasible for a colour CRT monitor.

14.4 GREY SCALE DISPLAY

14.4.1 Grey scale standard display function

- An image presented to an observer should ideally appear identical irrespective of the display device used, be it a CRT based or LCD based soft copy display, or hard copy displays, such as film laser printers or paper printers.
- The Digital Imaging and Communications in Medicine (DICOM) grey scale standard display function (GSDF) offers a strategy that ensures that a medical image displayed or printed at any workstation or printing system for which the GSDF is implemented has the same visual appearance, within the capabilities of the particular display device.

14.4 GREY SCALE DISPLAY

14.4.1 Grey scale standard display function

- This implies that a display device complying with the GSDF must be standardized and calibrated, and that a scheme of regular quality control is required for the display systems on the PACS.
- Colour display systems may also be used for the purpose of displaying grey scale images if calibrated to the GSDF.

14.4 GREY SCALE DISPLAY

14.4.1 Grey scale standard display function

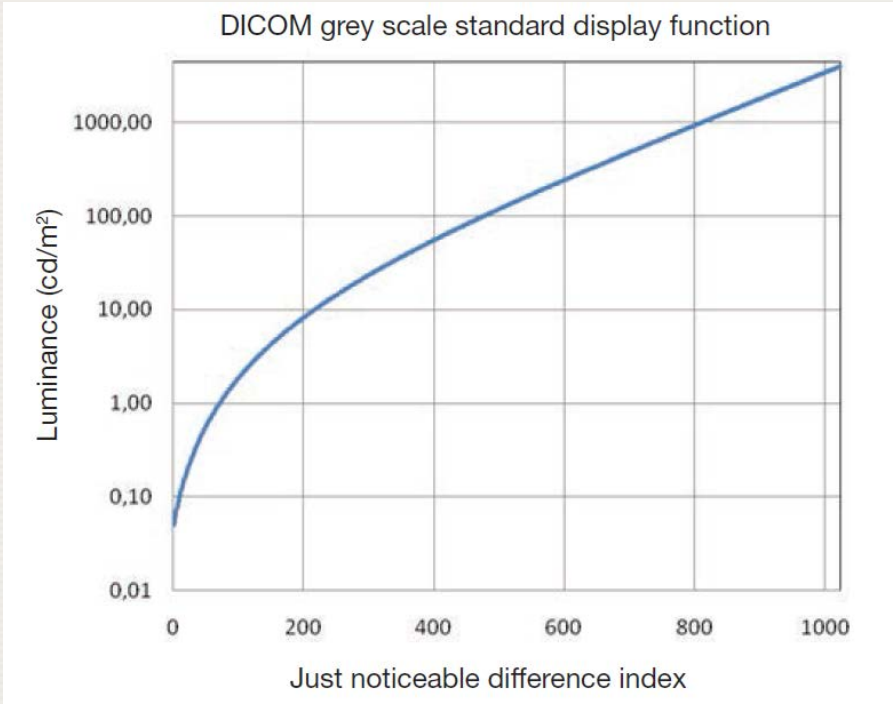
- The visual appearance of a native image as produced by the acquisition device (gamma camera, PET scanner, CT scanner) depends, if no corrections are applied, on the characteristic curve of the particular display device used at a display workstation.
- An image displayed using the characteristic curves inherent to a particular device could be significantly different in visual perception from the optimal presentation.

14.4 GREY SCALE DISPLAY

14.4.1 Grey scale standard display function

- Part 14 of the DICOM standard standardizes the display of grey scale images. It does so by introducing the GSDF which can be seen as a universal characteristic curve (Fig. 14.4).

FIG. 14.4. DICOM grey scale standard display function (GSDF). The GSDF is based on human contrast sensitivity and covers a luminance range from 0.05 to 4000 cd/m2. The minimum luminance is the lowest that can be used in practice with a CRT display, whereas the maximum luminance is slightly above the luminance of a very bright unattenuated light box used for the examination of mammography X ray films, so that it covers the range of luminance values of all display devices in current use. Human contrast sensitivity is non-linear within this range.



14.4 GREY SCALE DISPLAY

14.4.1 Grey scale standard display function

- Perceptual similarity of a displayed image is achieved by linearizing the GSDF with respect to contrast sensitivity. This is done by introducing the JND index.
- One step in the JND index corresponds to a luminance difference that is just noticeable, regardless of the mean luminance level. The DICOM standard contains the standard GSDF as a tabulation of luminance (brightness) against the JND index.

14.4 GREY SCALE DISPLAY

14.4.1 Grey scale standard display function

- Table 14.1 shows the first and the last few JND indices of the tabulation. It can be seen clearly that the relative changes of luminance need to be much larger on the dark side of the curve than on the bright side to achieve a JND.

TABLE 14.1. TABULATED JUST NOTICEABLE DIFFERENCE INDICES OF THE GREY SCALE STANDARD DISPLAY FUNCTION

Just noticeable difference	Luminance (cd/m^2)
1	0.0500
2	0.0547
3	0.0594
4	0.0643
—	—
—	—
—	—
1021	3941.8580
1022	3967.5470
1023	3993.4040

Note: The relative difference between the luminance of consecutive just noticeable difference indices is much higher for low indices (~9%) than for high indices (~0.6%).

14.4 GREY SCALE DISPLAY

14.4.1 Grey scale standard display function

- An individual display device with a luminance range $L_{\min}$–$L_{\max}$ and a DDL range of, for example, 8 bits exhibits a characteristic luminance curve as a function of the DDL as shown in Fig. 14.5.

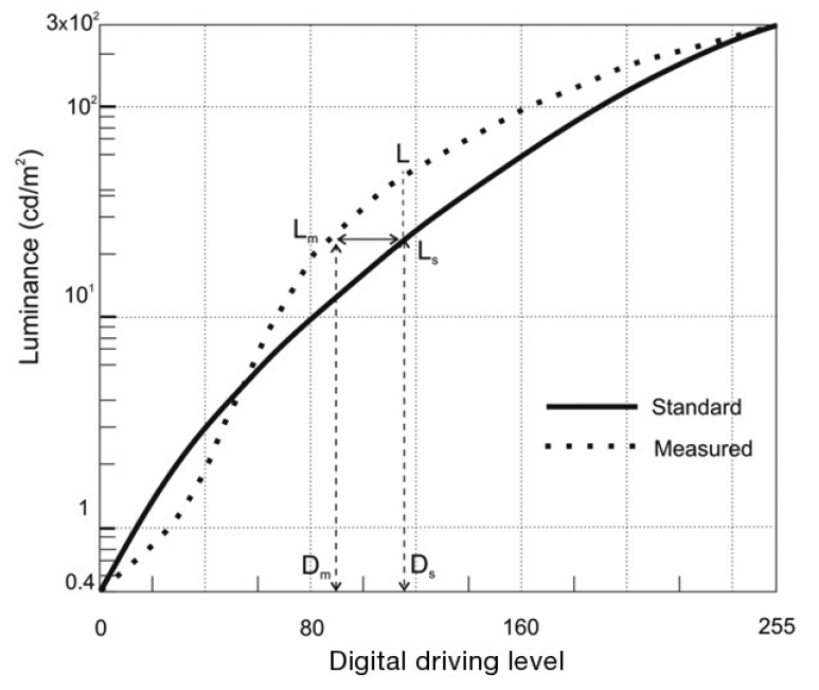


FIG. 14.5. Mapping of digital driving level D_s to the value D_m, so that for input level D_s which should produce the standard luminance value L_s the transformed value D_m will produce the correct luminance as given by the grey scale standard display function.

14.4 GREY SCALE DISPLAY

14.4.1 Grey scale standard display function

- The device specific characteristic curve will usually not match the corresponding segment of the GSDF. A transformation is needed, which is implemented as an LUT that maps a digital driving level D_s to the value D_m which produces the correct luminance (Fig 14.5).
- The transformation LUT may be implemented directly in the display device or in the video memory of the display controller.
- It generates a characteristic curve identical to the GSDF.

14.5 COLOUR DISPLAY

- The human eye can distinguish millions of different colours. The full range of colours the average human can see is given by the spectrum of sunlight.
- Each colour can be characterized as a mixture of three primary colours in a colour space.
- One of the first colour spaces introduced in 1931 is the International Commission on Illumination (CIE) xyz colour space [1]. It is derived from a model of human colour perception and uses three tri-stimulus values - one for luminance (brightness) and two for chromacity (hue) - to compose a colour.

[1] SMITH, T., GUILD, J., The C.I.E. colorimetric standards and their use, Trans. Optical Soc. 33 (1931) 73–134.

14.5 COLOUR DISPLAY

- Fig. 14.6 shows the well known CIE 1931 chromaticity diagram in which all colours the human visual system can perceive are represented as a function of two coordinates, x and y.
- The 3rd coordinate, brightness, changes the saturation. Varying it for the chromaticity 'white' provides levels of grey from black to the maximum white a display device can render.

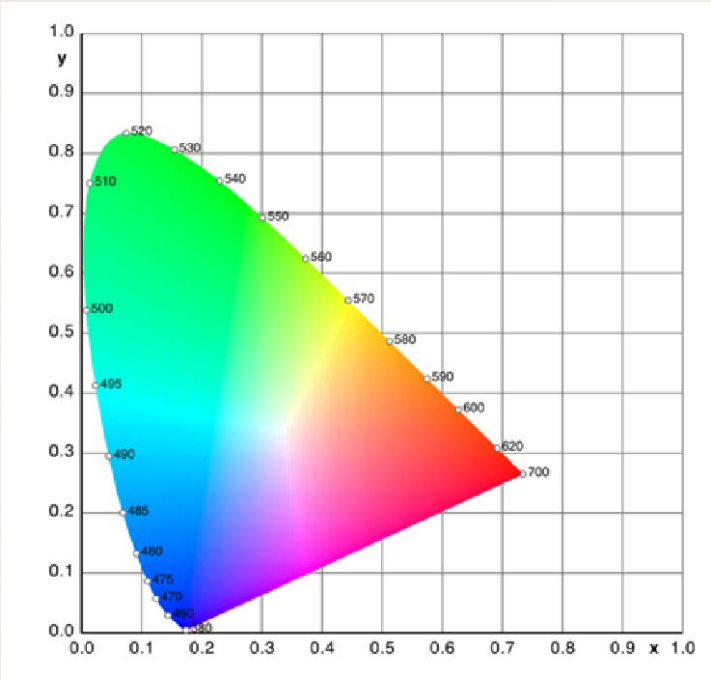


FIG. 14.6. International Commission on Illumination xy chromaticity diagram. The outer curved boundary is the spectral locus, with wavelengths shown in nanometres.

14.5 COLOUR DISPLAY

- Another frequently used colour space is the red, green, blue (RGB) space, a natural colour space for a CRT or LCD colour monitor. It uses as coordinates the intensities of the red, green and blue primary colours to generate a colour pixel (Fig. 14.7).

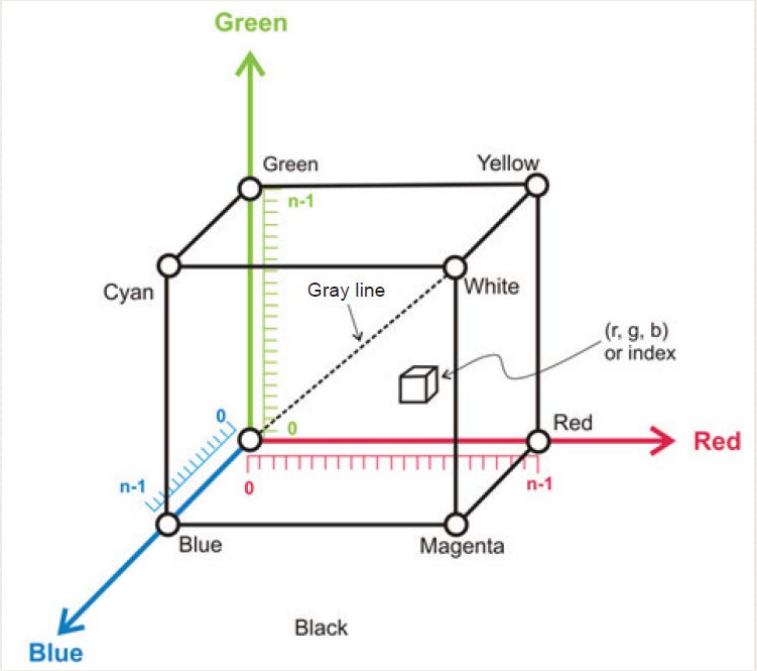


FIG. 14.7. Red, green, blue colour cube with a grey line as diagonal. The number of (r, g, b) voxels, i.e. colours available, depends on the bit depth of each coordinate. A depth of 8 bits for each component would result in 256^3 (16,777,216) colours.

14.5 COLOUR DISPLAY

- The colour space used for hard copy printers is the CMYK (cyan, magenta, yellow, key (black)) space.

14.5 COLOUR DISPLAY

- The quality of the colour image depends on the colour depth (the range of colour intensities) with which each subpixel contributes. Colour quality increases with subpixel depth.
- A common classification of the display controller's ability to reproduce colours is: 8 bit colour (256 colours), 15/16 bit colour (high colour: 65,536 colours), 24 bit colour (true colour: 16,777,216 colours) and 30/36/48 bit colour (deep colour: over a billion colours).
- A nuclear medicine display controller can usually handle true colour pixel depths, with 8 bits available for each primary colour.

14.5 COLOUR DISPLAY

- Colour was utilized in nuclear medicine at an early stage of the development of digital displays.
- Since the original image data contain no colour information, the allocation of colour to an image pixel can be freely chosen. The allocation takes the form of a CLUT.
- Conceptually, the CLUT is an array structure containing the colour coordinates for each colour included in the table. A colour is defined by three values representing the intensities of the red, green and blue subpixels. Each pixel intensity in the image maps to an array index of the LUT, so that each intensity is associated with a particular colour.

14.5 COLOUR DISPLAY

- The CLUT is stored in the memory of the graphics card.
- The CLUT is usually much smaller in size than the image. Usual CLUTs contain 64–256 elements. An advantage of a CLUT is that changing colours can be done by changing the CLUT, resulting in better display performance.
- The addition of colour information to native nuclear medicine and X ray images always results in a pseudo-colour image, with the colours chosen by the user.

14.5 COLOUR DISPLAY

- A modern nuclear medicine system typically uses 16–32 different CLUTs. The choice of colours is a complex issue. A continuous colour scale can be achieved if the individual components vary slowly and continuously. Pseudo-colour can be used to increase the PDR relative to grey scale; other CLUTs may emphasize regions with a specific intensity, as, for example, when performing a Fourier analysis of the beating heart to highlight amplitude and phase information.

14.5 COLOUR DISPLAY

14.5.1 Colour and colour gamut

- As with grey scale images, it is expected that a colour image displayed on a PACS display device has the same colour appearance regardless of the type or the individual characteristics of the display device.
- Fortunately, the problem of producing digital colour images with the same perception of colours regardless of the display device, including display monitors and hard copy printers, has already been resolved by the printing industry and the photographic industry.

14.5 COLOUR DISPLAY

14.5.1 Colour and colour gamut

- Since each colour is a unique entity, it is to be expected that unambiguous transformations exist between the coordinates representing the colour in different colour spaces. Such transformations are indeed available and are the basis of a CMS.
- The purpose of a CMS is to produce a colour image that is perceived as being the same by a human observer regardless of the output device used.

14.5 COLOUR DISPLAY

14.5.1 Colour and colour gamut

- The gamut or colour gamut is defined as the entire range of colours a particular display device can reproduce.
- The gamut depends on the type of display and on design characteristics. The number of vertices of the gamut is given by the number of primary colours used to compose a colour.
- In the case of an LCD or a CTR monitor, the three primary colours, red, green and blue, are used to produce a colour.
- Most printers can create dots in a total of six colours: cyan, yellow, magenta, red (yellow plus magenta), green (yellow plus cyan) and blue (cyan plus magenta).

14.5 COLOUR DISPLAY

14.5.1 Colour and colour gamut

- Typical gamuts for an LCD monitor and for a printer are shown in Fig. 14.8.
- Note that the monitor can display colours unavailable to the printer and vice versa.

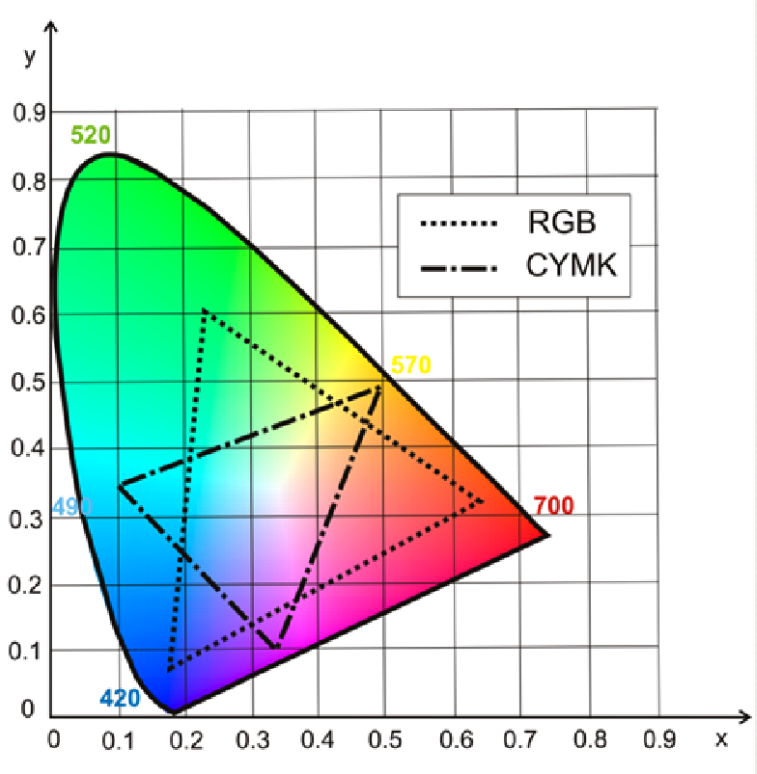


FIG. 14.8. Typical gamuts for an LCD monitor and a colour printer. Note the large non-overlapping areas of the colours which cannot be reproduced by the other device and must be substituted by similar colours.

14.5 COLOUR DISPLAY

14.5.1 Colour and colour gamut

- The International Color Consortium (ICC) has published procedures including colour transformations that ensure that a colour image that is displayed on, for example, a monitor has the same appearance on, for example, a colour printout [1].
- The colour properties of a display device are described by an ICC colour profile. This profile contains manufacturer-provided or, preferably, the measured, gamut of the display device in a format which permits transformation of the colours between the representation on the device and an intermediary colour space (e.g. CIE xyz or CIE lab space).

[1] INTERNATIONAL COLOR CONSORTIUM, The Role of ICC Profiles in Colour Reproduction System (2004).

14.5 COLOUR DISPLAY

14.5.1 Colour and colour gamut

- The intermediary colour space acts as a colour reference and is called the profile connection space (PCS).
- The PCS is utilized by DICOM, analogous to the GSDF for grey scale displays, as a reference space for the transformation of colours from one colour display device to another.
- Unlike the GSDF, it does not claim to linearize perceived contrast.

14.5 COLOUR DISPLAY

14.5.1 Colour and colour gamut

- The colours of an individual display device can be transformed with the help of the ICC profiles to any other display device including hard copy colour printers while maintaining the same visual perception of the colours.
- For colours available on one device but not on the other, the PCS substitutes colours similar in perception to the missing ones.
- ICC profiles must be all available for all display systems involved. The DICOM standard formalizes the information required by the CMS by adding the necessary tags to the data dictionary, and colour transformations are performed transparently to the user.

14.6 IMAGE DISPLAY MANIPULATION

14.6.1 Histograms

- The intensity histogram of an image represents the distribution of the grey values in an image. It is obtained by dividing the range of grey values into intervals of equal width, the bins, and calculating the number of pixels with intensity values falling into each bin.
- The number of bins to store the frequencies can be freely chosen, but the most informative displays are obtained with bin numbers between 32 and 256.

14.6 IMAGE DISPLAY MANIPULATION

14.6.1 Histograms

- The graphical display of the histogram transmits a rough idea about the distribution of intensities (Fig. 14.9).

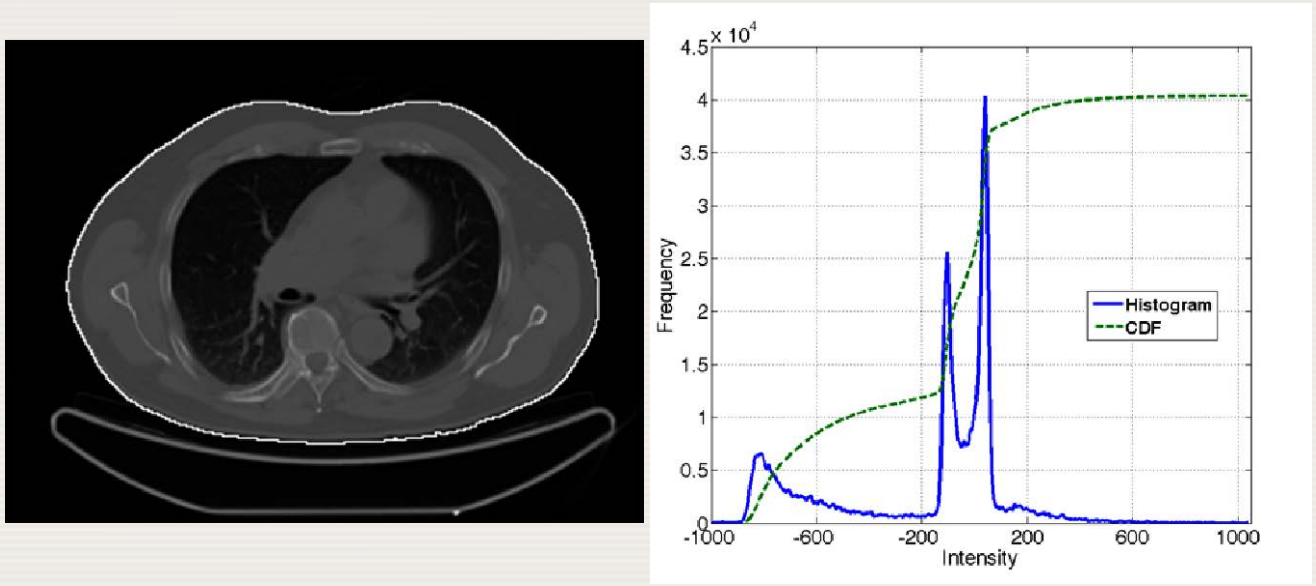


FIG. 14.9. Transverse CT slice at the height of the heart (left), with the corresponding intensity histogram, using only the pixels within the region surrounding the trunk. The number of bins is 256. Even when excluding all background pixels, the unequal distribution of intensities is seen, especially the lack of high intensity values which is in agreement with the small proportion of bony structure in the image.

- The most basic intensity transformations used in image display are to transform a pixel intensity I to a grey scale intensity value r within the available grey scale range Q of the display monitor:

$$r = T(I) \qquad (14.1)$$

- Q is normally in the range 0...255. The transformations do not take into account the values of surrounding pixels; each pixel is processed independently.

14.6 IMAGE DISPLAY MANIPULATION

14.6.2 Windowing and thresholding

- Windowing and thresholding are linear intensity transformations of that type. They provide an easy method to emphasize contrast and visibility of structures in areas of interest by only mapping intensity values within an intensity window defined by a threshold and a window width to the available range of brightness values.
- Values below the threshold are set to black; values above the upper level are set to maximum display intensity.

- Thus, for an intensity threshold level t and a window width w, the pixel intensity I is transformed into the grey scale value r according to:

$$r = \begin{cases} \beta I, t \le I \le t + w \\ 0, I < t \\ Q, I > t + w \end{cases} \qquad (14.2)$$

with $\beta = Q/w$.

14.6 IMAGE DISPLAY MANIPULATION

14.6.2 Windowing and thresholding

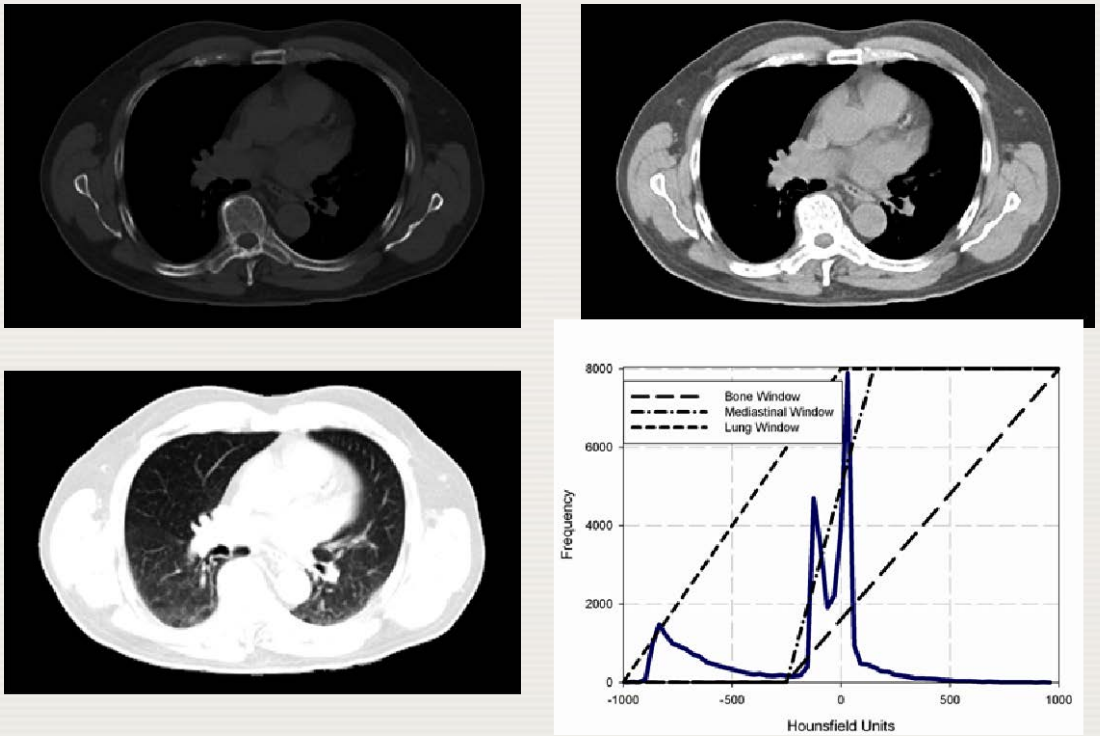
- Windowing and thresholding may be hardware implemented, i.e. the values may be changed by turning knobs on the monitor or the console or, more frequently, by software implementation using mouse movements, sliders or the arrows on the keyboard of the display workstation.
- The diagnostic value offered by windowing and thresholding can be appreciated when using typical CT windows for bone, mediastinum and lung.

14.6 IMAGE DISPLAY MANIPULATION

14.6.2 Windowing and thresholding

- This is shown for a trans-axial CT slice through the chest, together with the range of intensity values actually visualized out of the total histogram (Fig. 14.10).

FIG. 14.10. CT slice from Fig. 14.9 with typical lung and mediastinal windowing (upper row from left to right), a bone window (bottom left) and a histogram with corresponding linear window functions (bottom right).



14.6 IMAGE DISPLAY MANIPULATION

14.6.3 Histogram equalization

- Image intensity values may utilize the range of display intensities inefficiently. The CT slice of Fig. 14.9 is a typical example of a medical image and demonstrates that most of the intensity values are the Hounsfield units for soft tissue and the lung.
- Histogram equalization aims at utilizing each grey scale level available for display with the same frequency.

- If all intensity values were present in equal numbers in the image, the histogram would be flat, and the corresponding cumulative density function would increase linearly. A redistribution of intensity values s to approximately equally distributed grey scale intensity values r can be achieved using the transformation:

$$r_{eq} = \mathrm{CDF}(I) \times (Q-1)/(M \times N) \qquad (14.3)$$

where $\mathrm{CDF}(I)$ is the cumulative density function of the original image, Q is the range of grey scale values, and the image size is $M \times N$ pixels. For more details see [1].

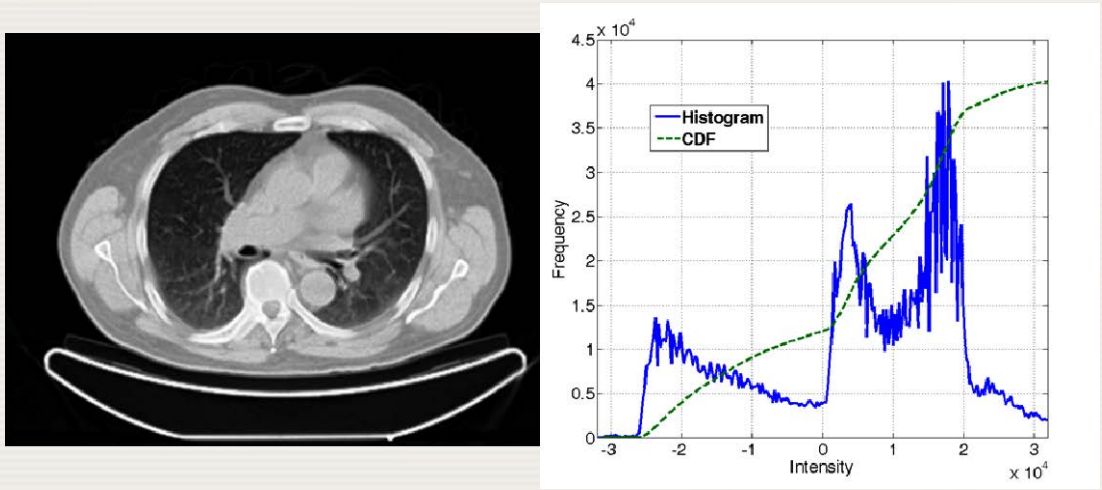
[1] SONKA, M., HLAVAC, V., BOYLE, R., Image Processing, Analysis, and Machine Vision, Brooks/Cole Publishing Company, Pacific Grove, CA (1999).

14.6 IMAGE DISPLAY MANIPULATION

14.6.3 Histogram equalization

- Figure 14.11 demonstrates the effect of histogram equalization using the standard algorithm of the image processing software package ImageJ [1] on the CT slice of Fig. 14.9.

FIG. 14.11. CT slice from Fig. 14.9 after histogram equalization with a corresponding intensity histogram, using only the pixels within the region surrounding the trunk. The number of bins is 256. The cumulative density function is now approximately linear. The intensity values are no longer related to Hounsfield units. Owing to the better distribution of the intensity values, all of the structures of interest, including the bone and the bronchi of the lung, are visualized simultaneously.



[1] http://imagej.nih.gov/ij/

14.6 IMAGE DISPLAY MANIPULATION

14.6.3 Histogram equalization

- In the processed image, the structures of both the bronchi of the lung and the ribs are visualized in the same image without underflow or overflow and with approximately the same information content as in the three windowed images of Fig. 14.10 together.
- The drawbacks of the method are that the visual appearance of an image depends on the shape of the histogram and may, therefore, be significantly different between patients, and the fact that the resulting intensity data can no longer be used to extract quantitative information (note that the x-axis values in the histogram are no longer CT numbers).

14.7 VISUALISATION OF VOLUME DATA

14.7.1 Slice mode

- An image volume data set consists of a series of adjacent image slices through the patient's body.
- The slices can be displayed sequentially with manual stepping through the images or automatically as a movie, or they can be displayed simultaneously as a montage of several images. Specialized viewing software offers easy ways to manipulate the display further and permits, for example, zooming and panning.
- Panning consists of quickly moving around a zoomed image too large to be displayed completely on the screen by utilizing the mouse, a joystick or a scroll wheel.

14.7 VISUALISATION OF VOLUME DATA

14.7.1 Slice mode

- Presenting the orthogonal views simultaneously on the screen facilitates the anatomical location of structures, especially with linked cursors which identify corresponding anatomical locations.

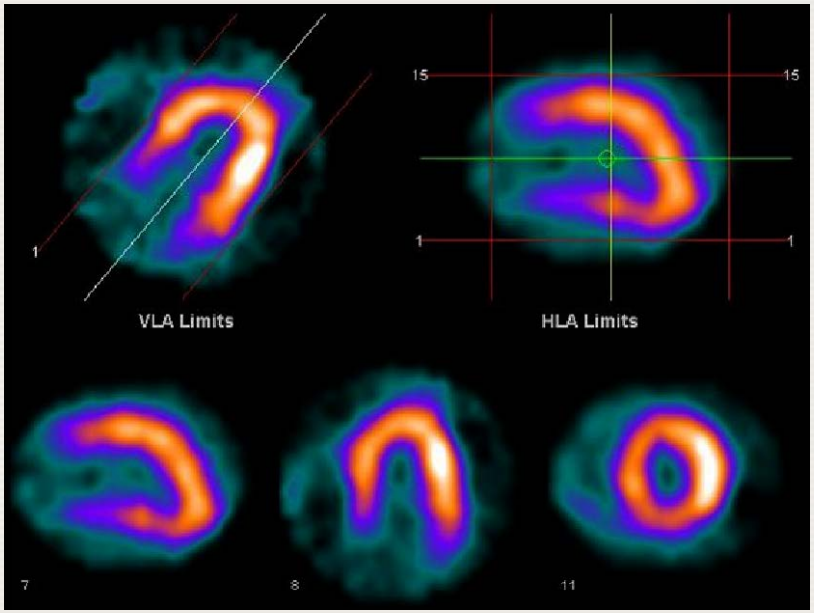


FIG. 14.12. Orthogonal views of myocardial perfusion SPECT with orientation of the slices along the long axis of the heart. The upper row shows an original trans-axial slice through the myocardium with the white line indicating the long axis (left) and a sagittal slice (right). The bottom row shows the reoriented views with the vertical and horizontal slices through the long axis, and a slice perpendicular to the long axis (from left to right). (Image courtesy of B. König, Hanuschkrankenhaus, Vienna.)

14.7 VISUALISATION OF VOLUME DATA

14.7.2 Volume mode

- Volume mode display refers to techniques which extract the information about structures in the 3-D image dataset by selecting intensity information directly from the volume dataset and projecting the selected values on the display screen.
- The ray casting technique projects a line from a viewpoint through the data starting from a pixel on the display screen. It calculates the value of interest using the image intensities along its path. The dominant ray casting geometry in nuclear medicine applications and in dual mode imaging is parallel projection. Another less commonly used technique is ‘splatting’ [1].

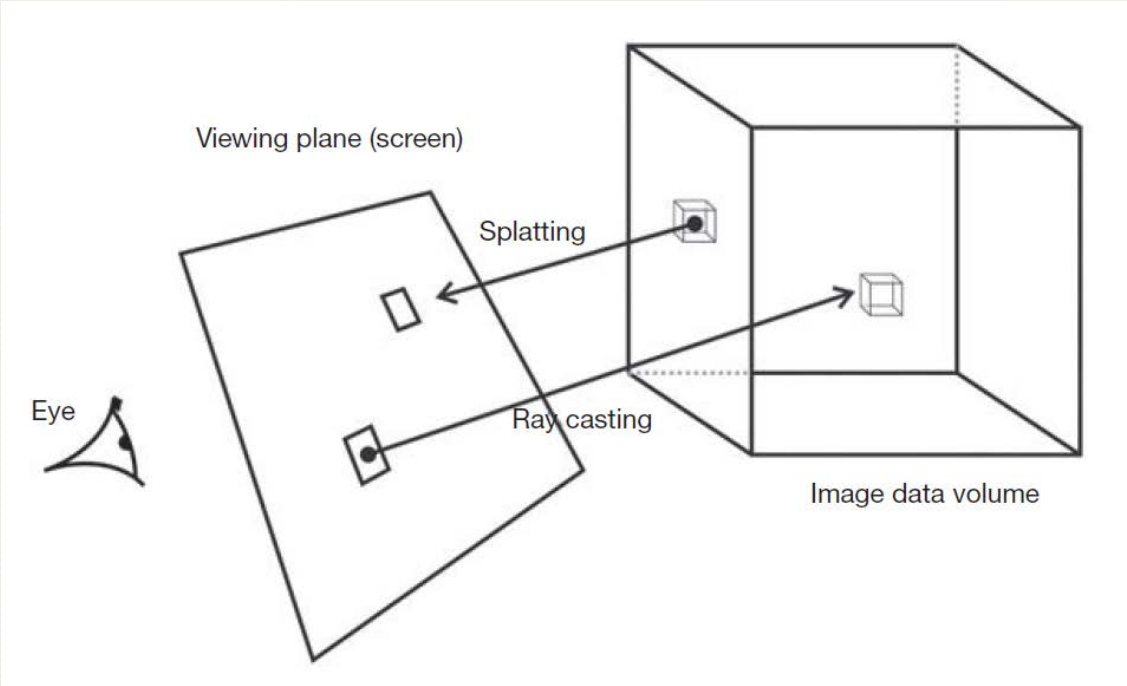
[1] BIRKFELLNER, W., et al., Wobbled splatting - a fast perspective volume rendering method for simulation of X-ray images from CT, Phys. Med. Biol. 50 (2005) N73–N84.

14.7 VISUALISATION OF VOLUME DATA

14.7.2 Volume mode

Transmission type volume rendering

FIG. 14.13. Principle of ray casting and splatting geometry. In ray casting, the ray collects intensity transformation throughout its trajectory. A voxel is usually hit outside its centre which has to be corrected for by interpolation. Splatting starts from the centre of a voxel and distributes its intensity on several screen pixels.



14.7 VISUALISATION OF VOLUME DATA

14.7.2 Volume mode

- Maximum intensity projection (MIP) consists of projecting the maximum intensity value encountered along the trajectory of the ray through the data volume on the corresponding screen pixel.
- It improves the visualization of small isolated hot areas by enhancing the contrast).
- MIP is successfully employed for lesion detection in PET oncological whole body studies. Its efficiency for the detection of lesions is further increased by displaying the MIP projections as a sequence of projection angles in cine mode.

14.7 VISUALISATION OF VOLUME DATA

14.7.2 Volume mode

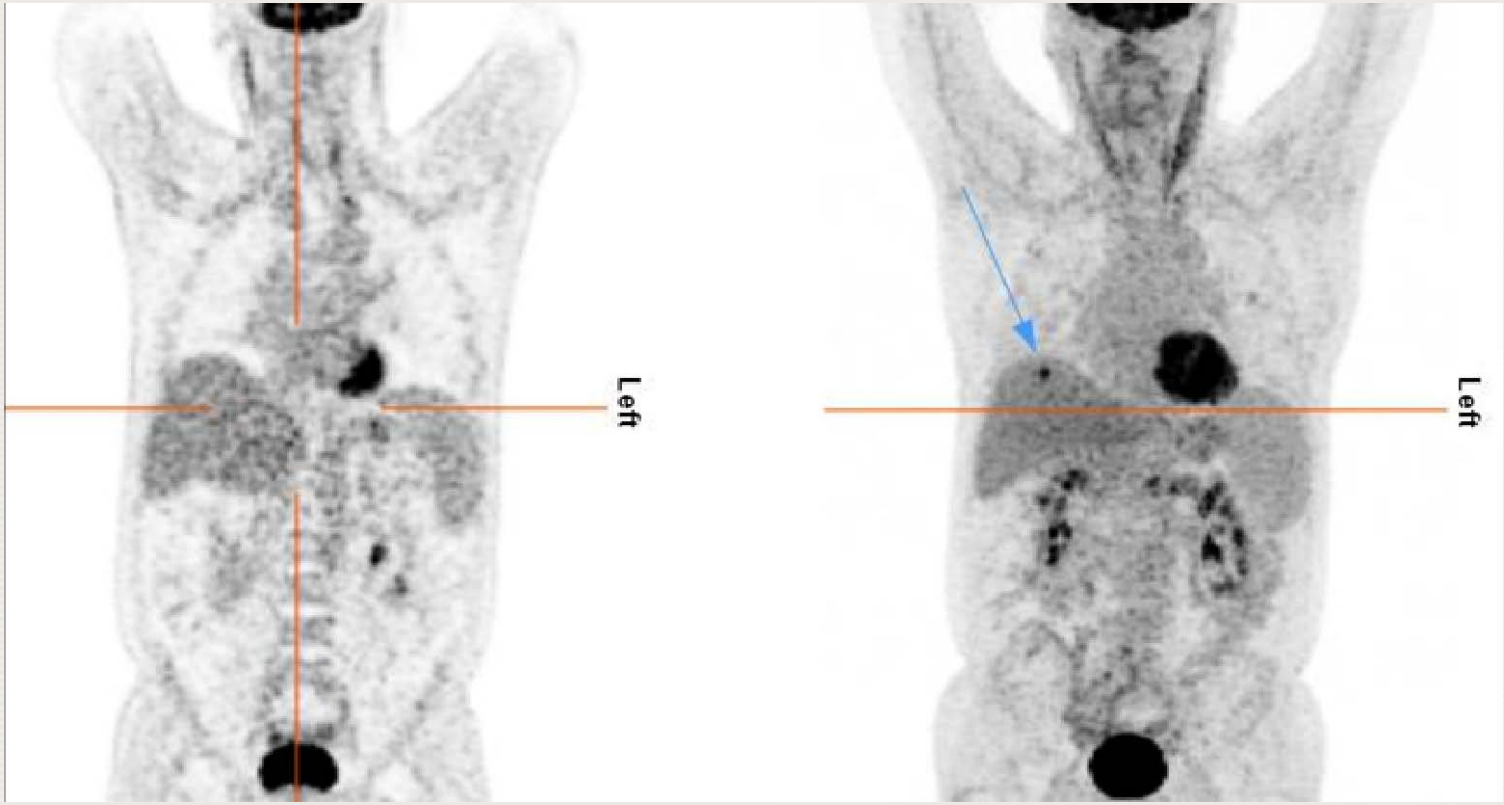


FIG. 14.14. A maximum intensity projection (right) compared to a standard coronal slice. A solitary lesion is clearly visible in the maximum intensity projection image (arrow) while it is missing in the coronal standard view.

14.7 VISUALISATION OF VOLUME DATA

14.7.2 Volume mode

- Summed voxel projection produces the rendered image by summing all intensities along a ray trajectory.
- If applied to a CT volume, it is known as a digitally rendered radiograph.
- If central projection geometry is used, the projection image simulates a conventional X ray image. Digitally rendered radiographs of CT data are used in radiotherapy for the positioning and registration of patients. Tomographic datasets from nuclear medicine displayed as digitally rendered radiographs may be used to compare lesion extensions with planar X ray images of the patient.

14.7 VISUALISATION OF VOLUME DATA
14.7.2 Volume mode

Reflection type volume and surface rendering

- The purpose of surface and volume rendering is to visualize structures in volume datasets as objects and display them in a pseudo-3-D mode.
- Volume rendering techniques extract information about objects directly from the 3-D volume data. They start by casting rays through the image volume data and by processing the intensities of the voxels along the ray trajectory.
- Depending on the handling of the intensities, different types of 3-D display can be generated.

14.7 VISUALISATION OF VOLUME DATA

14.7.2 Volume mode

- Three dimensional rendering utilizes standard computer graphics techniques, such as illumination, shading and the application of textures, to produce a realistic appearance of anatomical structures and tumours.
- This is useful for the visualization of complex anatomical relationships, can improve the orientation of surgeons and resolve ambiguities of localization.

14.7 VISUALISATION OF VOLUME DATA

14.7.2 Volume mode

- For registered images originating from different imaging techniques, such as MRI and PET, anatomical and functional data can be displayed simultaneously, thereby taking advantage of the excellent morphological resolution of one modality and of functional, blood flow or metabolic information of the other modality.
- Such combined images are capable of displaying the spatial relationships between different objects, such as, for example, the surface of the left ventricle and the location of the coronary arteries, or the surface of the brain grey matter rendered from MRI combined with the blood flow obtained by HMPAO SPECT.

14.7 VISUALISATION OF VOLUME DATA

14.7.2 Volume mode

- In surface rendering, 3-D surfaces are generated by specifying an intensity threshold. The method is closely related to the generation of contours. When a ray encounters the threshold value along its trajectory, the location of that voxel is interpreted as a surface point of the structure of interest. The surface is then represented as a mosaic of triangles.
- The appearance of a 3-D image is improved further by utilizing illumination and shading techniques. To apply these effects, additional knowledge about the orientation of the surface element is required for which gradient techniques are employed.

14.7 VISUALISATION OF VOLUME DATA

14.7.2 Volume mode

- Voxel gradient shading is the most successful technique to produce illuminated and shaded surfaces. It calculates a gradient vector from a voxel neighbourhood and renders a realistic pseudo-3-D image by calculating diffuse reflective illumination from an external light source and applying shading. Noise in the surface is reduced by smoothing (Fig. 14.15 middle).

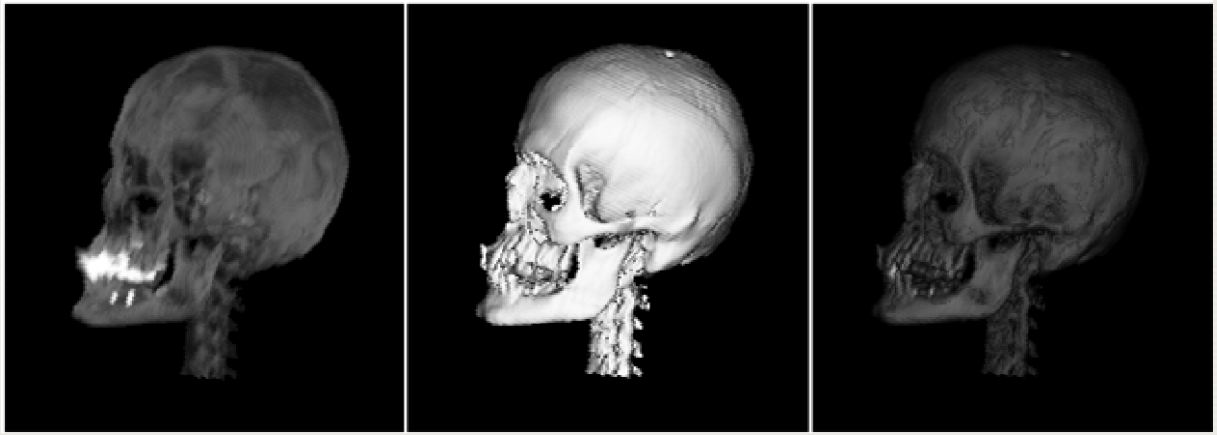


FIG. 14.15. Surface of a skull from CT image data using (from left to right) maximum intensity projection, voxel gradient shading and volume compositing for rendering. Rendered images were produced with ANALYZE© 9.0.

14.7 VISUALISATION OF VOLUME DATA

14.7.3 Polar plots of myocardial perfusion imaging

- Myocardial perfusion imaging is a tomographic technique using a myocardial perfusion tracer such as the potassium analogue ^{201}Tl or ^{99m}Tc-MIBI to produce SPECT images of the perfusion of the left ventricle.
- Myocardial perfusion is reduced or absent in ischaemic and infarcted areas. The size and severity of perfusion defects is of high diagnostic and prognostic value.
- Display methods tailored to the reliable detection of perfusion defects were developed shortly after the introduction of myocardial perfusion SPECT.

14.7 VISUALISATION OF VOLUME DATA

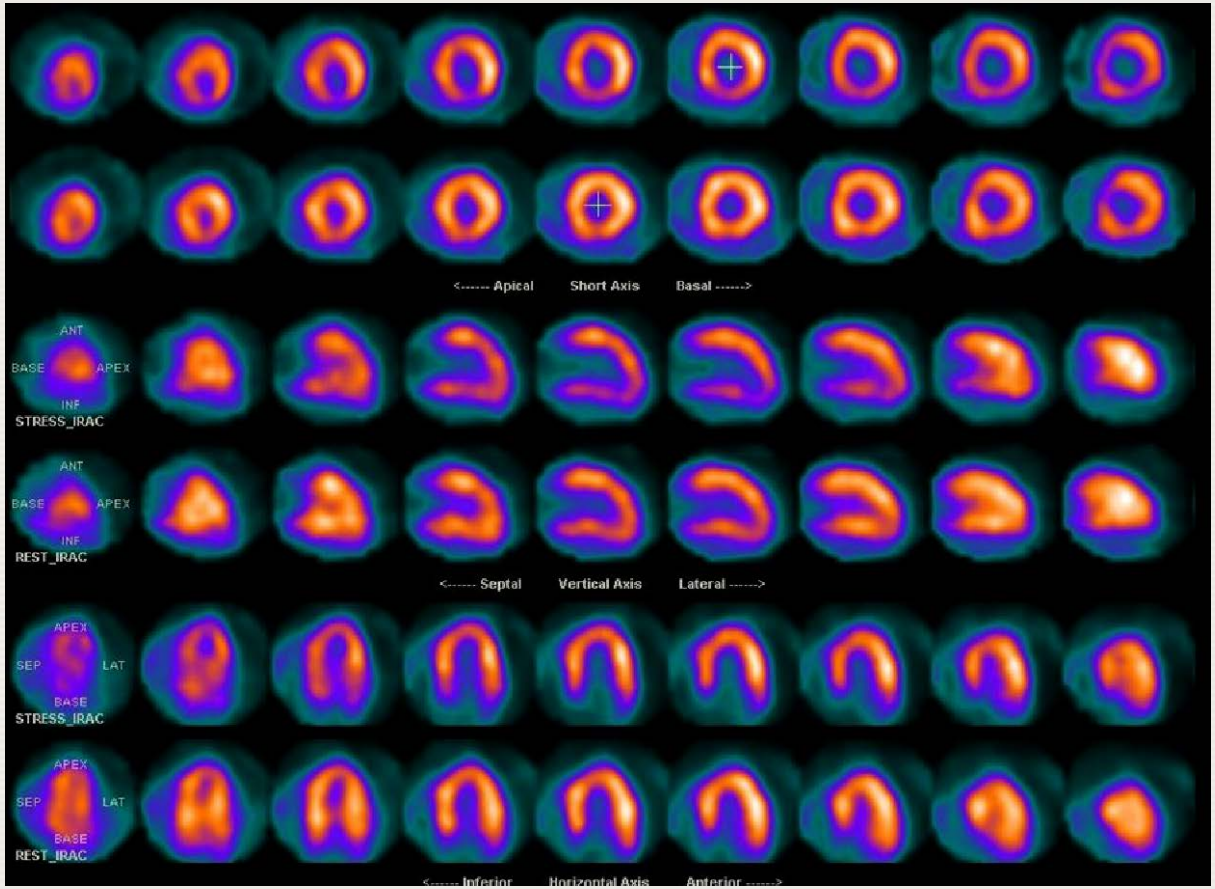
14.7.3 Polar plots of myocardial perfusion imaging

- The initial visual presentation of the tomographic images makes use of a coordinate system natural to the anatomy of the left ventricle.
- One coordinate axis passes through the long axis of the heart; the other two are perpendicular to the long axis and to each other (Fig. 14.16 next slide).
- The standard display consists of slices perpendicular to the long axis, the short axis slices and two sets of slices parallel to the long axis.

14.7 VISUALISATION OF VOLUME DATA

14.7.3 Polar plots of myocardial perfusion imaging

FIG. 14.16. Results of a stress–rest perfusion study with 99mTc-methoxyisobutylisonitrile (MIBI) with the orientation of slices adapted to the long axis of the heart. Images show hypo-perfusion of the inferior wall. The upper rows are stress images; the lower rows are images at rest. (Image courtesy B. König, Hanuschkrankenhaus, Vienna.)



14.7 VISUALISATION OF VOLUME DATA

14.7.3 Polar plots of myocardial perfusion imaging

- The left ventricle has an annular shape in the short axis slices. These annuli can be aggregated into one image using a polar map representation.
- First, each annulus is reduced to a circumferential profile, e.g. by taking the maximum intensity or mean intensity at each angular step.
- Arranging all of the profiles into one image, starting with the profile representing the apex at the innermost position, with each following profile surrounding the previous one, results in the bull's-eye display or polar map (Fig. 14.17 next slide).

14.7 VISUALISATION OF VOLUME DATA

14.7.3 Polar plots of myocardial perfusion imaging

- The term ‘polar’ map refers to the fact that the intensity along a given annulus is displayed in a polar coordinate system. The intensities displayed for each annulus correspond to the perfusion in that slice / segment.

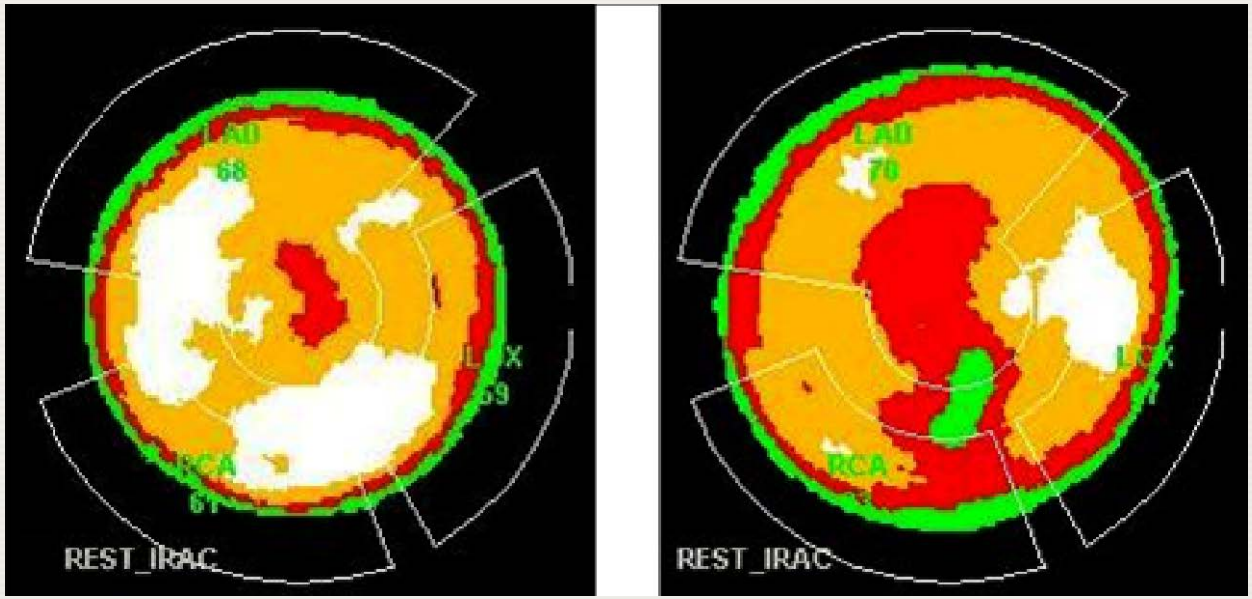


FIG. 14.17. Bull’s-eye displays of myocardial perfusion. Normal perfusion (left), hypo-perfusion of inferior wall (right). The colours indicate the degree of perfusion: white - normal, orange - acceptable, red - hypo-perfused and green -no perfusion. Also indicated are the perfusion areas for the main coronary vessels LAD, LCX and RCA. (Courtesy B. König, Hanuschkrankenhaus, Vienna.)

14.7 VISUALISATION OF VOLUME DATA

14.7.3 Polar plots of myocardial perfusion imaging

- Absolute perfusion values cannot be derived from the intensities. The method to obtain an estimate of the degree of hypo-perfusion and of the location of the perfusion defect consists of comparing the relative intensity values in different segments of the annuli to the maximally perfused segments of the same patient, and then comparing the pattern of relative perfusion of the individual study with normal perfusion patterns.
- This permits an estimate of both the degree and extent of the perfusion defects as well as a good anatomical allocation to the coronary arteries causing the hypo-perfusion.

14.8 DUAL MODALITY DISPLAY

- Several techniques have been developed to display registered images originating from different modalities, such as from a PET/CT study.
- The simplest technique is to display the images belonging together side by side. Anatomical information can be gained easily by using the linked cursor technique. The CT image which has superior spatial resolution is, thus, used to determine the anatomical location of a lesion visible in the PET image.
- The linked cursor technique, while providing precise anatomical information, is impractical if several lesions are present in the image.

14.8 DUAL MODALITY DISPLAY

- When several lesions are present, alpha blending is helpful, which combines both the CT and the PET image into one composite image.
- Alpha blending consists of adding the images pixelwise with different weight. The weight is called the transparency factor α, with $0 \leq \alpha \leq 1$. The composite pixel I_{CS} is given by:

$$I_{CS}(m,n) = \alpha \times I_{BG}(m,n) + (1-\alpha) \times I_{FG}(m,n) \qquad (14.4)$$

where I_{BG} is the intensity of the background pixel and I_{FG} is the intensity of the foreground pixel.

14.8 DUAL MODALITY DISPLAY

- When using the native grey scale images for both modalities, it is difficult to distinguish which intensity comes from which modality. This is easier if one of the images uses a CLUT, e.g. applying Eq. (14.4) to each colour component separately:

$$R_{CS}(m,n) = \alpha \times R_{BG}(m,n) + (1-\alpha) \times I_{FG}(m,n) \quad (14.5)$$

$$G_{CS}(m,n) = \alpha \times G_{BG}(m,n) + (1-\alpha) \times I_{FG}(m,n) \quad (14.6)$$

$$B_{CS}(m,n) = \alpha \times B_{BG}(m,n) + (1-\alpha) \times I_{FG}(m,n) \quad (14.7)$$

where R, G and B are the colour components of the background image and I is the grey value of the foreground image.

14.8 DUAL MODALITY DISPLAY

- In PET/CT alpha blending, the background image is usually the PET image whereas the CT image as the foreground image retains the grey scale (Fig. 14.18).

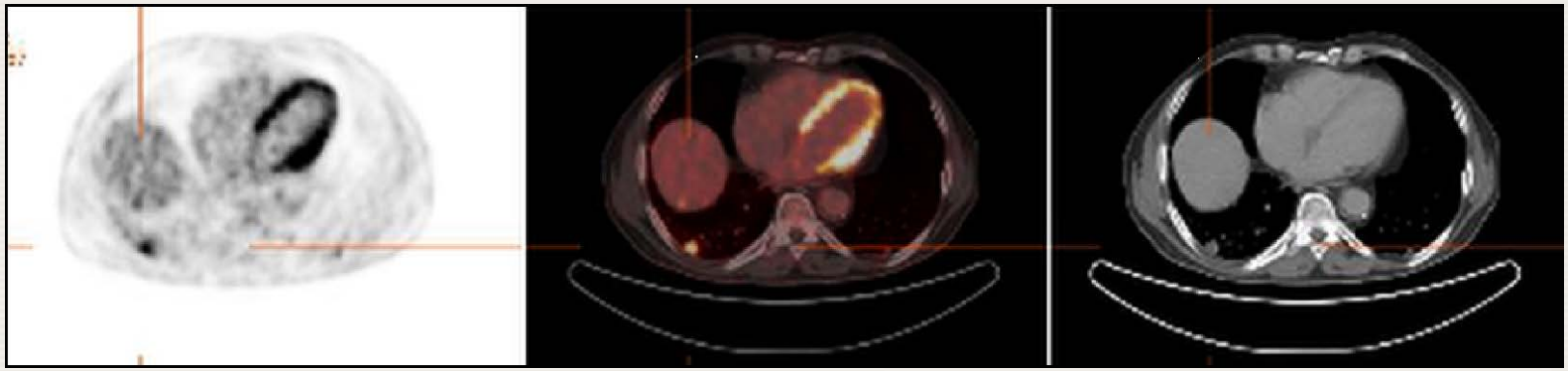


Fig. 14.18. PET/CT fused image display with a PET image on the left showing a hot lesion at the border between the lung and rib cage. The fused image in the middle shows the location inside the lung close to the pleura; the CT image on the right confirms and permits close inspection of the position. Linked cursors point to the position of the lesion. The transparency factor α is 0.5.

14.8 DUAL MODALITY DISPLAY

- The composite display can be further improved by changing thresholds and windows for each modality separately and interactively.
- For CT, the traditional windows are usually employed.

14.9 DISPLAY MONITOR QUALITY ASSURANCE

- Several standards define the performance parameters of display systems (see, for example, Refs [1, 2]).
- Report No. 18 of the American Association of Physicists in Medicine (AAPM) task group TG18 offers an exhaustive up to date set of performance parameters for current medical display monitors, together with procedures and accompanying test images to assess performance [3].
- It contains limits of acceptance for all parameters, distinguishing between primary devices and secondary devices.

[1] DIN V 6868-57. DIN V 6868-57: Sicherheit der Bildqualität in röntgendiagnostischen Betrieben, Teil 57: Abnahmeprüfung an Bildwiedergabegeräten, Normenausschuß Radiologie (NAR) im DIN Deutsches Institut für Normung e.V. (2001).

[2] VIDEO ELECTRONIC STANDARDS ASSOCIATION, Flat Panel Display Measurement Standard, Version 2, Milpitas, CA (2001).

[3] AMERICAN ASSOCIATION OF PHYSICISTS IN MEDICINE, Task Group 18 (TG18), Assessment of Display Performance for Medical Imaging Systems, AAPM On-Line Report No. 03, College Park, MD (2005).

14.9 DISPLAY MONITOR QUALITY ASSURANCE

- In addition to quality assurance aimed at the individual display device, a major component of quality assurance is to ensure a consistent display of the image at all display workstations of a PACS, including different ambient light conditions.
- This is resolved by including the calibration and validation of the DICOM GSDF into the quality assurance framework.
- Quality control of CRT and LCD display devices is required at regular intervals because the performance may change over time, due to ageing processes of the display device, and due to changes in environmental lighting with time.

14.9 DISPLAY MONITOR QUALITY ASSURANCE

14.9.1 Acceptance testing

- The purpose of acceptance testing is to ensure that the performance of purchased equipment complies with the specifications established in the sales contract.
- The user should clearly specify in the contract the required performance, the test procedures to assess the performance parameters and the limits of acceptability.
- Ref. [1] lists a set of performance parameters which completely characterize the performance of a soft copy display device. These are summarized in Table 14.2 (next slide).

[1] AMERICAN ASSOCIATION OF PHYSICISTS IN MEDICINE, Task Group 18 (TG18), Assessment of Display Performance for Medical Imaging Systems, AAPM On-Line Report No. 03, College Park, MD (2005).

14.9 DISPLAY MONITOR QUALITY ASSURANCE

14.9.1 Acceptance testing

TABLE 14.2. PERFORMANCE PARAMETERS OF DISPLAY MONITORS AND EQUIPMENT FOR MEASUREMENT (according to AAPM, Task Group 18)

Test	Major required tools	
	Equipment	Patterns
Luminance response	Luminance and illuminance meters	TG18-LN, TG18-CT, TG18-MP
Luminance dependencies	Luminance meter	TG18-UNL, TG18-LN, TG18-CT
Reflection	Luminance and illuminance meters	TG18-AD
Resolution	Luminance meter, magnifier	TG18-QC, TG18-CX, TG18-PX
Geometric distortions	Flexible ruler or transparent template	TG18-QC
Noise	None	TG18-AFC
Veiling glare	Baffled funnel, telescopic photometer	TG18-GV, TG18-GVN, TG18-GQs
Chromacity	Colorimeter	TG18-UNL80

14.9 DISPLAY MONITOR QUALITY ASSURANCE

14.9.1 Acceptance testing

- For each of the parameters, several tests at various levels of sophistication are described in detail. Most of the parameters can be assessed visually by analysing the test images listed in Table 14.2, possibly with additional use of templates on transparency sheets, such as for the assessment of distortions.
- An exhaustive set of test images has been made electronically available for these tests, both in Joint Photographic Experts Group (JPEG) and DICOM format.

14.9 DISPLAY MONITOR QUALITY ASSURANCE

14.9.1 Acceptance testing

- For quantitative tests, such as for the calibration of luminance characteristic curves, of the DICOM GSDF and of chromaticity values, luminance meters and colorimeters with computer readout of the measured values and special software are necessary.

14.9 DISPLAY MONITOR QUALITY ASSURANCE

14.9.2 Routine quality control

- To ensure that a display system meets the expected performance during its economic lifetime, assessment of performance parameters at regular intervals is necessary. AAPM recommends a subset of the tests in Table 14.2, namely geometric distortions, reflection, luminance response, luminance dependencies, resolution and chromaticity be performed at monthly to quarterly intervals, depending on the monitor's stability.
- Tests for geometric distortions and for resolution are more important for CRTs, whereas the dependence of luminance on the viewing angle is important only for LCD displays.

14.9 DISPLAY MONITOR QUALITY ASSURANCE

14.9.2 Routine quality control

- In addition, AAPM recommends that a daily check prior to clinical work be performed by the user. It consists of evaluating anatomical test images or a suitable geometrical test image such as a TG18-QC test image (Fig. 14.19) to verify adequate display performance.

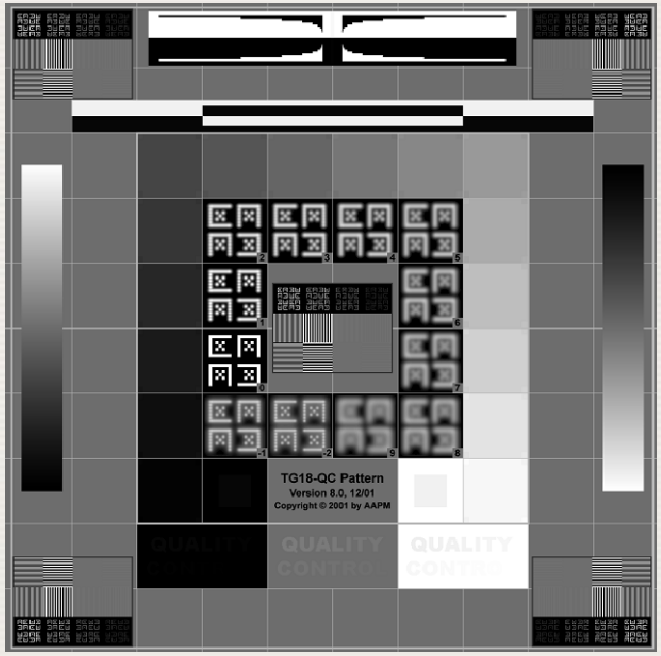


FIG. 14.19. Test pattern TG18-QC suitable for daily quality control of display monitor performance using visual inspection.

14.9 DISPLAY MONITOR QUALITY ASSURANCE

14.9.2 Routine quality control

Box 14.1. Instructions for visual assessment of image quality using the TG18-QC test pattern as part of daily quality control by the user [14.23]

1. General image quality and artefacts: Evaluate the overall appearance of the pattern. Note any non-uniformities or artefacts, especially at black-to-white and white-to-black transitions. Verify that the ramp bars appear continuous without any contour lines.
2. Geometric distortion: Verify that the borders and lines of the pattern are visible and straight and that the pattern appears to be centered in the active area of the display device. If desired, measure any distortions (see section 4.1.3.2).
3. Luminance, reflection, noise, and glare: Verify that all 16 luminance patches are distinctly visible. Measure their luminance using a luminance meter, if desired, and evaluate the results in comparison to GSDF (section 4.3.3.2). Verify that the 5% and 95% patches are visible. Evaluate the appearance of low-contrast letters and the targets at the corners of all luminance patches with and without ambient lighting.
4. Resolution: Evaluate the Cx patterns at the center and corners of the pattern and grade them compared to the reference score (see section 4.5.3.1). Also verify the visibility of the line-pair patterns at the Nyquist frequency at the centre and corners of the pattern, and if desired, measure the luminance difference between the vertical and horizontal high-modulation patterns (see section 4.5.3.1).

14.9 DISPLAY MONITOR QUALITY ASSURANCE

14.9.2 Routine quality control

- The most frequent influence on reporting comes from changes in ambient lighting. An increase in the level of ambient light results in poorer discrimination of structures in the darker parts of the image. This has to be compensated for by adapting the GSDF to the current light level.
- Modern medical display monitors, therefore, provide automatic measurement and recalibration features.

14.9 DISPLAY MONITOR QUALITY ASSURANCE

14.9.2 Routine quality control

- A typical, high performance LCD display used as a primary device includes a luminance meter covering a small area of the monitor to continuously control the display characteristic curve and the maximum brightness level.
- A second photometer records the average ambient lighting. With such an arrangement, it is possible to adjust the GSDF continuously to the DICOM required luminance values, taking into account the changes in L'_{min} and L'_{max}, the minimum and maximum luminance values including the luminance L_{amb} added by ambient light.

14.9 DISPLAY MONITOR QUALITY ASSURANCE

14.9.2 Routine quality control

- As an annual quality control of a display device, the AAPM TG18 working group recommends performing all tests carried out during acceptance.