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Digital imaging in radiology practice: An introduction to few fundamental concepts

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Digital imaging is integral to current radiology practice, wherein images are acquired, processed, post-processed, and displayed in black and white, grayscale, or color, using binary numbers.

The sources of digital images in radiology are varied and diverse when compared with other specialities. They comprise imaging equipment such as USG, computed radiography (CR), digital radiography (DR), CT scan, MRI, PET/CT and the like; input devices such as digital cameras or scanners, interface graphics hardware connecting these devices with computers; and output devices such as printers, monitors, and video projectors.[1] In such circumstances, digital images can be viewed on a monitor, manipulated by basic and advanced post-processing, printed on paper/laser films, archived on CD/DVDs, or transferred across networks.

Besides radiology, digital imaging is important to other 'image-handling' medical specialties, such as anatomy, pathology, ophthalmology, etc. Evidently, outside medical sphere, it is considered important in diverse professional fields such as astronomy, arts and museum, publishing, photography, media, cinema, remote sensing, and satellite imagery, etc., all of which exclusively deal with photographs, images, artwork, manuscripts, printed texts, and pictures.

Here is an elemental question to begin with: What endears digital imaging to such a wide-ranging variety of vocations and professions? The answer lies in the powerful advantages that it inherently offers, which comprise:[2]

a) **Robustness**: Digital images 'do not deteriorate physically or degrade chemically over time.'[2].
b) **Consistency**: Digital images allow true reproduction quality 'from copy to copy and from generation to generation.'[2]
c) **Flexibility**: Digital images allow a variety of manipulation,[3] e.g., magnification, cropping, edge enhancement, compression, swapping colors, etc.
d) **Featured contents**: Digital images may be 'easily linked to textual descriptions and catalog records.'[2] In radiology, DICOM is a typical example using this attribute.
e) **Communicability**: Access, transfer, and storage of digital images is possible within existing computer, network, wireless, cell phone, and internet technologies.

Performance parameters

Digital imaging has a few important performance parameters such as pixels, grayscale, bit-depth, resolution, color, and file size. Their basic concepts are dealt with in this article. To begin with, it is relevant to note that these parameters are distinctly different for image acquisition equipment as compared to image output and viewing devices.

1. Pixels

Digital images are essentially 'electronic snapshots'[4] of a rectangular grid, containing individual picture elements or pixels. The pixel is the foundation block of digital imaging. It is the smallest complete sample of an image. A *screen* pixel is 'the smallest area that a particular combination of software and hardware can illuminate on a monitor.'[5] A *printer* pixel is 'the smallest dot the printer can produce.'[5]

Every pixel has a varied set of tones. These tones are blackor white, or shades of gray or color. A tonal value is allotted for the different tones in binary code, uniquely as zeros or ones. The binary digits for each pixel are termed as 'bits.'[4] Intrinsically, each pixel in a digital image has a bit-depth value, which will be discussed a little later. All the individual pixels with their tonal value combine collectively to create a digital image.[6]

Number crunching in practice: Pixel size is a measure of resolution, wherein the smaller the pixel, better the resolution. In radiography, depending on the equipment and type of model, pixel size in CR ranges from 50 to 200 microns, in DR from 100 to 200 microns, and in full- field digital mammography, from 50 to 100 microns. The pixel dimension is conventionally derived from the product of the number of pixels.

Pixel dimension in devices such as digital cameras, is expressed as the number of pixels horizontally and vertically (for example 2048 by 3072), which defines also the number of its sensor elements. Since digital camera images are large, their sizes are expressed in terms of 'megapixels,' where 1 megapixel represents 1 million pixels. For scanned documents, the pixel dimension is the document dimension multiplied by the dpi (dots per inch). Thus an 8 in × 10 in document that is scanned at 300 dpi has pixel dimensions of 2400 pixels by 3000 pixels.[7]

When it comes to computer monitors, the pixel numbers are dependant on the aspect ratio of the screen (its horizontal size compared to the vertical size) and the display size. Standard monitors, with a 4:3 aspect ratio have a width of 1024 pixels and a height of 768 pixels or other combinations like 1280 x 1024, 800 x 600 etc. Widescreen display monitors with a 16:9 aspect ratio, have a width of 1024 pixels and a height of 576 pixels or other combinations like 1680 x 1050,1280 x 768 etc. Pixels per inch (PPI) or pixel density is related to display size in inches and the total number of pixels in the horizontal and vertical directions. This is the measurement of the resolution of a computer display. To illustrate, a monitor display measuring 11 in by 8.5 in, with a maximum 1024 by 768 pixel resolution, displays about 93 pixels per inch in both horizontal and vertical directions.

2. Grayscale

Grayscale images are different from 'black and white' images. Unlike the latter, which have two colors (black, white), grayscale images have a number of shades of gray in between. These shades of gray that compose an image range from pure black at the weakest intensity to pure white at the strongest.

Number crunching in practice: For routine visual display, grayscale images contain 8 bits per sampled pixel. This 'allows 2^8 or 256 intensities (shades of gray) to be recorded, typically on a nonlinear scale.'[8] However, more shades of gray are required in medical imaging and therefore up to 16 bits per sample are necessary, which allows 2^{16} or 65536 gray levels.[7]

3. Bit-depth

Bit-depth indicates the shades of gray used to define each pixel. It is commonly measured as 'number of bits.' A larger bit-depth implies a greater number of grayscale or color tones in an image as well as a larger file size.[2] In imaging, variable bit-depth is used at three levels: in acquisition, during processing, and in display.

Number crunching in practice: Bit-depths of images are, as a rule, determined by the type of image (black and white, gray, or color), the bit-depth (number of bits per pixels), and the number of tones per pixel. These determinants are outlined in Table 1.

4. Color

While, the bulk of radiology practice is performed in grayscale, there is a growing trend towards using virtual color, in color Doppler, CT, and MRI, particularly during post-processing.

A color model called RGB (red, green, blue) is commonly used for generating on-screen color in televisions, computer monitors, and film recorders. In this model, also called as an 'additive' color model, three different phosphors are displayed on a monitor screen.[6] Here the pixel is a red, green, and blue phosphor dot, which when struck by an electron beam causes it to emit light of the same colour. A 'range of colors is emitted by varying which phosphor dots

Table 1: Basic types of images and bit depth[2,9]

No	Image type	Bit depth (number of bits/pixel)	Number of tones per pixel	Remarks
1	Grayscale	2 to 8 bits/pixel		
		2 bits/pixel in the most basic form	2^2 or 4 tones/pixel	4 possible combinations of tones/pixel; 2 bits of 0 and 1 offers 4 combinations, namely 00, 01, 10, and 11 If '00' is black and '11' is white, then '01' equals dark gray and '10' equals light gray
		8 bits/pixel	2^8 or 256 tones/pixel	256 different shades
2	Color	8 to 32 bits/pixel	24 bit image offers 2^{24} or 16.77 million color tones	With 24-bit color image, bits are divided into three groupings: 8 red, 8 green, and 8 blue 16 bit is termed high color 24 bit is termed true color

are struck and at what intensity'.[10] By their excitation at different intensities, the resulting mix is perceived as color by the human eye.[6]

In comparison, color printing on paper uses a 'subtractive' color model termed CYMK (cyan, yellow, magenta, black).[11] These combine on paper with a filter action absorbing few wavelengths of light while reflecting the remainder into the human eye.[6] Fundamentally, the two color models are differentiated by the mechanism of color creation.[12] While the RGB mode is based on the presence of a light source for creation of the image, the CMYK mode is based on the creation of the image on a reflective surface such as paper.

Number crunching in practice: Color has attributes of pixel depth, too. On a computer monitor, for viewing a simple black and white image, only 1 bit for each pixel is needed. However, for grayscale images, an 8 bit mode offering 256 shades of gray is adequate. For viewing color images on color monitors, PC video cards today support 24 bits to each pixel, resulting in a display of 224 or 16,777,216 colors.[13]

5. Spatial resolution

It describes the ability to distinguish fine spatial detail and to differentiate objects in an image. Broadly, in digital acquisition systems, resolution is governed by a term called spatial frequency which is used while sampling a digital image. Resolution implies how frequently an object is sampled. As a rule of thumb, a) increasing the sampling frequency helps to increase resolution and b) images composed with a greater number of pixels have a higher spatial resolution. On the flip side, images with higher resolution require larger file sizes [Figure 1 A to C].[2,14]

As regards specific radiology equipment, several unique factors determine their spatial resolution. In conventional radiography with X-rays, spatial resolution is determined by the focal spot size of the X-ray tube and film screen combination characteristics. In USG, spatial resolution depends on various factors such as the size of the active aperture of a transducer, center frequency, pulse length, the selected transmit focal depth and, to some extent, the bandwidth and attenuation. Furthermore in USG, axial resolution is generally better than lateral resolution.

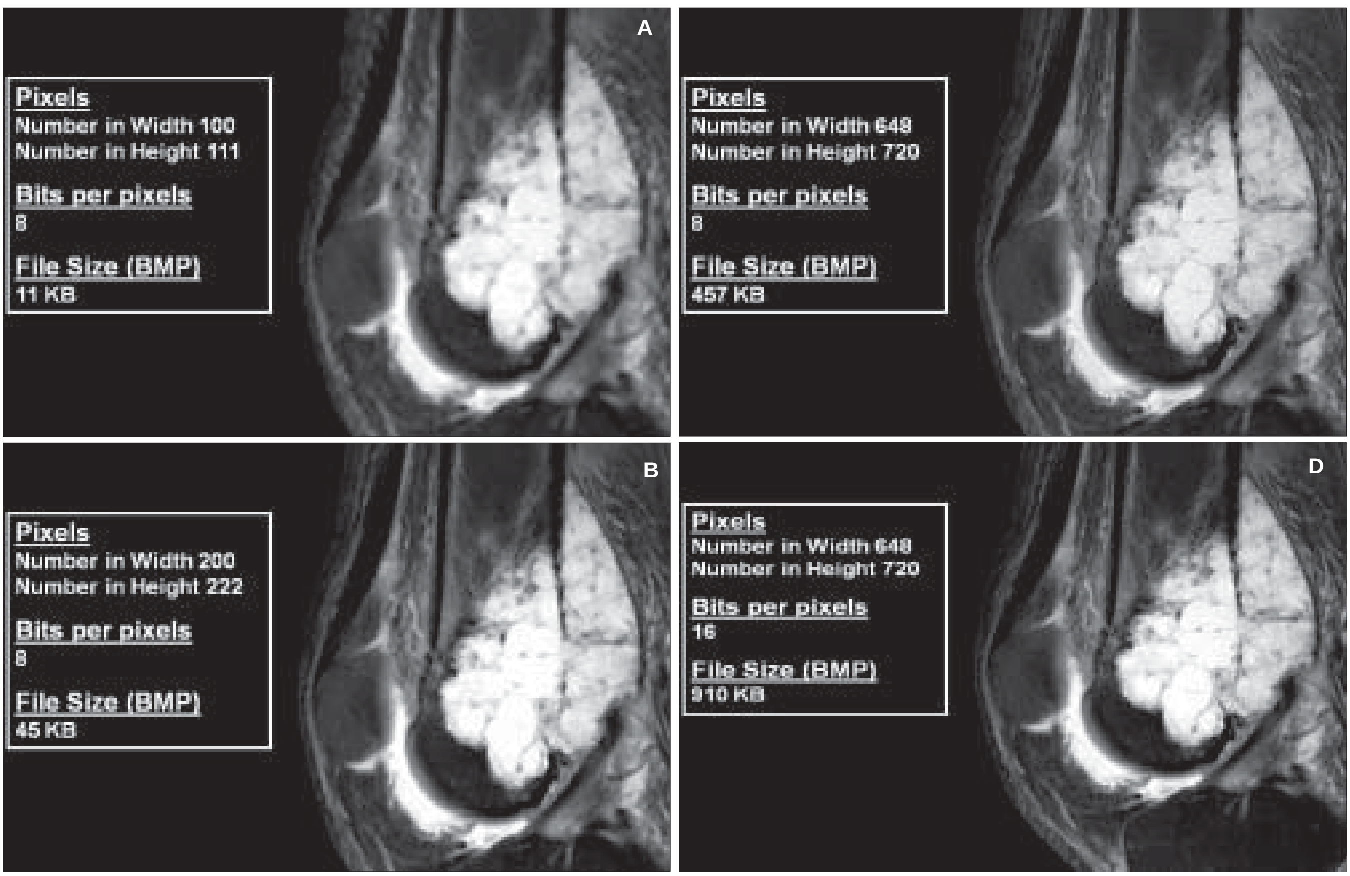

Figure 1 (A-D): Resolution and file size in a case of Ewing's sarcoma of the femur. Proton-density, fat-suppressed sagittal 3T MR images reveal that the image composed with a greater number of pixels has a higher spatial resolution and a larger file size. 'A' has 100 and 111 pixels, resulting in a BMP file of 11 KB size; 'B' has 200 and 222 pixels resulting in a BMP file of 45 KB size; 'C' has 648 and 720 pixels resulting in a BMP file of 457 KB size. This high-resolution image displays superior details of tumor matrix as well as multiple breaks in the posterior femoral cortex. 'D' has 648 and 720 pixels, but the number of bits per pixel has increased from 8 to 16, resulting in a large BMP file of 910 KB size. There is no appreciable difference in quality between 'D' and 'C,' demonstrating that 8 to 16 bits per pixel are often adequate for medical displays

In CT scanning, the spatial resolution is determined at two levels: the quality of the projection raw data and the reconstruction method. Projection data is influenced by geometric factors such as focal spot size, collimation, x-ray beam sampling, table speed, detector width, and detector crosstalk. Reconstruction is affected by the spiral interpolation algorithm, field of view, zoom factor, filters or kernel, and analysis in the in-plane or cross-plane directions.

In MRI, spatial resolution is determined by varied factors, such as the gradient or shape of the magnetic field, the number of phase-encoding steps, the field-of-view (FOV) selected, and the presence or absence of physiological motion.

Significantly, the image resolution in capturing devices is not synonymous with the image resolution of output devices such as computer monitors or printers.[6] In conventional radiography, the resolution is commonly expressed in line pairs per millimeter (lp/mm), whereas in film digitizers, the resolution is commonly expressed as dpi.[15] In general, for capturing devices, the image resolution is expressed as ppi (pixel per inch) and for output devices as dpi.[4]

Number crunching in practice: Spatial resolution in digital acquisition systems is expressed using the descriptors: pixel size, pixels/mm, or line pairs per mm (lp/mm). Line pairs per millimeter are a measure of resolution, wherein pairs of lines are closely approximated. The unaided human eye is capable of distinguishing about 10 to14 lp/mm. Higher resolution is indicated by identifying more lines placed within a millimeter.

So how does one integrate pixel size, pixels/mm, or line pairs per mm for a given digital acquisition system? To illustratively answer this, a digital system with a detector of 50 micron pixel size has a pixel pitch equivalent of 0.05 mm, which is the same as 20 pixels per mm or 10 line pairs per mm.

Regarding output devices, the typical resolution is 1280 × 1024 pixels for high-end video projectors,[12] 300–1200 dpi for laser printers, 1440 dpi for inkjet printers, and 300 dpi for dye-sublimation printers.[6] At a printer resolution of 300 dpi, each square inch is made up of 300 × 300 or 90,000 pixels. At 256 grayscale levels, with one byte per pixel, the information amounts to 90,000 bytes or 90 KB per square inch of image.[16]

6. Contrast resolution

It refers to the amount of grayscale or color differentiation that exists in an image. Contrast resolution is particularly an issue during imaging inherently low-contrast objects as breast masses and pulmonary nodules.[17] For digital image acquisition equipment, this means the number of shades of gray that a detector can capture.

In practice, the detectors of digital X-ray equipment have significant advantages over conventional film/screen imaging. Due to their wide dynamic range, a wide range of low-to-high signal intensities can be captured and due to their high contrast resolution, thousands of shades of gray can be displayed.[17] The spatial resolution of newer digital acquisition equipment such as CR and DR is comparable to each other, but less than film-screen radiography. The superior contrast resolution of digital modalities more than compensates for the reduced spatial resolution.[18]

A related term in contrast is 'dynamic range.' This term describes the range of tonal difference 'between the lightest light and darkest dark of an image.'[19] Dynamic range, in actuality, describes a digital system's ability to reproduce tonal information. Digital images with higher gray-level resolution have a larger number of gray shades as well as a greater dynamic range.[4,14]

7. File size

File size is the final outcome, indicating the size of information data representing an image. It is a mathematical relationship integrating the total number of pixels in an image with grayscale or color depth. Three additional parameters can influence file size, namely file format, amount of data compression and cropping to include the relevant region of interest (ROI).

File size is essentially dependant on pixel dimensions and bit-depth. Predictably, it is derived by multiplying the (number of horizontal pixels) × (number of vertical pixels) × (number of bits in shades of gray or color, i.e., bit-depth).[20]

Number crunching in practice: In its most basic form, file size is represented by two elementary units of measurement, namely a bit and byte. A bit is the smallest measurement indicating '1 or 0' or 'on or off.' Eight such bits comprise a byte.

When file size increases further, units such as kilobyte (1024 bytes), megabyte (1000 KB), and gigabyte (1000 MB) are used. File sizes larger than these are represented by terabytes (1000 GB), which is relevant, in practice, for picture archival and communications system (PACS) and large data storage.

Let us now examine the storage capacity of various types of commonly available media. A 12 cm standard compact disc (CD) holds 650 or 700 MB of data, a 12 cm single-sided standard digital video disc (DVD) has 4.7 GB (single layer) and 8.5 GB (dual layer) data holding capacities, while a 130 mm magneto-optical disc (MOD) commonly takes in 2.6 GB of data. The console computer of a CT scan machine possessing a hard disc capacity of 146 GB can store up to 250,000 uncompressed images of 512 × 512 matrix.[22]

It must be remembered that an increase in matrix and grayscale range improves image resolution, but also undesirably increases storage space and time of transmission through networks. Customarily, transmission time follows the laws of file size. For instance let us compare two digitized images: one with 512 × 512 × 8 bit-depth which comprises 2,097,152 bits, while the other with 1024 × 1024 × 12 which amounts to 12,582,912 bits.[23] Since the latter image has a file size six times larger than the former, the time taken to transmit this larger file across networks will be six times longer. Remedial options to decrease transmission time include increasing network/modem speeds or reducing the number of bits sent by using compression techniques.[23]

Human vision compared to digital devices

An analysis of digital imaging will be incomplete, without understanding a few fundamental concepts related to human vision. Issues related to the human eye, making it a standard reference (vis-a-vis digital imaging devices) are briefly outlined below.

The human eye is sensitive to the visible spectrum of electromagnetic radiation in the wavelength range between 400 and 700 nanometers.[24] The human eye's response under normal lighting conditions is called the photopic response. It is primarily supported by cones, whose peak sensitivity is 555 nanometers, indicating that the eye is most sensitive to yellowish-green color.[25] However, in dim lighting or near total darkness, a scotopic response occurs, wherein the rods are most active. The human eye, in such poor lighting states, is more sensitive to blue and violet and less sensitive and poorly discriminatory to yellow and red.[25] The human eye can discriminate many more shades of color than it can shades of grey. This is further dependent upon factors such as the age of the person and the quality of the eyesight.

Evidently, the human eye has a resolution and dynamic range more highly developed than digital cameras.[26] The eye is not merely an adaptive optical device, but is endowed with fast visual signal processing handled by complex neural networks, superior pattern recognition systems, and efficient handling of depth and edge characterization.[27]

Number crunching in practice: Images in radiology produced by x-ray detectors, CT scans, etc., contain 12 to 16 bits/pixel, [Table 2] corresponding to 4,096 to 65,536 shades of gray, while images visualized by medical displays in general, have much lower number of gray shades, often in the range of 8 bits or 256 shades of gray per pixel [Figure 1D].[28]

This raises the key question, 'Do we really know how many shades of gray a human eye can distinguish?' To evaluate the recognition of grayscales by humans in optimal conditions, biophysical models propounded by Movshon and Kiorpes, and Daly and Barten have been widely used.[28] Initial observations proposed that the human eye could distinguish 30 to 50 shades of gray.[29,30] It is now established that the human eye can discriminate 'between 700 and 900 simultaneous shades of gray for the available luminance range of current medical displays and in optimal conditions.' It is presently felt that it is of 'no use to simultaneously display more than 10 bits of gray (1,024 gray shades) because this already exceeds the capabilities of the human visual system.'[28]

In the end, the photographic term 'f-stops,' which compares the human eye with digital devices, needs analysis. Traditionally, the dynamic range in photography is influenced by the amount of light that passes through the lens to reach the camera or digital sensor. It is expressed as an f-number, wherein the suffix number is the ratio of the focal length to the diameter of the entrance pupil.[31] F-stops are a sequence of f-numbers that halve the amount

Table 2: Image sizes in radiology practice

No	Modality	Image matrix size (in Pixels)	Dynamic range (Bits per Pixel)	Typical file size per Image
1	MRI[21]	256 × 256	16	131 KB
2	CT Scan[21]	512 × 512	16	524 KB
3	USG[21]	512 × 512	8	262 KB
4	Color Doppler	768 × 576	8	442 KB
5	Digital Radiography (GE)	2022 × 2022	14 or 16	8 MB
6	DR Mammography FFDM (GE) 19 × 23 cm	1914 × 2294	14	9 MB
7	Digital Radiography (Canon, Agfa)	2688 × 2688	12 or 14	14.4 MB
8	Digital Radiography (Philips, Siemens)	3000 × 3000	12, 14 or 16	18 MB
9	DR Mammography FFDM (Siemens) 24 × 29 cm	3328 × 4096	14	27 MB
10	Computed Radiography (Fuji HR) 35 × 43 cm	3520 × 4280	12	30 MB
11	CR Mammography (Fuji) HPD 24 × 30 cm	3540 × 4740	12	33.5 MB

Note: Small matrix size is relevant to images from CT scan, MRI, USG, whereas large matrix size is commonly used in digital radiography and mammography.[15]

of light reaching the sensor, as in f/0.7, f/1, f/1.4, f/2, f/2.8, f/4, f/5.6, f/8, etc. In the world of photography, a scene with eight f-stops has a dynamic range or contrast ratio of 1: 2^8 or 1:256.[31]

The human eye accurately 'records detail with light intensities ranging over a factor of 15 stops in any one scene, but the absolute dynamic range - from fully dark-adapted to fully light-adapted conditions - approaches a factor of nearly 30 stops'[27] as compared to 8 stops of digital cameras.

Summary and Conclusion

The current practice of radiology across the world, involves extensive handling of digital images, often in black and white and varying shades of gray. In radiology, digital images are sourced from imaging equipment, archived in CDs/MODs/DVDs, as well as viewed in varying output devices such as monitors, paper, laser film and video projectors. In recent times, there has been a growing trend towards using virtual color in color Doppler, CT scan, and MRI applications.

At its very core, digital imaging is governed by a few important performance parameters like pixels, grayscale, bit-depth, resolution, color, and file size. These parameters are conceptually different for image acquisition equipment as compared to image output and viewing devices.

Set against this theme, radiologists as well as residents should recognize few basic concepts in digital imaging, which indeed is the focus of this article.

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