White Paper

Grayscale resolution: How much is enough?

What's inside?

- Look-Up tables explained
- What defines image quality
- What defines DICOM precision
- Facts and figures for existing LUT topologies

Paul Matthijs
General Manager Medical Imaging Systems
Barco
paul.matthijs@barco.com

Is 8 to 12 bits better than 10 to 10 bits? Is the highest number of bits a guarantee for best image quality? This white paper starts with the basic concepts defining resolution and compares the image quality performance of each topology.

Table of contents

Acknowledgement
I hereby thank Tom Tuytschaever for his support and advanced Excel skills that were key to the completion of this white paper.

List of acronyms

Acronym	Definition
8 to 8 bit LUT	LUT having 8 bits wide address (= LUT input) and 8 bits wide data (= LUT output)
CRT	Cathode Ray Tube
DDL	Digital Driving Level
GSDF	DICOM Grayscale Standard Display Function
JND	Just Noticeable Difference: the luminance difference that the average human observer can just perceive at a specified luminance level and viewing conditions
LCD	Liquid Crystal Displays
LUT	Look-Up Table

1. Terminology: What's in a name?

We all heard it before: Look-up tables, 8 to 10 bits, 1024 simultaneous shades of gray. In the jargon and figures describing grayscale resolution, it is easy to get lost. One may assume that the higher the numbers are, the better the image quality will be. But is this really so?

The answer to this question is more subtle. In fact, the highest numbers do not always yield the best image quality. The purpose of this white paper is to make technically as well as non-technically trained people understand what the figures and specifications mean and what to watch for when specifying display systems for medical imaging applications.

1.1 Look-up tables explained

A good understanding of the concept and technical capabilities of Look-up tables[1] (LUT) is essential for an in depth discussion of grayscale resolution. Look-up tables come in a large variety and are a key component defining what the final grayscale or color capabilities of a display system will be.

A LUT is a piece of memory inserted between the video memory, located on the graphic board or display controller, and the display. As every memory, the LUT has address lines defining which memory location we want to address. The address lines is called the input to the LUT and is connected to the video memory. Thus, the pixel content stored in the video memory is defining where to point in the memory block of the LUT.
The output of the LUT is formed by the contents of the memory cell itself, in general terms called data. The output of a LUT is connected to the display input. In analog systems, the digital output of the LUT is first converted to an analog value before feeding it to an analog display. In case of digital displays - LCD[2] displays are typically driven using digital signals – the digital LUT output is fed directly to the display. The situation of a digital display is illustrated in Fig. 1 below.

---

[1] LUT: Look-Up Table
[2] LCD: Liquid Crystal Displays

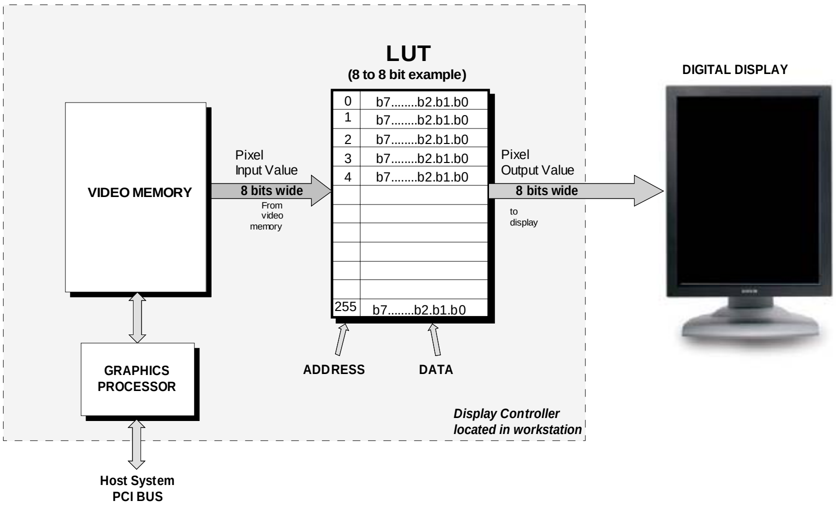

Fig. 1 Situating the LUT in the display system

In this particular case, the video memory is 8 bits wide, meaning that every video memory location contains pixel values of 8 bits wide. The data output of the video memory is connected to the address lines of the LUT, that in its turn, has 8 bits wide memory locations. The data output of the LUT is then connected to the digital display. This scheme is reproduced for every color Red (R), Green (G) and Blue (B) in case of a color display system. In case of a grayscale display system, the scheme is only reproduced once describing the intensity values of the image.

The LUT in the case of Fig. 1 is said to be an **8 to 8 bit LUT**[3] since both input and output are 8 bits wide. Other options for LUT input and output widths will be discussed further in this paper. It should be clear that the LUT scheme does nothing else than a transformation of the pixel values into other pixel values, as defined by the content of the LUT. This transformation capability of a LUT is mostly used to define an arbitrary conversion from pixel values as stored in the video memory – sometimes called p-values - into display values to be fed to the display. This conversion may be required to compensate for the physical behavior of the display converting digital values into luminance values. This is illustrated in Fig. 2 below.
The LUT content can be changed on the fly, without interrupting the image to the display. Thanks to that possibility, LUTs are also intensively used to change the image representation dynamically, e.g. enhance contrast, or apply window and leveling functions in medical applications. Yet another application for LUTS is situated in color display applications to change the color palette available to the application.

[3] 8 to 8 bit LUT: LUT having 8 bits wide address (= LUT input) and 8 bits wide data (= LUT output)

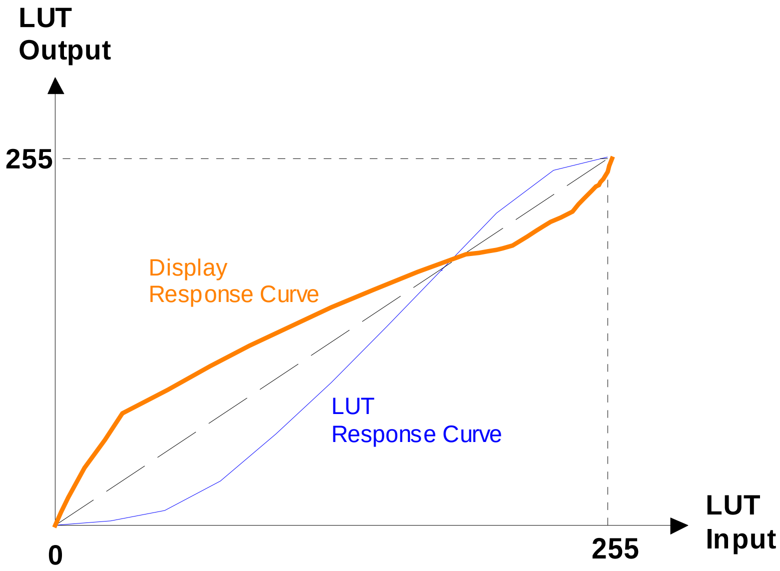

Fig. 2 LUT response compensating display transfer curve to obtain linear relationship

1.2 LUT Characteristics translated to image quality parameters

The physical characteristics have a dramatic impact on the color and grayscale capabilities of the display system. The input as well as the output resolution of LUTs are each related to different image properties. We refer to Fig. 1 above and Fig. 3 below.

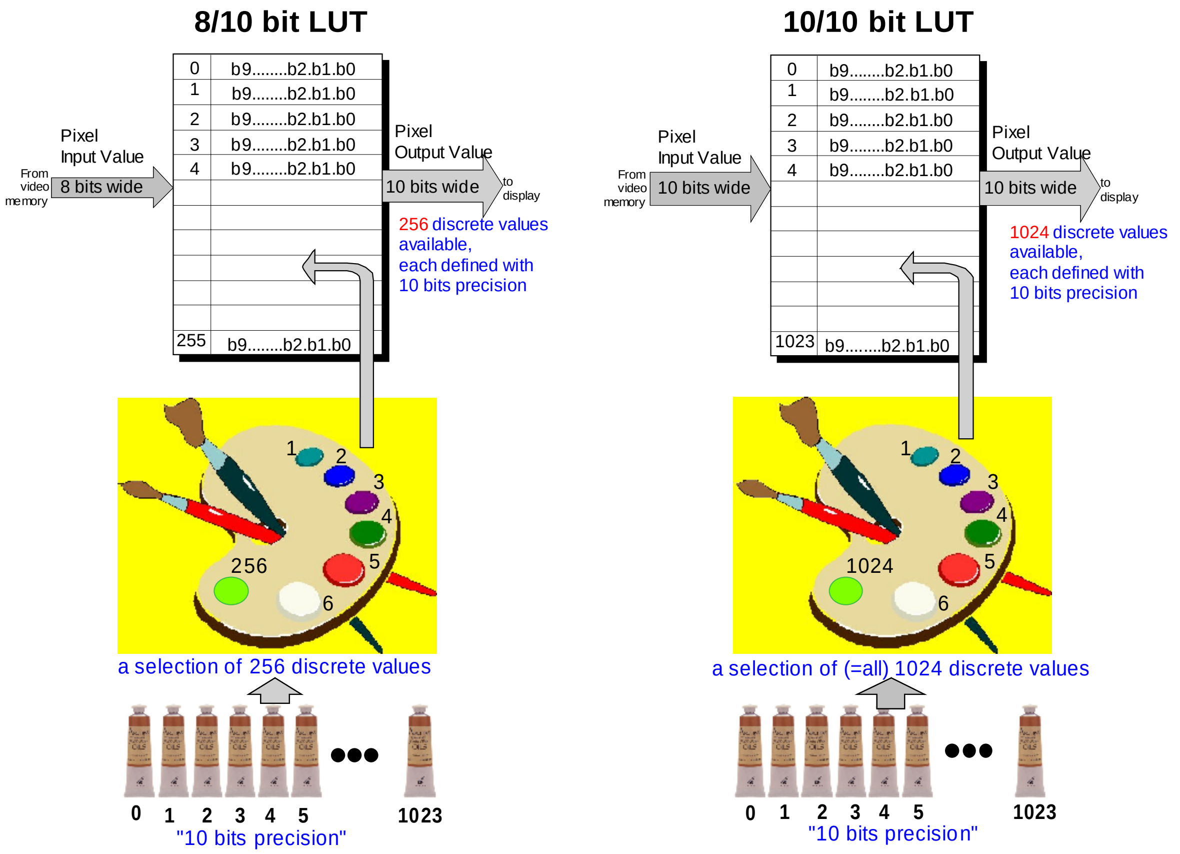

Fig. 3 LUT physical aspects and their impact on image parameters

The LUT in Fig. 1 above was referred to as an 8 to 8 bit LUT. This means that both the input as well as the output resolution of the LUT were 8 bits wide, yielding 256 possibilities at each side. Other set-ups are possible. As is illustrated in the Fig. 3, it is possible to have the LUT output be of different width than the input.
To the left of the figure, an 8 to 10 bit LUT is illustrated. The input values fed from the video memory to the LUT input are 8 bits wide. This means that at any given time, there are not more than 256 discrete and simultaneous possibilities to describe a pixel value in the image. This image characteristic is also referred to as the "**number of simultaneous shades**" in an image. In case of a grayscale display, the problem is one dimensional and the number of shades translates directly to the number of shades of gray. In case of color displays, the number of simultaneous shades are applicable to each of the three color channels. A color display having 256 simultaneous shades for each R, G and B will be capable of rendering 256 x 256 x 256 = 16,777,216 different colors.

Each of the entries to the LUT at the input side is corresponding to one LUT output at a given time. The LUT output is directly driving the display. Its width is defining the precision with which a pixel value can be rendered on the display. Clearly, 10 bits wide LUTs provide more precision to render exactly that color or gray-shade that one wants to reach as an ideal value. It is important to understand that whatever the width of the LUT is, and consequently, no matter how precise you can define the value of a certain pixel, the number of simultaneously available shades is defined by the input width of the LUT, or the width of the video memory.

Lets apply this concept to a real life, practical example. Suppose you are a painter, trying to reproduce a natural scene on a canvas. You dispose of a palette where you can blend your own colors from a set of basic colors from paint tubes. The blended colors on your palette will serve to finally paint the image.
In case of an 8 to 10 bit LUT (on the left in Fig. 3), you will be capable to choose from 1024 basic colors to make blends. This gives you quite some precision to match exactly that particular color that you see in the natural scene. However, you have a small palette: it only provides space for 256 different color blends, not more. This means that you need to reproduce the whole natural scene by just putting 256 different blends on your palette, not more. Any hobbyist painter will tell you that this is quite a challenge. Moreover, it doesn't help you a lot to dispose of an infinite number of base colors, when you can only use 256 resulting blends to paint the actual image.
Good painters will want to go for a 10 to 10 bit LUT (on the right in Fig. 3). This will allow them to not only define a blend exactly by being able to choose from 1024 base colors. They will also be able to use a large palette allowing them to put 1024 different blends on the palette. This gives not only a high color precision, but also a high color variety to exactly reproduce the scene.

By now, it should be clear what LUT parameter defines what type of image parameter.
We summarize this in the table below:

LUT parameter	Corresponds to
• **LUT input** width • LUT address width • Video Memory width	• Number of simultaneous shades • Number of grays/colors within one scene palette size • Number of blends on the palette
• **LUT output** width • LUT data width • Display input resolution	• Precision of shades or colors

The table refers in general terms to image quality. Later in this paper, we will quantify more exactly how many bits are required for what image quality. At this stage, it suffices to understand that the number of available shades of gray is very important to the overall image quality.

Besides affecting image quality, LUT parameters also have consequences to the precision with which one can precisely match a required relationship between pixel values and displayed luminance values. Defining this relationship is exactly what the DICOM standard does for medical imaging. We will first address the basic concepts of the DICOM standard. Then we will relate LUT and image quality parameters to DICOM precision.

1.3 The DICOM Grayscale Standard Display Function

In the early days of softcopy imaging, images would look differently, depending on the particular display system or workstation where the rendering was done. One important reason for this problem is that electronic displays – irrespective of the technology used - show a very variable behavior in converting electric input values to luminance. Clearly, this is unwanted in medical applications where the image and consequently, the diagnosis, needs to be invariable and consistent, independent when, where and on what hardware you choose to render the electronic image.
The main objective of the DICOM Grayscale Standard Display Function (for shortness abbreviated as GSDF[4], or referred to as “DICOM curve” in this paper) standard is to guarantee device independent representation of images.
Fig 4. below illustrates the DICOM curve.

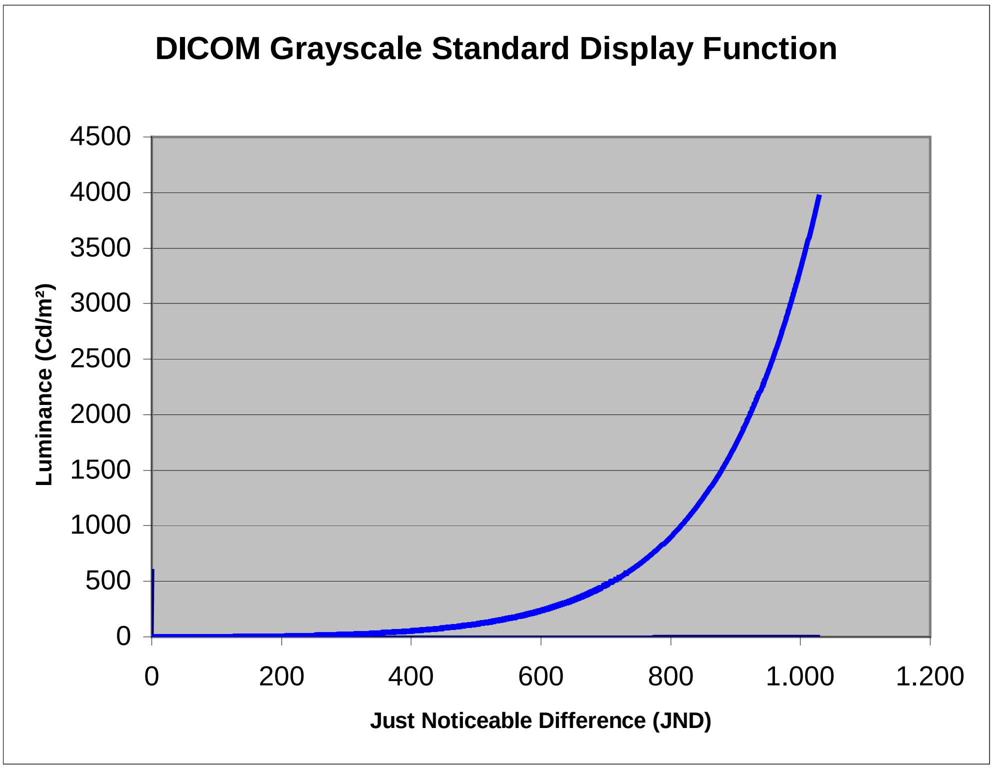

Fig. 4 The GSDF using a linear scale on the Y-axis

[4] GSDF: DICOM Grayscale Standard Display Function

It is not the purpose of this white paper to discuss the DICOM grayscale standard display function in detail. A detailed discussion can be found in Reference [1]. We limit this section to the most important characteristics of the DICOM display function:

- The curve is based on the contrast sensitivity of the human visual system. It describes what just noticeable contrast threshold (JND or Just Noticeable Difference[5] on the X-axis) is discernable by the human eye at a given (surrounding) luminance level (Y-axis, Candela/m²) for well specified viewing conditions. The shape of the curve shows that the human eye is more sensitive in the low luminance range: smaller contrast differences can be discerned at lower luminance levels. This behavior of the human system was investigated intensively by the Dutch researcher Barten and the GSDF is based on Bartens curve describing the eye contrast sensitivity (Reference [2]).
- As a consequence of the above principle, the DICOM curve is **perceptually linearized**. The same change at the input side (the same range of JNDs on the X-axis) is translated to a similar perception of contrast difference at the output (a luminance difference on the Y-axis), irrespective of the luminance level where it is situated. This is illustrated by Fig. 5 below, where C1 is perceived as the same contrast difference as C2, even given the difference in absolute luminance covered.

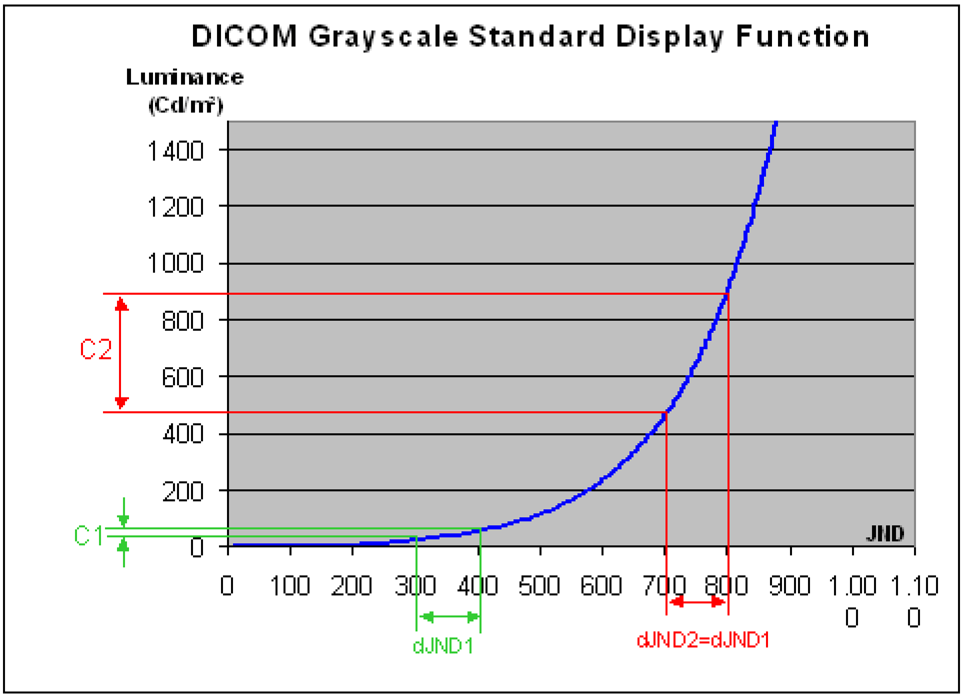

Fig. 5 The GSDFs perceptual linearization

[5] JND: Just Noticeable Difference

- The GSDF provides that images can be rendered perceptually similar on different display devices, if that display has been standardized to behave like the GSDF. The process of standardizing an electronic display requires to calibrate the displays transfer curve, e.g. its conversion from Digital Driving Levels (DDL[6]) to luminance. A display standardized to the GSDF will exactly mimic what the DICOM curve is describing: at the input, the JNDs of the GSDF will be linearly mapped to the DDLs of the display. At the output, the luminance response generated on the screen will correspond to the shape of the curve described by the GSDF. Standardizing an electronic display system to the GSDF curve is basically what is meant with calibration of a display system or printer.

1.4 What defines image quality?

Image quality is partly a subjective matter and hard to quantify. In what follows, some important parameters describing Medical Image Quality will be discussed and analyzed for various display driving resolutions.

One first parameter is **DICOM precision**, or the capability of the display system to behave like described in the theoretical DICOM curve. It can be expected that real life behavior of actual display systems will be an approximation of this curve. How precise the approximation is will be exactly quantified for various display and LUT configurations.

A second parameter has to do with the display's capability to address a sufficient number of individual grayscales within one single image. This capability is defined by what is called **contrast resolution** of a display system. Following the same approach as above, this characteristic will be defined numerically for various display system configurations and compared.

A third category of parameters affecting image quality is harder to describe quantitatively in the limited scope of this white paper. The most important effect associated to display resolution is **mach banding**, a physiological effect associated to a particular image content. We will describe the effect of mach banding and how it is noticeable in images.

[6] DDL: Digital Driving Level

2. DISPLAY GRAYSCALE RESOLUTION AND DICOM PRECISION

2.1 How LUT topologies define DICOM precision

The DICOM display curve is an ideal continuous curve that must be approximated by a digital display system that is limited to “discrete steps”. This is illustrated by the Fig. 6 below. The DICOM curve, approximated by the digital display system, shows a stepwise approximation (red curve). This stepwise approximation is caused by the digital nature of the display system that is capable to only assume a discrete and finite number of values. The digital curve crosses the ideal DICOM curve (blue curve) only at certain points.

There are two dimensions to the quality of the approximation of the DICOM curve, e.g. on the X-axis and Y-axis. Each is defined by a different physical design parameter of the display system. This is illustrated by the text boxes near to the X and Y-axis of Fig. 6 below.

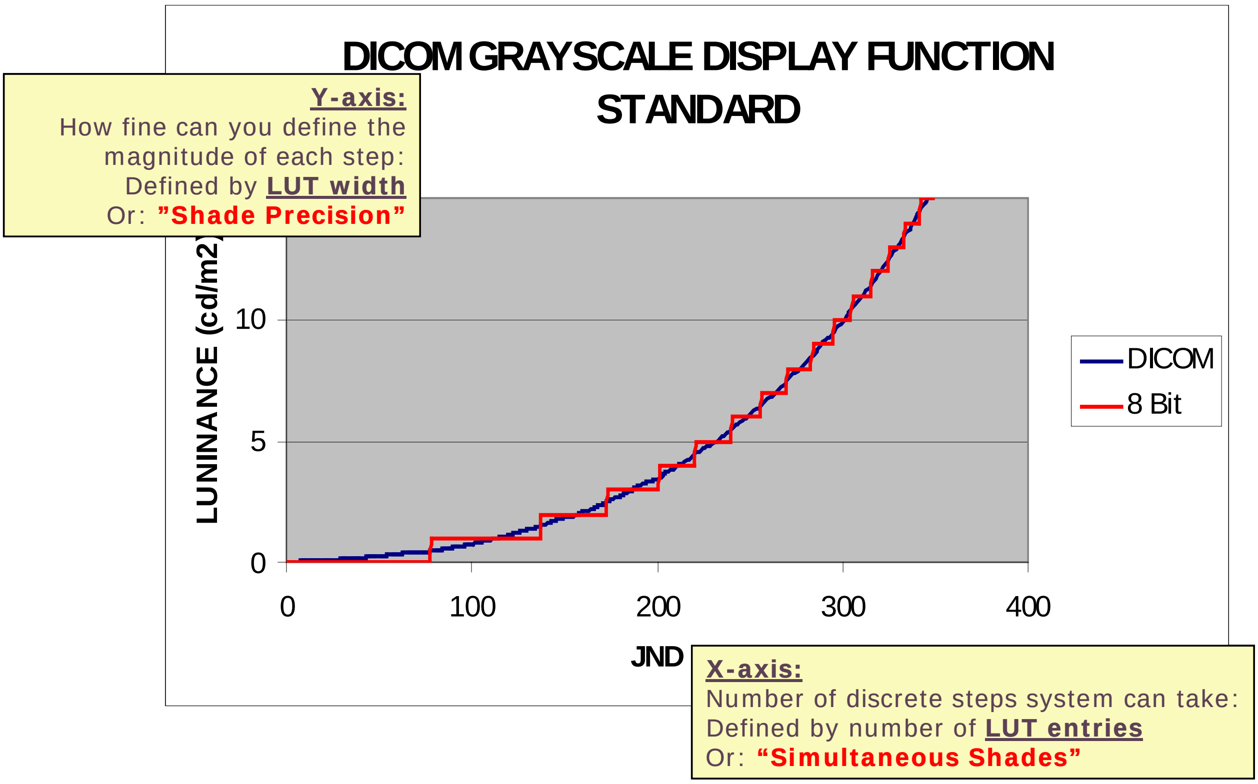

Fig. 6 Linking LUT physical characteristics to the GSDF

On the one hand, the number of simultaneous gray shades, as defined by the width of the video memory and the number of entries in the look-up table, defines how many discrete steps can be taken on the X-axis to precisely approach the GSDF.

On the other hand, the LUT width and the input resolution of the display defines how precise the amplitude (Y-axis) of each luminance step can be defined.

It will be clear that the more bits are available to describe X and Y values, the more precise the digital system will "behave" like the ideal DICOM behavior. A **resolution balance** in both X and Y to describe the GSDF precisely will yield the highest precision in the approximation of the GSDF. On the contrary, a complete unbalance between LUT width and the number of simultaneous shades of gray is useless: it makes no sense to precisely define the luminance level corresponding to a certain JND, if you can only select a very limited number of discrete gray values on the X-axis to draw the complete image.

Repeating the table mentioned in 1.2, we can add the GSDF characteristics (in red).

LUT parameter	Corresponds to
• **LUT input** width • LUT address width • Video Memory width	• Number of simultaneous shades • Number of grays/colors within one scene Palette size • Number of blends on the palette **GSDF:** • **number of JNDs** • **number of discrete steps on X-axis**
• **LUT output** width • LUT data width • Display input resolution	• Precision of shades or colors **GSDF:** • **luminance precision** • **precision of the luminance corresponding to each step**

Based on this understanding, we will investigate the error or deviation from the ideal GSDF as a function of different LUT implementations, and thus, as a function of different driving resolutions.

2.2 Defining DICOM precision: the theoretical approach

How the approximation to the ideal DICOM curve exhibited by a digital display system can be calculated is illustrated in Fig. 7 below. The ideal DICOM curve is approximated by the stepwise curve. The stepwise curve is calculated from a simple mathematical model describing the digital conversion of an ideal, continuous behavior. The triangles indicated the differences between the stepwise curve and the ideal curve. These are the errors. When we subtract the stepwise curve from the ideal curve for every JND value, we obtain the

curve of the form in the bottom of Fig. 7. We can then normalize the difference by dividing the difference by the ideal DICOM value to obtain a percentage deviation from the ideal DICOM curve.
It should be clear by now that higher resolution systems will obtain smaller error triangles, resulting in lower peaks and thus smaller values on the error curve.

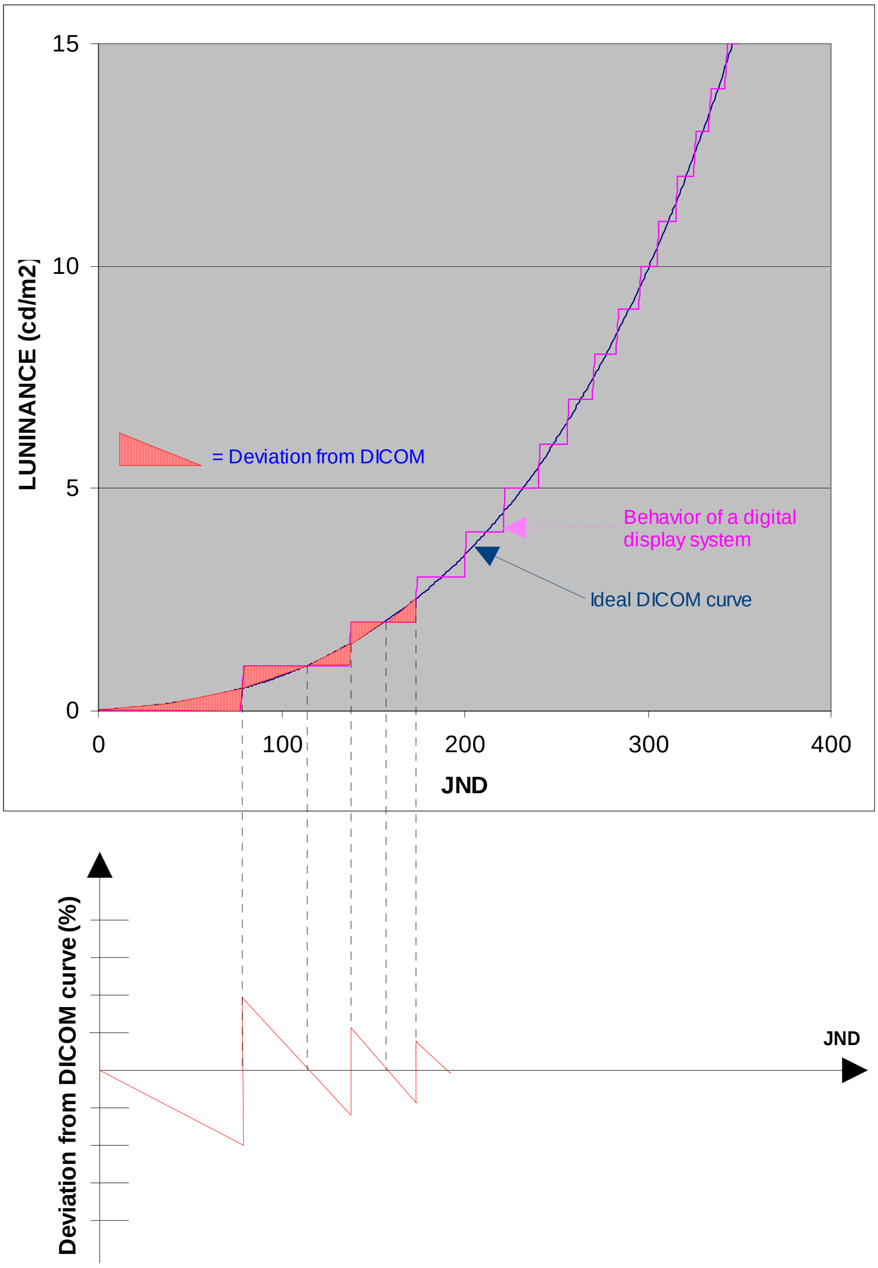

Fig. 7 DICOM precision

This calculation principle has been realized for the LUT topologies that are offered on the market as of today: e.g. 8 to 8, 8 to 10, 10 to 10 and even 10 to 12 bit systems. As such, we obtain the "ideal" DICOM precision of those various systems. Ideal refers to the fact that the behavior of the digital display systems has been calculated, it is a simulation of the real life.

2.3 DICOM precision for various LUT topologies

The resulting DICOM percentage deviation curves are displayed in the following figures. On the vertical axis, the deviation from the DICOM curve is normalized (%). On the X-axis, the JND sequence is expressed as a 14 bit value (0 to 16383).

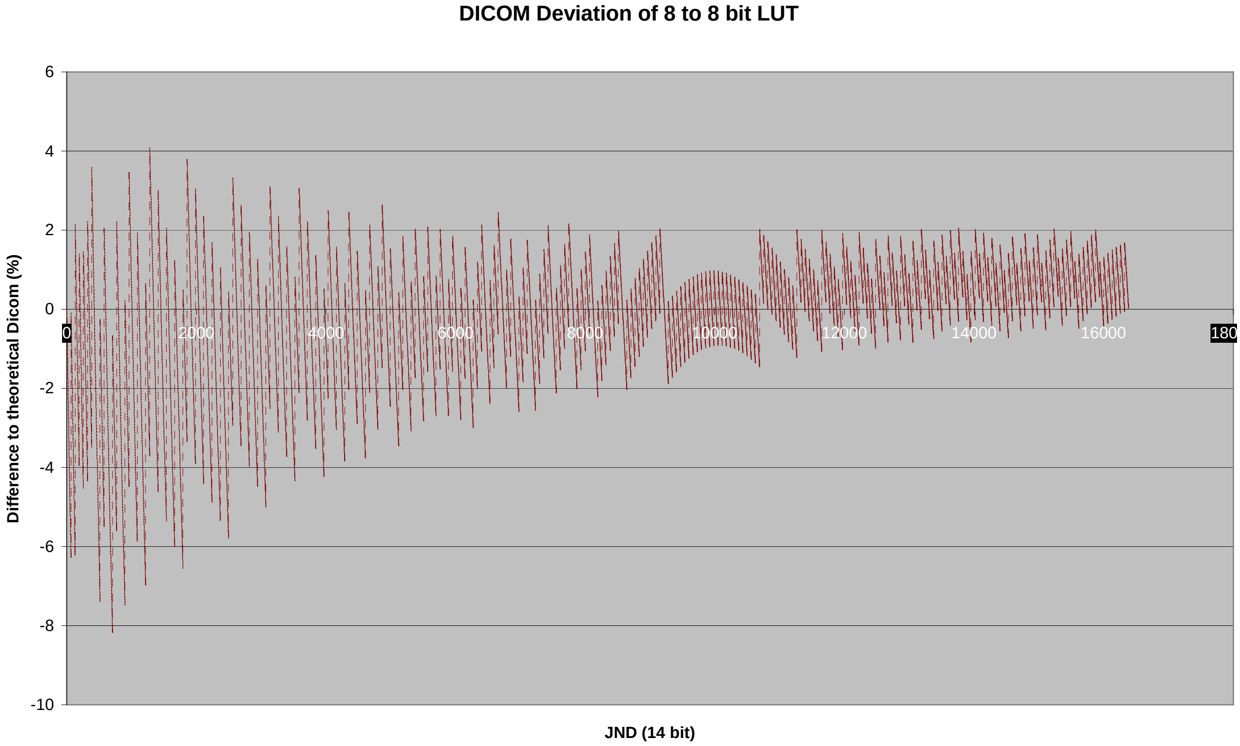

Fig. 8 DICOM precision of display system with 8 to 8 bit LUT

Fig. 8 shows the deviation curve for an 8 to 8 bit system. This is the most basic display controller topology in the market today. This topology allows to describe only 256 discrete Digital Driving Levels (X-axis in DICOM curve) because the video memory and the LUT input is only 8 bits wide. At the same time, the amplitude of each level (Y-axis on DICOM curve) is quantified using 8 bits only, giving a rather course approximation of the desired continuous DICOM value. This topology results off course in the largest errors. As can be seen in the figures, errors are as high as 8%. Over a very large range of the JND range, the error is about 4% peak to peak.

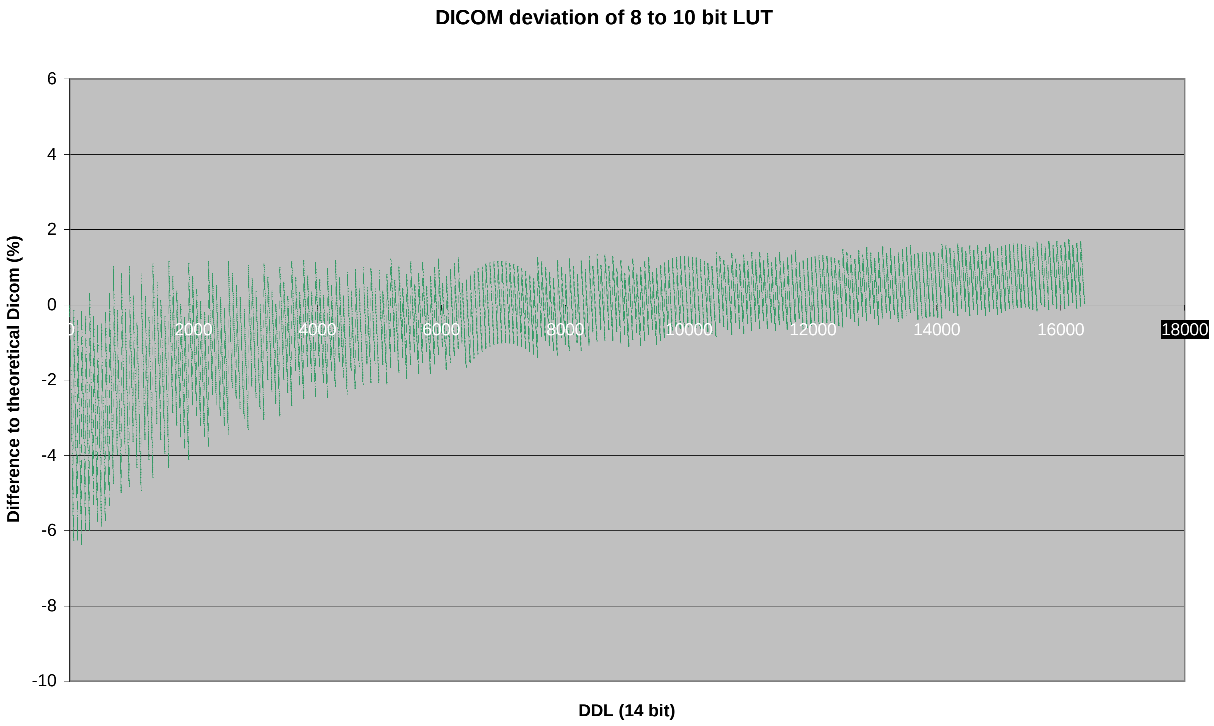

Fig. 9 DICOM precision of display system with 8 to 10 bit LUT

Fig. 9 above shows the deviation curve for an 8 to 10 bit system. This is the most common display controller topology in the market today. This topology allows to describe again only 256 simultaneous Digital Driving Levels (X-axis in DICOM curve) within one image. But, the amplitude of each level (Y-axis on DICOM curve) is quantified using 10 bits, giving a better approximation of the desired continuous DICOM value. This topology results in better error figures than the 8 to 8 bit system. The largest error is 6%. Over a very large range of the JND range, the error is around 1.8% peak to peak.

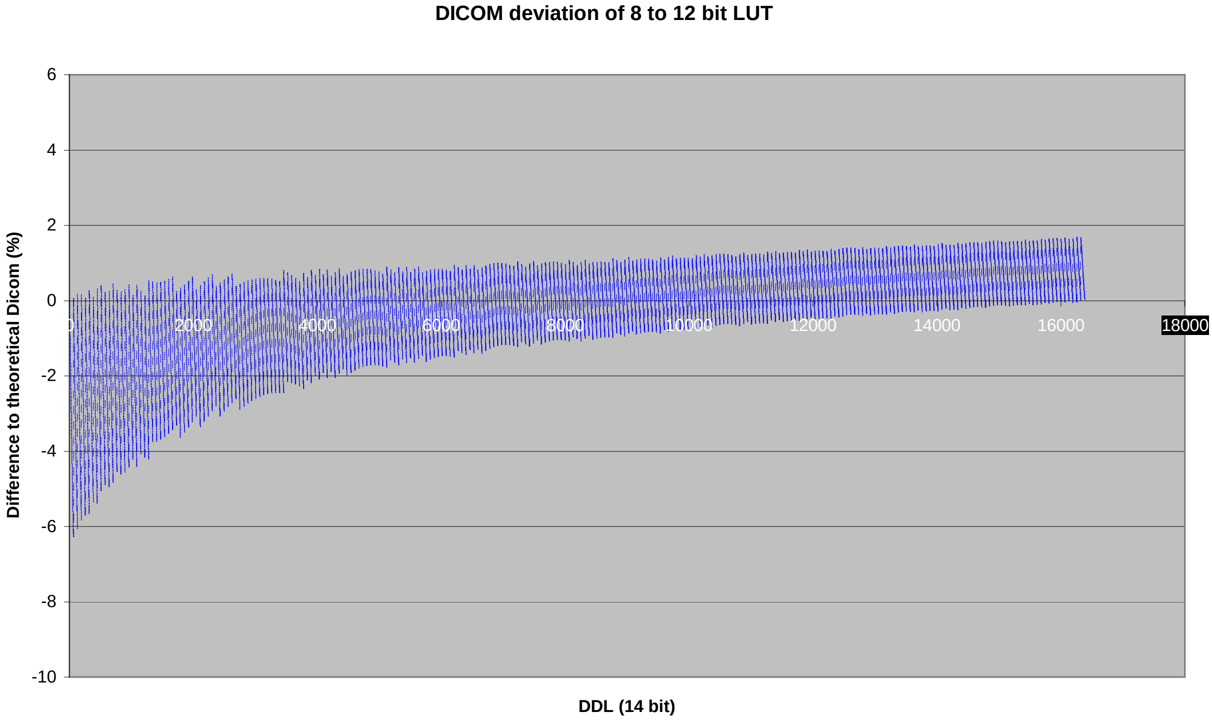

Fig. 10 DICOM precision of display system with 8 to 12 bit LUT

Fig. 10 above shows the deviation curve for an 8 to 10 bit system. This is a topology claimed by some of the medical display vendors. This system is quite asymmetrical in terms of resolution: the topology allows to describe again only 256 discrete Digital Driving Levels (X-axis in DICOM curve). The amplitude of each level (Y-axis on DICOM curve) can be quantified extremely precise using 12 bits.

However, the gains obtained with this topology are only marginal compared to 8 to 10 bit systems. The peak error is the same 6%. Over a very large range of the JND range, the error is again around 1.8% peak to peak, however with less peaks and more constant than in the 8 to 10 bit case.

From the comparison of Fig. 9 above and Fig. 10 above it is clear that there is little to gain with a very high resolution on the Y-axis of the DICOM curve, combined with a limited 256 discrete and simultaneous values on the X-axis. Or in other words: it makes little sense to have very accurately defined shades of gray, if you only dispose of 256 discrete values to describe an image.

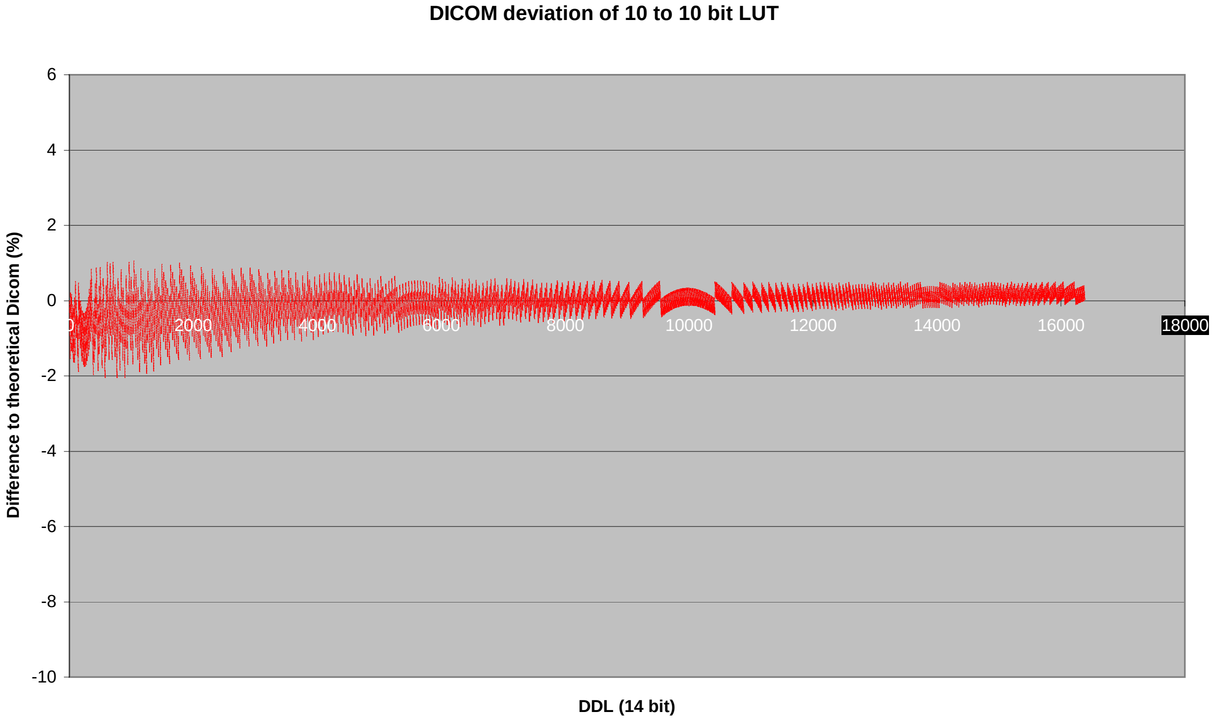

Fig. 11 DICOM precision of Barco's industry leading 10 to 10 bit LUT topology

From the discussion above, it will be clear that the resolution of the available number of DDLs needs to be increased beyond 8 bit to obtain a substantially better performance.

Fig. 11 above shows the deviation curve for an 10 to 10 bit system. This is a unique topology by Barco. This system is quite symmetrical in terms of resolution: the topology allows to describe 1024 discrete and simultaneous Digital Driving Levels (X-axis in DICOM curve).
At the same time, the amplitude of each level (Y-axis on DICOM curve) can be quantified precisely using 10 bits.
The 10 to 10 bit architecture yields the best precision overall. The peak error is 2%. Over a very large range of JNDs, the error is less than 1% peak to peak.

2.4 Summary about DICOM precision

Topology	Peak error (%)	Average Peak to Peak error (%)
8 to 8 bit	8	4
8 to 10 bit	6	1.8
8 to 12 bit	6	1.8
10 to 10 bit	2	1

The figures of the graphs in the previous paragraph are summarized in the table. The DICOM precision of the 10 to 10 bit system is a factor 2 to 3 better than the best 8 bit system with only 256 simultaneous shades of gray.
The table shows that there is no gain in further widening the LUT, when there is no increase of the number of simultaneous shades of gray.
There seems to be no other equivalent to increasing the number of simultaneous shades of gray. This feature is not obtained easily. It requires that not only the digital image pipeline is 10 bits wide, but also the complete on-board video memory is at least 10 bits wide.

The figure below may help to understand the cause of the benefit of a 10 to 10 against 8 to 12 bit architecture. In Fig. 12 below the acquisition happens at 12 bit precision as in most digital scanners. The 8 to 12 bit architecture than shrinks the pipeline to 8 bit for the majority of the processing, and then at the end expands it to 12 bit. However, the initial precision present upfront in the image pipeline (at acquisition and initial storage) is lost and can not be retrieved.

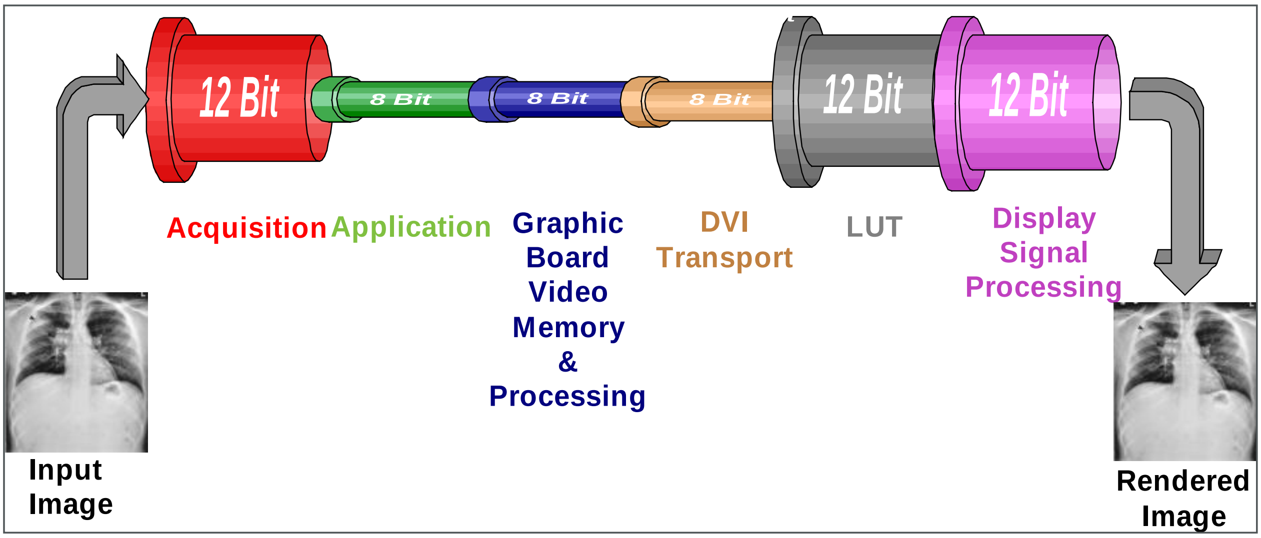

Fig. 12 The image pipeline of an 8 to 12 bit topology

The 10 to 10 bit pipeline in Fig. 13 below shows a more sensible arrangement where the initial resolution is reduced to 10 bits and then maintained throughout the image pipeline. It is understandable that more of the initial image information is maintained at the end.

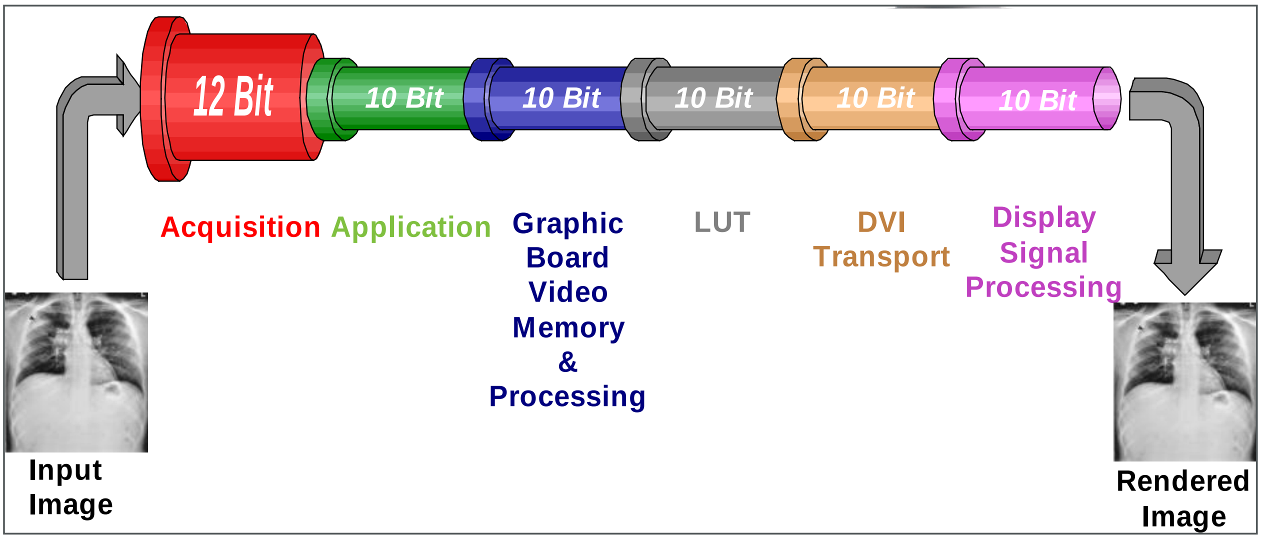

Fig. 13 The image pipeline of an 10 to 10 bit topology

The analogy with the painter trying to paint a scene also applies here: it is of no use supplying a painter with 4096 base colors to blend new colors. If he can only use 256 different new blends on his palette to paint real nature, his approximation of real nature will be far off, no matter how many base colors he had to begin with.

3. CONTRAST RESOLUTION DEFINING IMAGE QUALITY

3.1 Contrast resolution explained

The DICOM curve or GSDF describes absolute luminance levels. Hence it is easy to map the practical display luminance range to the GSDF. This is illustrated for current flat panel display technology in Fig. 14 below. As is concluded from the figure, a modern flat panel display covering a wide luminance range of 0.8 to 500 Cd/m² allows for the human eye to discern 720 JNDs. In other words, on this display, a person will be able to discern 720 different levels of gray, or 720 discrete contrast steps. There is discussion whether all these JNDs are actually visible within one scene. However, research (reference[3]) shows that trained professionals like radiologists are capable of discerning between 800 and 1000 JNDs when looking at a narrow luminance range, i.e. by working with masking, within one single scene.

One first dramatic consequence of the GSDF shows: **if one wants to dispose of all discernable JNDs to describe an image, it will be required to dispose of an equal number of digital driving levels to drive the display**. Indeed, each JND should correspond with a particular digital driving state at the displays input. So, to cover 720 JNDs, 256 discrete digital driving levels (or 8 bits LUT input resolution) will simply not be enough. A LUT input resolution of at least 10 bit, allowing for 2^10 or 1024 different states, will be required to be able to describe all 720 different JNDs at the input.

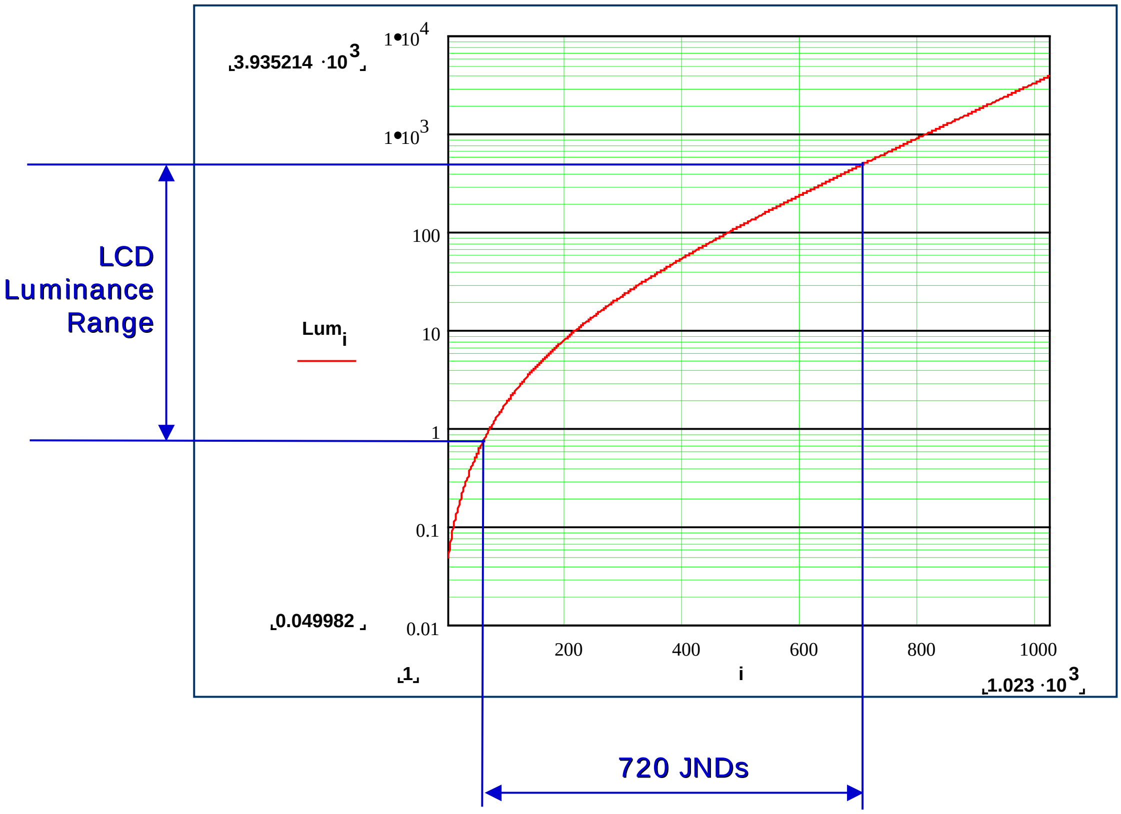

Fig. 14 The practical luminance range of an LCD display and the number of corresponding JNDs

This conclusion leads to the concept of **contrast resolution of a display**:

$$Display\_Contrast\_Resolution = \frac{Maximal\_Possible\_JNDs}{Number\_of\_vailable\_DDLs}$$

In case every individual JND can indeed be covered by the display system, one speaks about a **unity contrast display**. A 10 bit display system having the luminance range indicated in Fig. 14 will allow to display at unity contrast.

Most modern displays, in particular the LCD based displays, cover a luminance range that requires more than 256 or 8 bit JNDs. Hence, such displays should be driven with more than 256 DDLs. However, most display systems and display controllers still only offer a 8 bit wide video memory and signal pipeline, yielding not more than 256 available DDLs.

What is done to overcome this limitation? In that case, linear mapping of JNDs to DDLs will be required to make sure that the complete luminance range is covered, albeit by taking jumps of several JNDs per single DDL. An 8 bit resolution system having the luminance range indicated in Fig. 14 will need to cover 2 to 3 JNDs per Digital Driving Level (because there are only 256 different available driving levels) in order to cover the whole luminance range from 0.8 to 500Cd/m². This compromise may yield a high contrast image, but not an accurate image. Any gray shade modulation in the image coded to be less than 3 JNDs will not be perceived, and will be rendered as zero modulation. Modulations of 3 to 6 JNDS will all be equally mapped to one single modulation value of 3 JNDs. It may even be so that mach banding (contours of equal gray level being visible in certain image scenes) appears and obscures the real image content. This physiological phenomenon is discussed later in this paper.

It can be understood that the phenomenon of mapping of different gray values to one single approximated value in the image will seriously degrade the image quality. Reference[4] confirms that unity contrast displays, that maintain one JND per DDL, render the best image quality.

3.2 Contrast resolution for various LUT topologies

In this section, contrast resolution will be quantitatively defined for various LUT topologies. A way to plot a measure of contrast resolution is to plot the number of JNDs that is covered by every sequential Digital Driving Level applied to the display. This method is in fact another way to assess the adherence of the actual display to the ideal DICOM Grayscale Standard Display Function and is also specified in Reference [1]: the GSDF is characterized by exactly one JND per DDL over the entire driving range of the display.

This approach will yield a curve as indicated in Fig. 15. The X-axis lists the subsequent driving intervals to the displays, thus each discrete Digital Driving Level. The Y-axis lists for each increase in DDL, the corresponding increase in luminance, expressed in Just Noticeable Differences (JND[7]). A display perfectly adhering to the DICOM standard would reach one JND per DDL.

The curves obtained in the following figures were calculated from an ideal model of a display system using different LUT topologies. E.g., the curves represent the most ideal behavior of an actual display system using a specific LUT architecture. Other real life conditions such as various sources of noise and environmental disturbances were thus not taken into account.
This approach serves our purpose of indicating what a certain display system architecture is capable off in the best conditions. We will see that quantization errors introduced by the limited resolution of digital display systems introduce a large variety of errors, depending on the specific LUT architecture.

Fig. 15 below shows the situation for the most basic display system configuration used in medical applications: an 8 to 8 bit LUT allowing 256 simultaneous shades of gray each defined with 8 bit precision. For certain DDL steps, the increase in the number of JNDs is up to 4.6, e.g. the intermediate JND levels are skipped and can not be rendered by this display system. When stepping from one DDL level to a next, an increase that was meant to be one

[7] JND: Just Noticeable Difference: the luminance difference that the average human observer can just perceive at a specified luminance level and viewing conditions. Less than one JND is not noticeable.

JND in the original image data will be rendered with an increase of 4.6. Because of a poor spread of the available resolution, some other DDL steps correspond to a zero increase of JNDs.

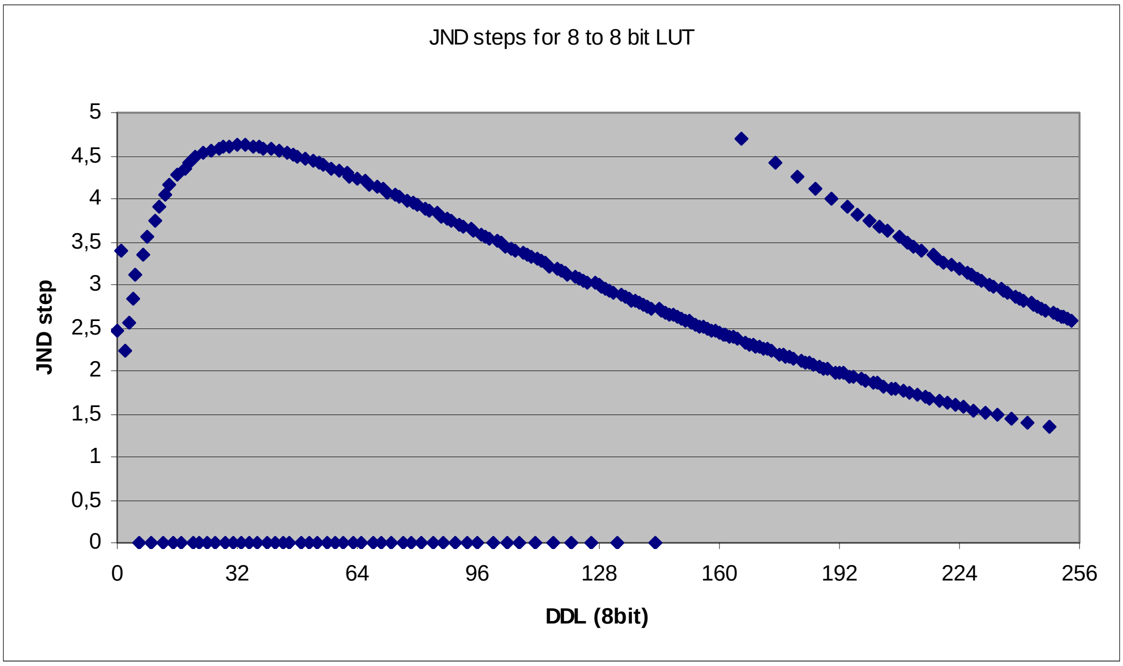

Fig. 15 JND steps per DDL for an 8 to 8 bit LUT topology

Fig. 16 below shows the situation for an 8 to 10 bit LUT allowing 256 simultaneous shades of gray each defined with 10 bit precision. The median luminance increase per DDL is in this case around 2.5. Discrete steps of only one JND can not be rendered.

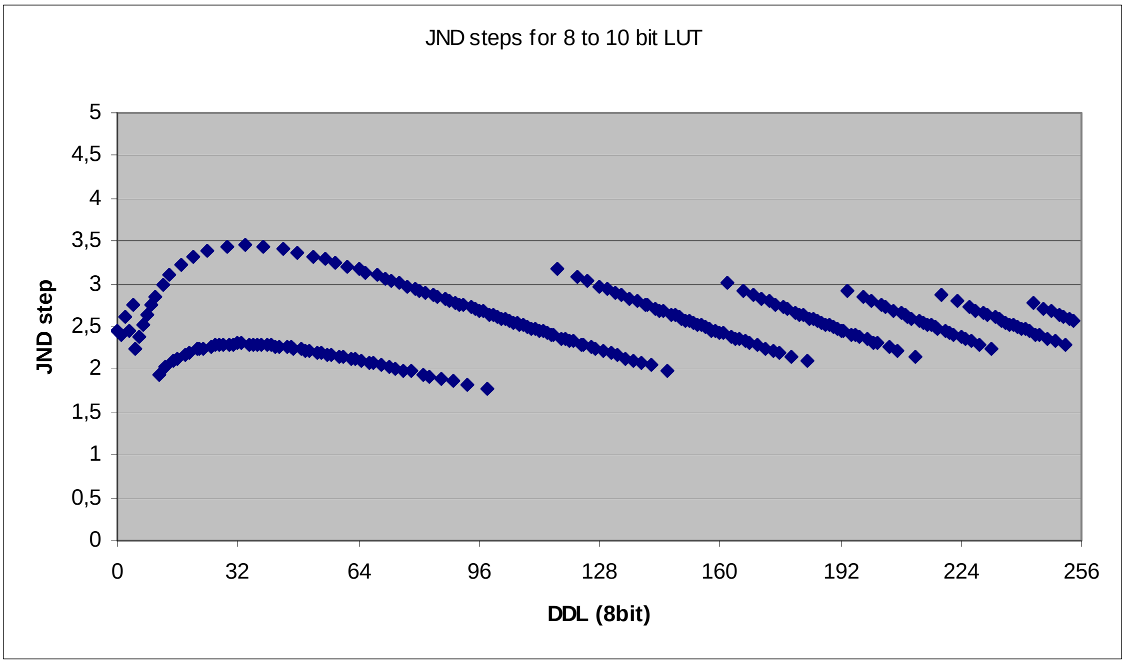

Fig. 16 JND steps per DDL for an 8 to 10 bit LUT topology

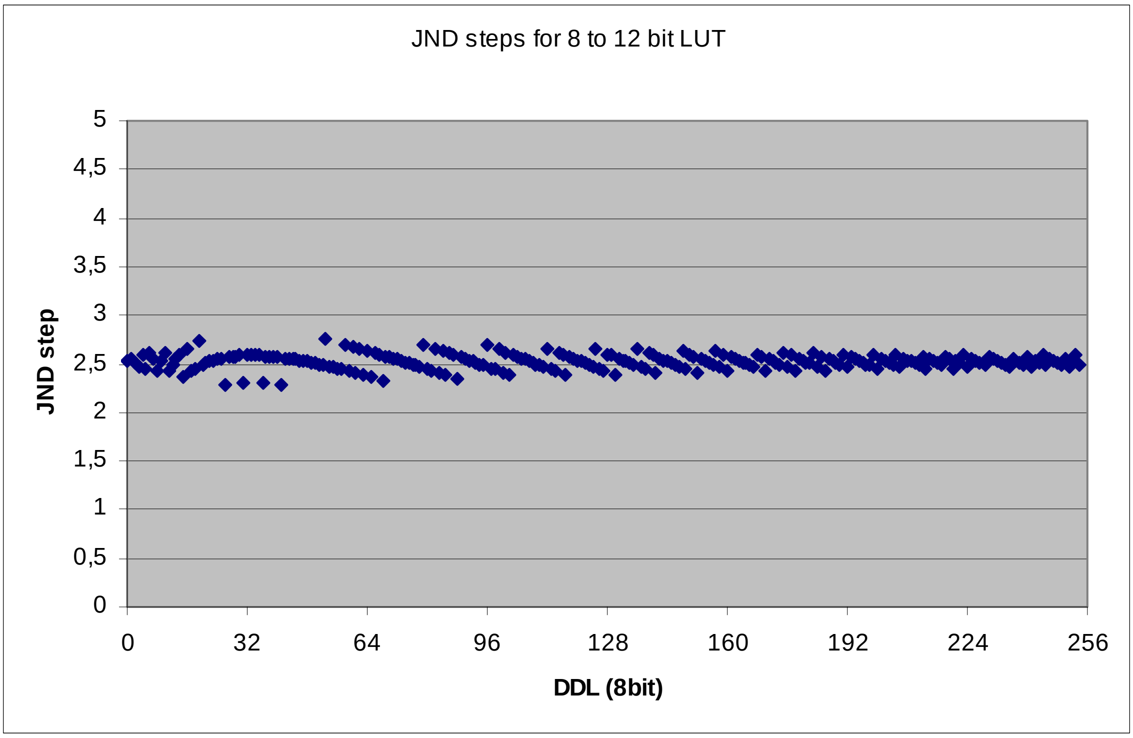

Fig. 17 JND steps per DDL for an 8 to 12 bit LUT topology

Fig. 17 shows the situation for an 8 to 12 bit LUT allowing 256 simultaneous shades of gray each defined with 12 bit precision. It is interesting to note that the extra 2 bits do only yield a lower spread on the basic JNDs per DDLs. The median value is still around 2.5, which means that on average, at every DDL this display system will “jump” from one luminance level to a next with as much as 2.5 JNDs. This is very different from the DICOM target realized by a unity contrast display of one JND per DDL.

It will be clear by now that the basic problem of contrast resolution is not solved by increasing only the LUT output width. Also the LUT input width needs to be widened and with this also the complete image pipeline preceding the LUT. Fig. 18 below shows the result for a Barco display system with 10 to 10 bit LUT allowing 1024 simultaneous shades of gray each defined with 10 bit precision.
Of all display system implementations, this is the configuration that best approaches the ideal DICOM curve. The average luminance steps is around 0.6 JNDs. Only for a minority of the range of DDLs, the target of 1 JND is exceeded and is always lower than 1.2. As most of the steps are one JND or less, it also does not present a problem that certain DDLs yield a zero increase in luminance because the difference between zero and less than 1 JND is invisible.

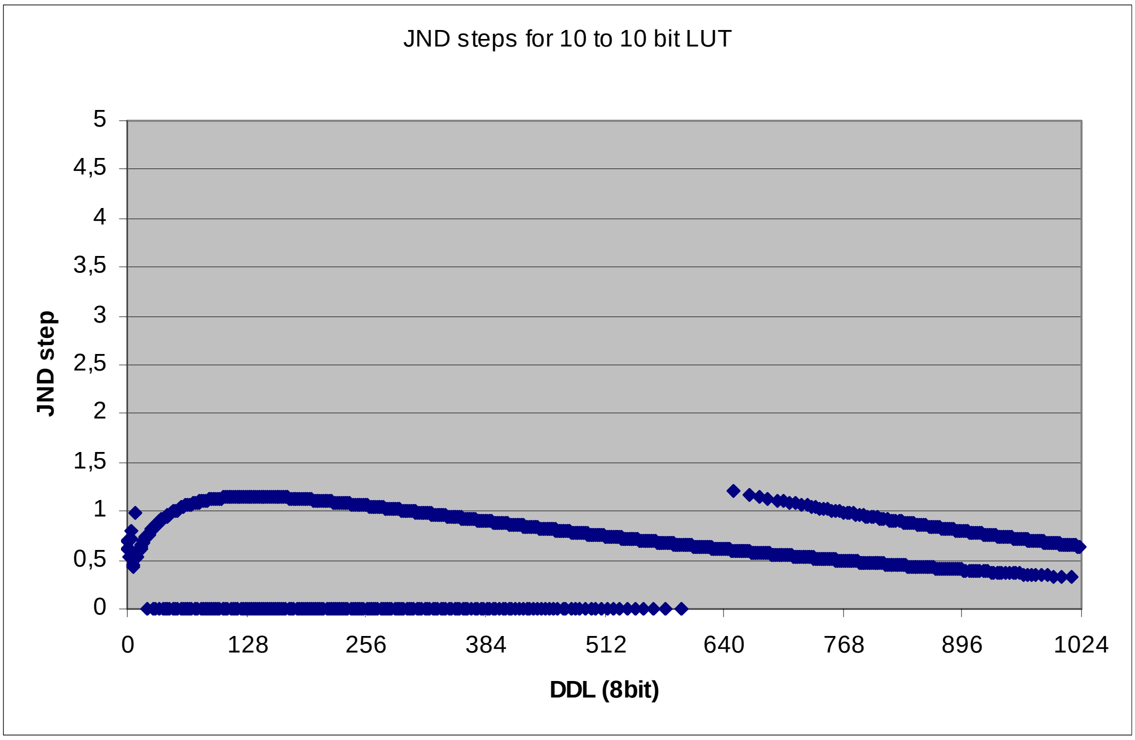

Fig. 18 JND steps per DDL for an 10 to 10 bit LUT topology

3.3 Summary about contrast resolution

Contrast resolution expresses the displays capability to render continuous gray tones and provide optimal perception of single contrast steps.

The table below summarizes the findings of the previous paragraph. For ease of interpretation, we will quantify the curves visually using two key figures: the maximum (peak) JND steps, and the median value of JND steps.

From the figures, we conclude that display systems with a 10 to 10 bit LUT (1024 continuous shades of gray) are about twice as good as the 8 to 12 bit systems, and 3 to 4 times better than 8 to 10 bit systems.
This comparison also shows that increasing the LUT width or output resolution only marginally improves contrast resolution.
A fundamental improvement is offered only by increasing the LUT input width, defining the simultaneously available number of gray shades.

LUT topology	**Simultaneous shades of gray**	**Peak JND per DDL**	**Median of JND per DDL**
8 to 8 bit	256	4.6	2.3
8 to 10 bit	256	3.5	2.65
8 to 12 bit	256	2.75	2.5
10 to 10 bit	1024	1.3	0.65

4. Mach banding

Besides perceptual linearity forming the basis to the DICOM requirements, there are other physiological effects caused by the human visual system, that give rise to requirements with respect to a minimal grayscale resolution in image display systems.
One phenomenon known as Mach banding (discovered by the physicist Ernst Mach in the 1860s) effectively increases the perceived contrast along the boundaries of well aligned zones of different luminance (or radiance).

Hide all but one of the bars using two sheets of paper
Watch the boundaries of this bar become more even in luminance as you hide the neighbouring patches

Fig. 19 Mach banding example

The effect can be understood by analyzing the Fig. 19 above and hide all but one of the gray patches using two sheets of paper. You will see that your eye has added information that is not there. When the patch was surrounded by other patches with a well aligned boundary, your visual system decreases the luminance just before, and increase the luminance just after the boundary as indicated in Fig. 20 below.

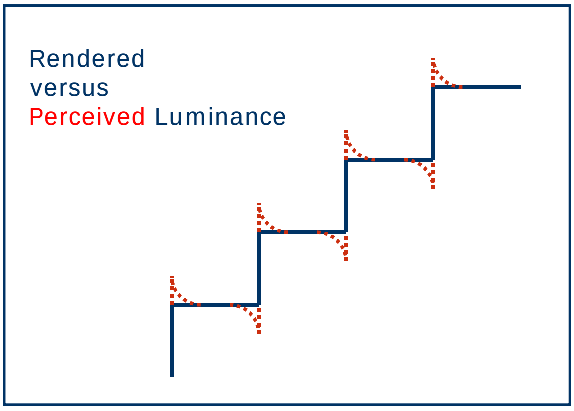

Fig. 20 Mach banding

Several effects cause mach banding to be more pronounced:

1. A limited grayscale resolution causes the contrast difference between subsequent gray values to be larger. E.g. for an 8 to 8 bit LUT system, increasing the digital driving level with one bit results in more than 4 JNDs added on the luminance scale. As a consequence, in regions where a gradual change of gray shades was intended and coded in the image, a stepped approach is rendered by the display system. This effect is not Mach banding in itself, but it increases the opportunity for the human system of being disturbed by Mach banding.

2. When the luminance range of a display system is increased, the contrast difference between subsequent digital driving levels is more pronounced. In fact, the differences between the different levels of gray is stretched. Modern LCD based display systems have a luminance range of 500Cd/m2, or on average the double compared to older CRT systems.

3. Digital screens like LCDs using a matrix arrangement of pixels isolated by a black matrix (black boundaries around each pixel) are more prone to showing mach banding because the visual systems acts more on well defined boundaries. Cathode Ray Tubes characterized by partially overlapping pixels are less prone to showing Mach banding.

Consequently, modern flat panel displays having a well defined pixel structure offering a wide luminance range are more prone to show Mach banding than CRTs for a given data set.

High quality medical images can suffer from mach banding in particular regions, even when 8 bits are used for rendering of the image. However, little practical research on Mach banding has been done in the context of medical imaging. The quantitative assessment of Mach banding falls out of the scope of this paper. Consequently, a standpoint about how many bits is enough to avoid Mach banding can not be expressed.

Mach banding is very dependent of the image content and should be evaluated using actual images. Zones to watch for have slowly varying intensity values around well aligned geometric borders. Mach banding will show as contoured zones of equal luminance, just like lines of equal height on a geographic map.

5. Conclusions

Two parameters driving the required grayscale resolution of image display systems were numerically analyzed.

The first, DICOM conformance, is expressed as a percentage deviation from the ideal DICOM Grayscale Standard Display Function, and was compared for different display system topologies.

The figures show that 10 to 10 bit systems having 1024 simultaneous shades of gray perform more than twice as good as 8 to 12 bit systems having only 256 simultaneous shades of gray.

The comparison also shows that the performance difference between 8 to 10 and 8 to 12 bit systems is close to zero.

In other words, there seems to be no means as powerful as increasing the number of simultaneous shades of gray to obtain fidelity to the DICOM standard.

A second parameter, Contrast resolution, corresponds to a displays ability to render continuous gray tones and provide optimal perception of single contrast steps.

In general, optimal results are obtained when the number of available DDLs in the system match or exceed the number of JNDs as defined by the displays luminance range on the DICOM grayscale standard display function.

For modern display systems offering a wide luminance range, this characteristic is obtained only by systems offering at least 1024 simultaneous shades of gray, and a grayscale resolution (precision) of 10 bit.

It was shown numerically that even in the best of circumstances, 10 to 10 bit systems perform twice as good as 8 to 12 bit systems. The numerical comparison also shows that increasing the output resolution from 8 to 10 and even 12 bits has a limited effect as long as the number of simultaneous shades of gray stays limited to 256.

An overall conclusion is that the best image performance is provided by a system topology with a balanced design, meaning that the LUT input width (number of simultaneous shades of gray), as well as the LUT output width (precision of the gray shades) needs to be sufficiently (10 bits) high.

References

[1] NEMA, DICOM standard supplement 28 proposal PS3.14, "Grayscale Standard Display Function", 1998 http://medical.nema.org/dicom/final/sup28_ft.pdf

[2] Barten P.G.J., "Physical model for contrast sensitivity of the human eye", Proc. SPIE 1666, 57-72 (1992)

[3] Blume H., Muka E., "Hard-Copies for Digital Medical Images", SPIE Vol. 2413

[4] Peters K., "Natural Display Mode for Digital DICOM-conformant Diagnostic Imaging", Academic Radiology, Vol. 9, No 9, Sept 2002