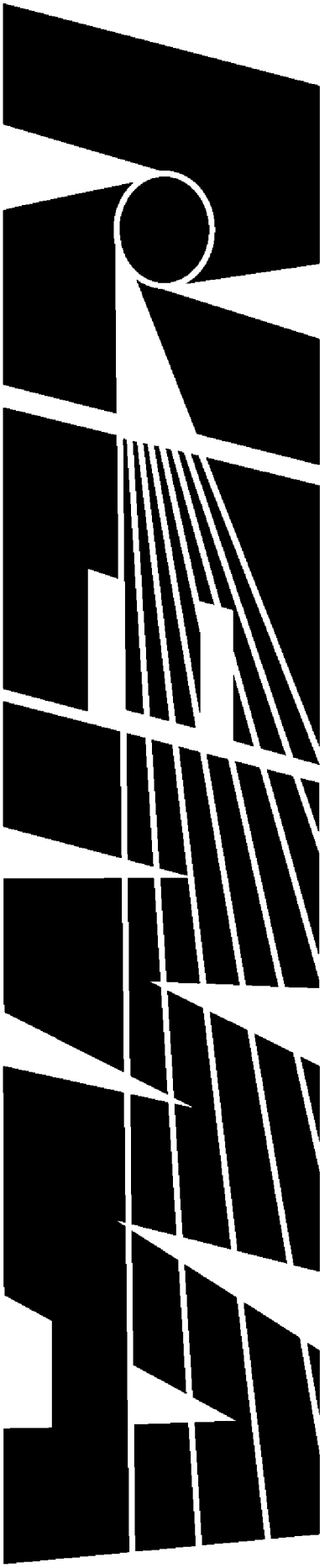
DICOM

Part 14

Grayscale Standard Display Function



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Digital Imaging and Communications in Medicine

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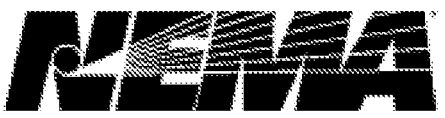

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Digital Imaging and Communications in Medicine (DICOM)

Part 14: Grayscale Standard Display Function

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FOREWORD

The American College of Radiology (ACR) and the National Electrical Manufacturers Association (NEMA) formed a joint committee to develop a standard for Digital Imaging and Communications in Medicine (DICOM). While other parts of the DICOM Standard specify how digital image data can be moved from system to system, it does not specify how the pixel values should be interpreted or displayed. PS 3.14 specifies a function that relates pixel values to displayed Luminance levels.

A digital signal from an image can be measured, characterized, transmitted, and reproduced objectively and accurately. However, the visual interpretation of that signal is dependent on the varied characteristics of the systems displaying that image. Currently, images produced by the same signal may have completely different visual appearance, information, and characteristics on different display devices.

In medical imaging, it is important that there be a visual consistency in how a given digital image appears, whether viewed, for example, on the display monitor of a workstation or as a film on a light-box. In the absence of any standard which regulates how these images are to be visually presented on any device, a digital image which has good diagnostic value when viewed on one device could look very different and have greatly reduced diagnostic value when viewed on another device. Accordingly, PS 3.14 was developed to provide an objective, quantitative mechanism for mapping digital image values into a given range of Luminance. An application which knows this relationship between digital values and display Luminance can produce better visual consistency in how that image appears on diverse display devices. The relationship that PS 3.14 defines between digital image values and displayed Luminance is based upon measurements and models of human perception over a wide range of Luminance, not upon the characteristics of any one image presentation device or of any one imaging modality. It is also not dependent upon user preferences, which can be more properly handled by other constructs such as the DICOM Presentation Lookup Table.

PS 3.14 was reviewed by other standardization organizations including CEN TC251 in Europe and JIRA in Japan, and by other organizations including IEEE, HL7, and ANSI in the USA.

PS 3.14 was developed according to NEMA procedures.

PS 3.14 is structured using the guidelines established in the following document:

ISO/IEC Directives, 1989 Part 3 : Drafting and Presentation of International Standards.

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1. Scope and Field of Application

PS 3.14 specifies a standardized Display Function for display of grayscale images. It provides examples of methods for measuring the Characteristic Curve of a particular Display System for the purpose of either altering the Display System to match the Grayscale Standard Display Function, or for measuring the conformance of a Display System to the Grayscale Standard Display Function. Display Systems include such things as monitors with their associated driving electronics and printers producing films which are placed on light-boxes or alternators.

PS 3.14 is neither a performance nor an image display standard. PS 3.14 does not define which Luminance and/or Luminance Range or optical density range an image presentation device must provide. PS 3.14 does not define how the particular picture element values in a specific imaging modality are to be presented.

PS 3.14 does not specify functions for display of color images, as the specified function is limited to the display of grayscale images.

.

2. Normative References

The following standards contain provisions which, through reference in this text, constitute provisions of this Standard. At the time of publication, the editions indicated were valid. All standards are subject to revision, and parties to agreements based on this Standard are encouraged to investigate the possibilities of applying the most recent editions of the standards indicated below.

ISO/IEC Directives, 1989 Part 3 - Drafting and presentation of International Standards.

3. Definitions

For the purposes of PS 3.14 the following definitions apply.

Characteristic Curve: The inherent Display Function of a Display System including the effects of ambient light. The Characteristic Curve describes Luminance versus DDL of an emissive display device, such as a CRT/display controller system, or Luminance of light reflected from a print medium, or Luminance derived from the measured optical density versus DDL of a hard-copy medium and the given Luminance of a light-box. The Characteristic Curve depends on operating parameters of the Display System.

Note: The Luminance generated by an emissive display may be measured with a photometer. Diffuse optical density of a hard-copy may be measured with a densitometer.

Contrast Sensitivity characterizes the sensitivity of the average human observer to Luminance changes of the Standard Target. Contrast Sensitivity is inversely proportional to Threshold Modulation.

Contrast Threshold: A function that plots the Just-Noticeable Difference divided by the Luminance across the Luminance Range.

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Digital Driving Level (DDL): A digital value which given as input to a Display System produces a Luminance. The set of DDLs of a Display System is all the possible discrete values that can produce Luminance values on that Display System. The mapping of DDLs to Luminance values for a Display System produces the Characteristic Curve of that Display System. The actual output for a given DDL is specific to the Display System and is not corrected for the Grayscale Standard Display Function.

Display Function: A function that describes a defined grayscale rendition of a Display System, the mapping of the DDLs in a defined space to Luminance, including the effects of ambient light at a given state of adjustment of the Display System. Distinguished from Characteristic Curve, which is the inherent Display Function of a Display System.

Display System: A device or devices that accept DDLs to produce corresponding Luminance values. This includes emissive displays, transmissive hardcopy viewed on light boxes, and reflective hardcopy.

Illuminance: Light from the environment surrounding the Display System which illuminates the display medium. It contributes to the Luminance that is received by an observer from the image display. Ambient Light reduces the contrast in the image.

Just-Noticeable Difference (JND): The Luminance difference of a given target under given viewing conditions that the average human observer can just perceive.

JND Index: The input value to the Grayscale Standard Display Function, such that one step in JND Index results in a Luminance difference that is a Just-Noticeable Difference.

Luminance is the luminous intensity per unit area projected in a given direction. The Système Internationale unit (used in PS 3.14) is candela per square meter (cd/m^2), which is sometimes called nit. Another unit often used is footlambert (fL). 1 fL = 3.426 cd/m^2.

Luminance Range: The span of Luminance values of a Display System from a minimum Luminance to a maximum Luminance.

P-Value: A device independent value defined in a perceptually linear grayscale space. The output of the DICOM Presentation LUT is P-Values, ie. the pixel value after all DICOM defined grayscale transformations have been applied. P-Values are the input to a Standardized Display System.

Grayscale Standard Display Function: The mathematically defined mapping of an input JND index to Luminance values defined in PS 3.14.

Standardized Display System: A device or devices that produce Luminance values which are related to input P-Values by the Grayscale Standard Display Function. How this is performed is not defined, though it may be achieved by transformation of P-Values into DDLs accepted by a Display System.

Standard Luminance Level: Any one of the Standard Luminance levels in Table B-1.

Standard Target: A 2-deg x 2-deg square filled with a horizontal or vertical grating with sinusoidal modulation of 4 cycles per degree. The square is placed in a uniform background of a Luminance equal to the mean Luminance of the Target.

Note: The Standard Target is defined in terms of the subtended viewing angle, not in terms of the distance from the viewer to the target.

Threshold Modulation: The minimum Luminance modulation required by the average human observer to detect the Standard Target at a given mean Luminance level. The Threshold Modulation corresponds to the Just-Noticeable Difference in Luminance of the Standard Target.

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4. Symbols and Abbreviations

The following symbols and abbreviations are used in PS 3.14.

ACR	American College of Radiology
ANSI	American National Standards Institute
CEN TC251	Comite' Europeen de Normalisation - Technical Committee 251 - Medical Informatics
DICOM	Digital Imaging and Communications in Medicine
HL7	Health Level 7
IEEE	Institute of Electrical and Electronics Engineers
ISO	International Standards Organization
JIRA	Japan Industries Association of Radiation Apparatus
NEMA	National Electrical Manufacturers Association

5. Conventions

The following conventions are used in PS 3.14:

The terminology defined in Section 3 above is capitalized throughout PS 3.14.

6. Overview

PS 3.14 defines, mathematically, the Grayscale Standard Display Function of Standardized Display Systems. These systems may be printers producing hard-copies viewed on light-boxes or electronic Display Systems for soft-copies.

Hard-copies may consist of transmissive films as well as reflective prints. The image in these prints is represented by optical density variations in transmission or diffuse reflection. To an observer, every element of the image appears with a certain Luminance depending on the Illuminance and the optical density of the image element.

Soft-copies may be produced by emissive Display Systems (such as CRT monitors) or electronic light valves (such as light sources and liquid crystal displays).

For the purpose of PS 3.14, Display Systems take a Digital Driving Level and produce Luminance or optical density variations which represent the image. Predictable application of image transformations, such as the modality, value-of-interest, and presentation look-up tables specified in the DICOM standard, requires knowledge of the Characteristic Curve of the Display System. Standardizing the response function expected of the Display System simplifies the application of such image transformations across several different Display Systems such as encountered in a network environment.

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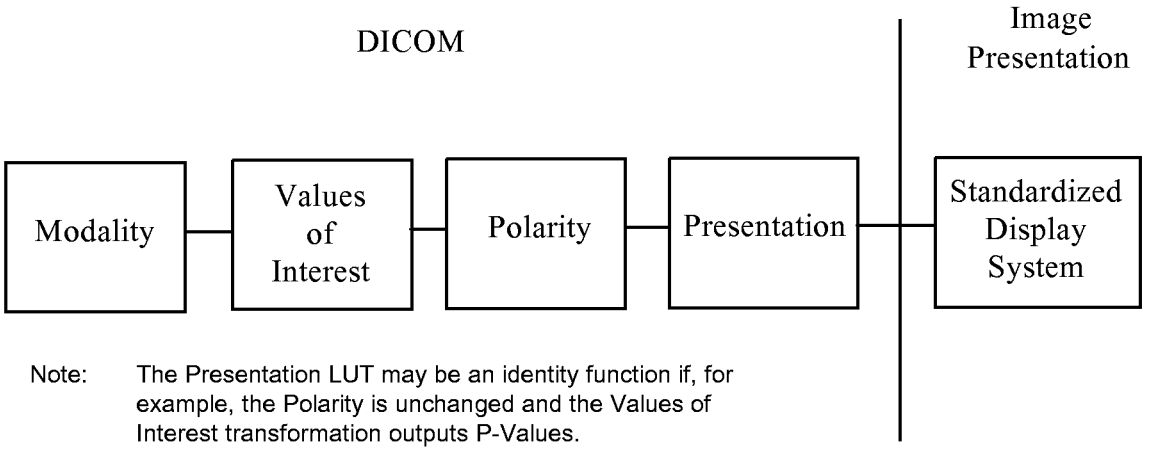
PS 3.14 does not define when conformance with the Grayscale Standard DIsplay Function is achieved or how to characterize the degree of conformance reached.

Note: A definition of conformance would require thorough evaluations of human visual system sensitivity to deviations of Display Functions from the Grayscale Standard Display Function for medical images.

Figures 6-1 and 6-2 show the context for the Grayscale Standard Display Function. The Grayscale Standard Display Function is part of the image presentation. There will be a number of other modifications to the image before the Grayscale Standard Display Function is applied. The image acquisition device will adjust the image as it is formed. Other elements may perform a "window and level" to select a part of the dynamic range of the image to be presented. Yet other elements can adjust the selected dynamic range in preparation for display. The Presentation LUT outputs P-Values (presentation values). These P-Values become the Digital Driving Levels for Standardized Display Systems. The Grayscale Standard Display Function maps P-Values to the log-luminance output of the Standardized Display System. How a Standardized Display System performs this mapping is implementation dependent.

The boundary between the DICOM model of the image acquisition and presentation chain, and the Standardized Display System, expressed in P-Values, is intended to be both device independent and conceptually (if not actually) perceptually linear. In other words, regardless of the capabilities of the Standardized Display System, the same range of P-Values will be presented ìsimilarlyî.



Note: The Presentation LUT may be an identity function if, for example, the Polarity is unchanged and the Values of Interest transformation outputs P-Values.

Figure 6-1. The Grayscale Standard Display Function is an element of the image presentation after several modifications to the image have been completed by other elements of the image acquisition and presentation chain.

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Plotting these values gives the curve of Figure D.2-3.

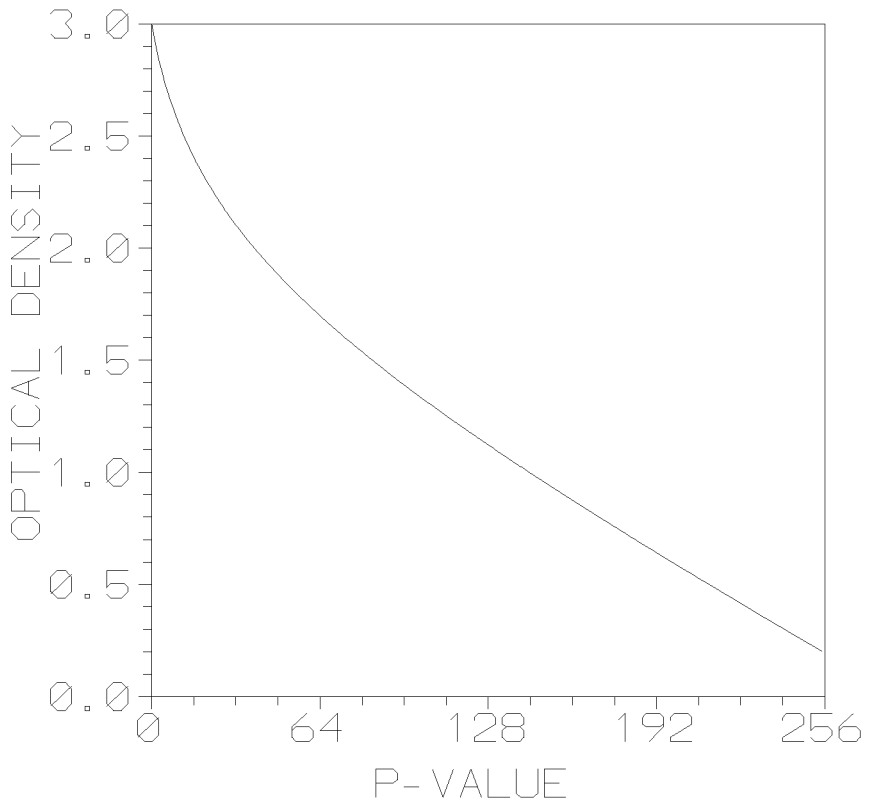

Figure D.2-3. Plot of OD vs P-Value for an 8-Bit Printer

D.2.4. Measures of Conformance

As an example, a bar pattern with 32 optical densities was printed on transmissive media (film). Beforehand, the printer had been set up to print over a density range from 0.2 (Dmin) to 3.0 (Dmax) and had been pre-configured by the manufacturer to use the Grayscale Standard Display Function, converted by the manufacturer into the table of target density values vs. P-Values described earlier.

The test pattern which was used for this was an 8-bit image consisting essentially of 32 horizontal bars. The 32 P-Values used for the bars were as follows: 0, 8, 16, 25, 33, 41, 49, 58, 66, 74, 82, 90,99, 107, 115, 123, 132, 140, 148, 156, 165, 173, 181, 189, 197, 206, 214,222, 230, 239, 247, 255.

For a given film, the 32 bars' optical densities were measured (near the middle of the film), converted to Luminances (using the standard parameters of light-box Luminance and reflected ambient light described earlier),and converted to Just-Noticeable Difference Indices by mathematically computing j(L) from L(j), where L(j) is the Grayscale Standard Display Function of Luminance L as a function of the Just-Noticeable Difference Index j. For each of the 31 intervals between consecutive measured values, a calculated value of "JNDs per increment in P-Values" was obtained by dividing the difference in Just-Noticeable Difference Index by the difference in P-Values for that interval. (In these calculations, density, L, and j are all floating-point variables. No rounding to integer values is done, so no truncation error is introduced.)

In this example, the film's data could be reasonably well fit by a horizontal straight line. That is, the calculated "JNDs per increment in P-Values was essentially constant at 2.4. A mathematical fit yielded a slight non-zero slope (specifically, dropping from 2.5 to 2.3 as the P-Value went from 0 to 255), but the 0.2

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total difference was considerably smaller than the noise which was present in the 31 individual values of "JNDs per increment in P-Value" so is of doubtful significance. (The "noise" referred to here consists of the random, non-repeatable variations which are seen if a new set of measured data (e.g., from a second print of the same test pattern) is compared with a previous set of measurements.)

No visual tests were done to see if a slope that small could be detected by a human observer in side-by-side film comparisons.

Incidentally, if one considers just the 32 original absolute measured densities (rather than differential values based on small differences), one finds, in this case, quite reasonable agreement between the target and measured optical densities (within the manufacturer's norms for density accuracy, at a given density). But if one uses any metric which is based on differential information over small intervals, the results must be considered more cautiously, since they can be strongly affected by (and may be dominated by) various imperfections which are independent of a device's "true" (or averaged over many cases) characteristic behavior.

D.3 REFLECTIVE DISPLAY SYSTEMS

This last example illustrates how conformance with the Grayscale Standard Display Function may be achieved for a thermal-dye-transfer paper printer/office-light system. The thermal-dye-transfer printer produces black-and-white grayscale prints on a semi-glossy 8-inch x 10-inch heavy-gauge paper. The print is illuminated uniformly by fluorescent lamps so that the minimum reflective density produces a Luminance of 150 cd/m^2. The hypothetical transformation operator is assumed to have equal input and output digitization resolution of 8 bits.

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D.3.1. Measuring the system Characteristic Curve

A print with a 64-step grayscale tablet was printed for DDLs 4, 8, 12, ...,248, 252, 255. The reflection optical densities (from 0.08 to 2.80) were measured with a densitometer. The Luminance levels corresponding to the measured optical densities and illumination conditions are plotted in Fig. D.3-1.

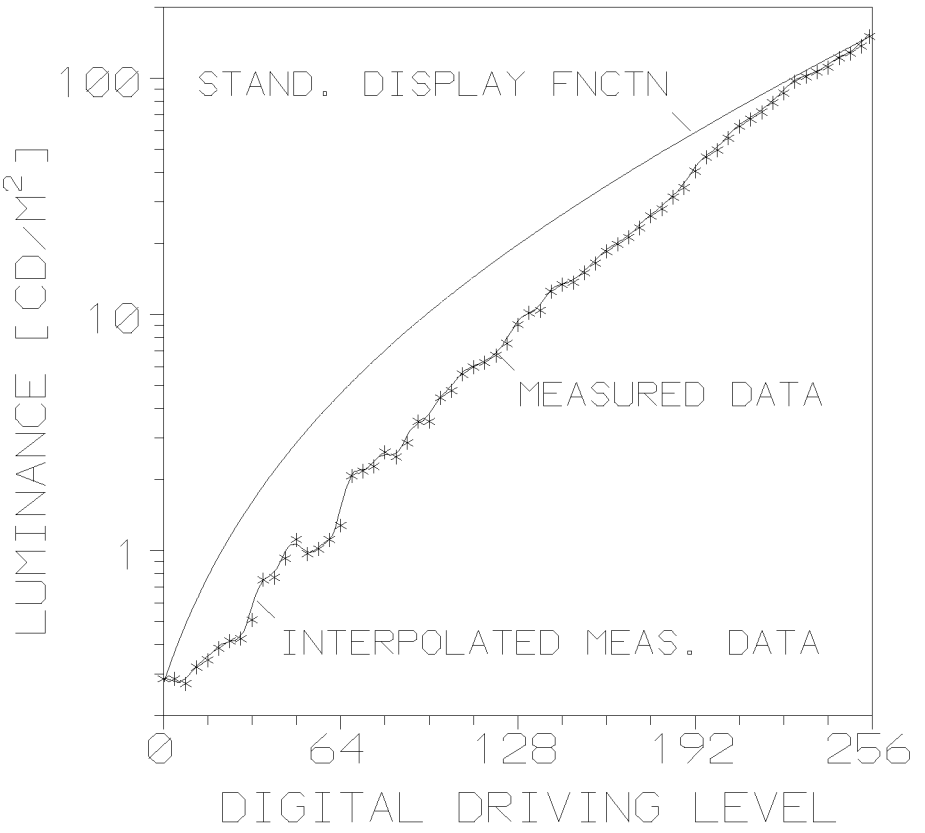

Figure D.3-1 Measured and interpolated Characteristic Curve and Grayscale Standard Display Function for a printer producing reflective hard-copies

D.3.2. Application of the Grayscale Standard Display Function

This last example illustrates how conformance with the Grayscale Standard Display Function may be achieved for a thermal-dye-transfer paper printer/office-light system. The thermal-dye-transfer printer produces black-and-white grayscale prints on a semi-glossy 8-inch x 10-inch heavy-gauge paper. The print is illuminated uniformly by fluorescent lamps so that the minimum reflective density produces a Luminance of 150 cd/m^2. The hypothetical transformation operator is assumed to have equal input and output digitization resolution of 8 bits.

D.3.3 Implementation of the Grayscale Standard Display Function

The measured Characteristic Curve is interpolated for the available DDLs yielding 256 Luminance levels $L_{I,m}$. The Grayscale Standard Display Function is also interpolated between JND_{min} and JND_{max} ($DJND = [JND_{max} - JND_{min}]/255$) yielding 256 Standard Luminance levels $L_{I,STD}$.

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For every $L_{I,STD}$, the closest $L_{J,m}$ is determined. The data pair *I*,*J* defines the transformation between D_{input} and D_{output} (Table D.3-1 and Fig. D.3-2) by which the Luminance response of the Display System is made to approximates the Grayscale Standard Display Function.

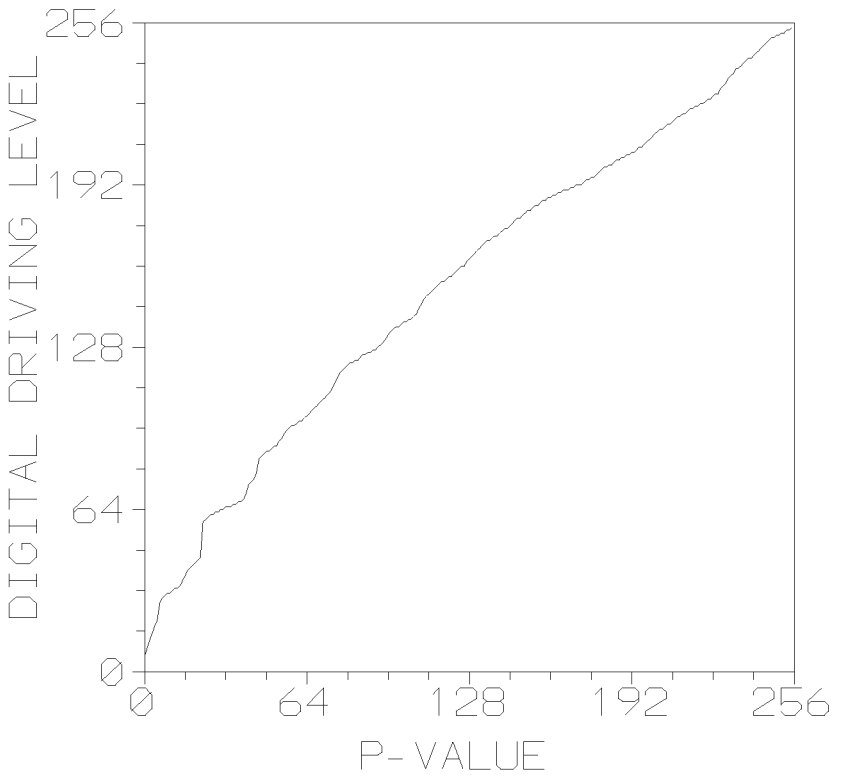

Figure D.3-2 Transformation for modifying the Characteristic Curve of the printer to a Display Function that approximates the Grayscale Standard Display Function

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Table D.3-1
Look-Up Table for Calibrating Reflection Hardcopy System

P-Value	DDL	P-Value	DDL	P-Value	DDL	P-Value	DDL
0	6	1	9	2	12	3	15
4	18	5	20	6	27	7	29
8	30	9	31	10	31	11	32
12	33	13	33	14	34	15	36
16	38	17	40	18	41	19	42
20	43	21	44	22	45	23	59
24	60	25	61	26	62	27	62
28	63	29	63	30	64	31	64
32	65	33	65	34	65	35	66
36	66	37	67	38	67	39	68
40	70	41	74	42	75	43	76
44	78	45	84	46	85	47	86
48	87	49	87	50	88	51	89
52	89	53	91	54	92	55	94
56	95	57	96	58	97	59	97
60	98	61	99	62	99	63	100
64	101	65	102	66	103	67	104
68	105	69	106	70	107	71	108
72	109	73	110	74	112	75	114
76	116	77	118	78	119	79	120
80	121	81	122	82	122	83	123
84	123	85	124	86	125	87	125
88	126	89	126	90	127	91	127
92	128	93	129	94	130	95	131
96	133	97	134	98	135	99	136
100	136	101	137	102	138	103	138
104	139	105	139	106	140	107	141
108	143	109	145	110	147	111	148
112	149	113	150	114	151	115	152
116	153	117	154	118	154	119	155
120	156	121	156	122	157	123	158
124	159	125	160	126	160	127	162
128	163	129	164	130	165	131	166
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152	182	153	183	154	184	155	184
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244	247	245	248	246	249	247	250
248	250	249	251	250	251	251	252
252	252	253	253	254	253	255	254

D.3.4 Measures of Conformance

The FIT and LUM metrics as proposed in Annex C are applied to determine the macroscopic and microscopic approximation of the $L_{J,m}$ to the $L_{I,STD}$. Fig. D.3-3 shows the perceptually linearized Display Function superimposed on the Grayscale Standard Display Function and Figure D.3-4 summarizes the results of the two metrics. FIT provides as best fit of the JNDs/Luminance interval a straight line almost perfectly parallel to the horizontal axis indicating good global fit of the transformed Display Function with the Grayscale Standard Display Function. The RMSE computed by LUM is relatively large indicating more pronounced local deviations from the Grayscale Standard Display Function as, for example, with the soft-copy Display System illustrated in Section D.1. At least in part, the larger RMSE is due to the fact that the input and output digitization resolution for the transform are equal. The transformation table (Table D.3-1) and Fig. D.3-2 show that several P-Values lead to the same Luminance levels on the transformed Display Function. In fact, only 205 of the 255 Luminance intervals lead to JNDs for the Standard Target.

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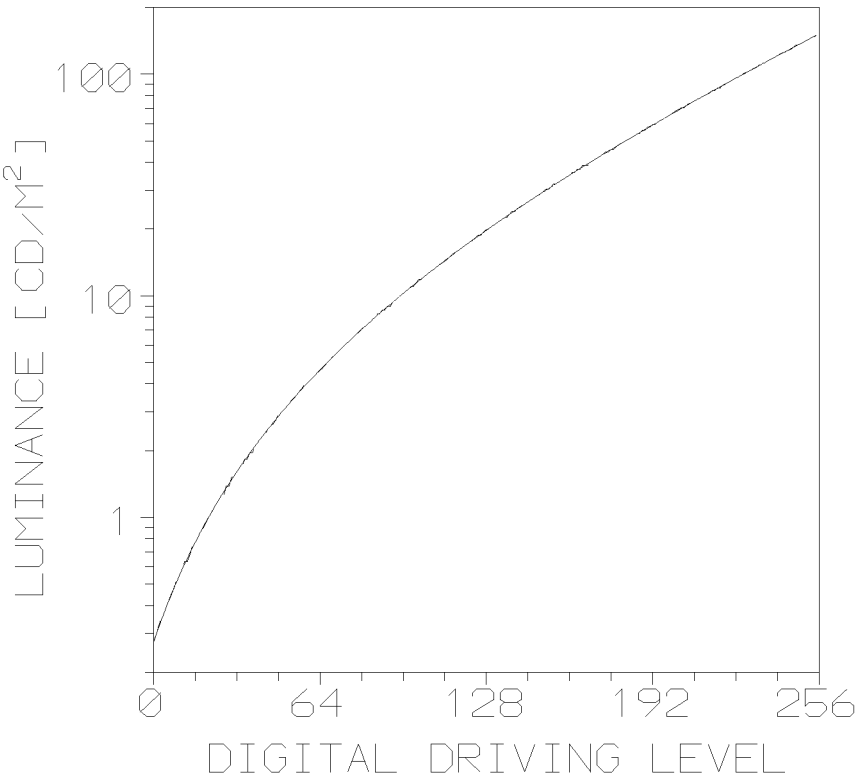

Figure D.3-3. Transformed Display Function and superimposed Grayscale Standard Display Function for a reflective hard-copy Display System. The transformed Display Function for this Display System matches the Grayscale Standard Display Function and the two curves are superimposed and indistinguishable.

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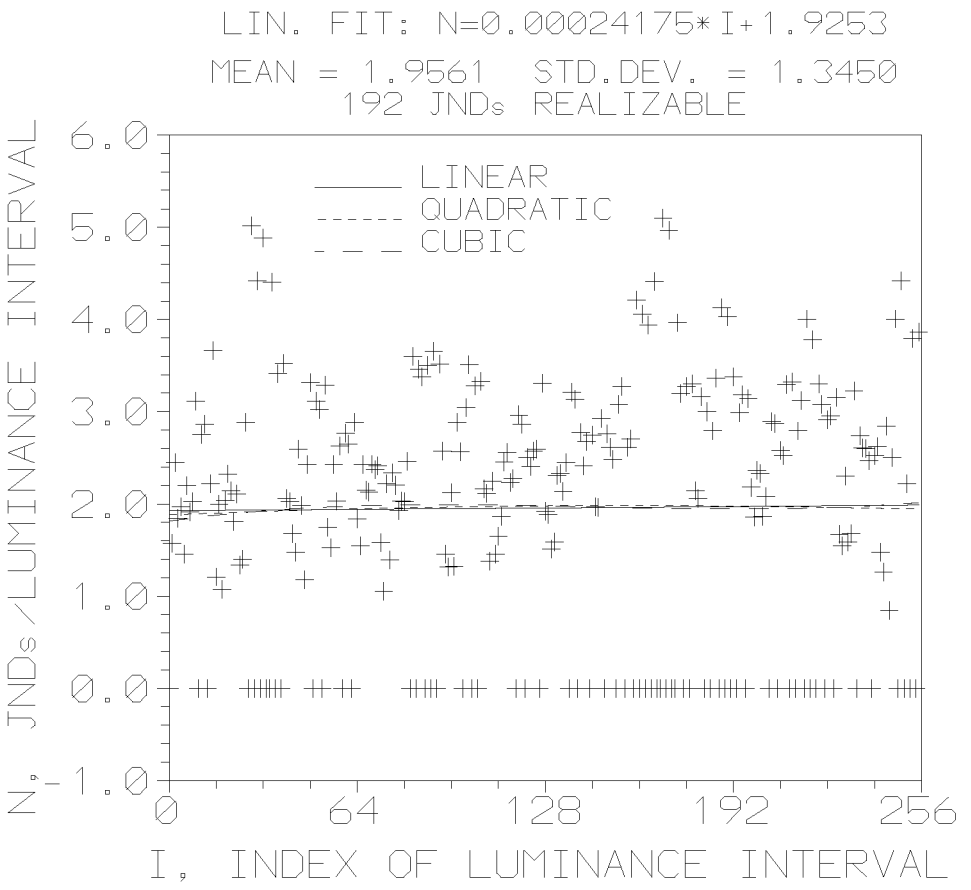

Figure D.3-4 Measures of conformance for a reflective hard-copy Display System with equal input and output digitization resolution of 8 bits

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Annex E (INFORMATIVE) REALIZABLE JND RANGE OF A DISPLAY UNDER AMBIENT LIGHT

Dynamic range is an often used measures of the information content that can be presented by a Display System. However, there are many definitions of dynamic range, and most such definitions do not take into account real world conditions that affect the actual amount of information which can be conveyed by a gray scale pixel. For example, Poynton [E1] refers to the *contrast ratio* of a gray scale display device as the ratio of display intensity between the brightest white and the darkest black of the particular display device in question. However, this definition of dynamic range applies to ideal viewing conditions. Real world conditions such as veiling glare, noise, spatial frequency content of the image, power supply saturation, and ambient lighting in a cathode ray tube (CRT) based viewing situation can degrade the measured dynamic range of the system significantly [E2, E3]. Because of all of these variables dynamic range is an ill-defined concept for a Display System.

Note: *Veiling Glare* is the phenomenon wherein internal light reflections inside the CRT creates a "background lighting" thus reducing the contrast range of the CRT device.

The methods used to determine the degree to which the Display Function of a Display System approximates the Grayscale Standard Display Function can also be used to define two measures which might better characterize the potential capabilities of a Display System to convey information content. Two measures, the theoretically achievable JNDs and the realized JNDs, are useful for comparing Display Systems [E4].

The number of theoretically achievable JNDs is simply the number of JNDs predicted by the visual model given the Luminance Range of the Display System used. The number of theoretically achievable JNDs of a Display System may be found from Table B-1 of Annex B by counting the number of JNDs in the table which fall between the measured minimum and maximum Luminance of the Display System.

This number of JNDs may not actually be achievable due to resolution limitations of other portions of the Display System, in particular, the quantization resolution given by the finite number of bits per pixel driving the Display System. For example, Table B-1 of Annex B may show that a particular Display System is capable of delivering 352 JNDs. However, if only 8 bits per pixel are presented to the Display System, the number of JNDs achievable cannot exceed $2^8 = 256$ JNDs because of the quantizing effect. In actual fact, the number of JNDs realized in a Display System will always be smaller than or equal to the lower of the theoretically achievable JNDs and the quantization limit. This is because some of the quantized values input to the display may not line up with the input value required to achieve the next JND.

The more useful number of realized JNDs, describes how many JNDs are actually achieved given the specifics of the Display System (i.e. the number of gray levels of contrast resolution and the distribution of Luminance values). This definition gives a measure of the information which can actually be conveyed by the system to a human observer, in essence, an informational dynamic range. This number is calculated beginning at the minimum Luminance of the Display System, and then stepping one JND in Luminance from the current Luminance value, and choosing the smallest increment in DDL value that achieves a step at least that large. Repeating this through all the available DDLs will produce a sequence of steps, all at least 1 JND apart, and the length of this sequence of steps is then the number of realizable JNDs of the Display System.

The methods of PS 3.14 cannot precisely duplicate all of the real world sources of degradation in a Display System. However, this uniform method of determining the realizable number of JNDs should give a measure of the actual performance of a particular Display System which would be experienced by a human observer when using the Display System in a real world situation such as the viewing of radiological images in medicine.

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References

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[E3] Gray, J.; "Use of the SMPTE Test Pattern in Picture Archiving and Communication Systems"; J. Digital Imaging, Vol. 5, No. 1, February 1992; pp. 54-58.

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