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A tool for designing digital test objects for module performance evaluation in medical digital imaging

O. KOCSIS†, L. COSTARIDOU†, E. P. EFSTATHOPOULOS†, D. LYMBEROPOULOS‡ and G. PANAYIOTAKIS†*

† *Department of Medical Physics, School of Medicine, University of Patras, Patras, 26500, Greece*

‡ *Wire Communications Laboratory, Department of Electrical and Computer Engineering, University of Patras, Greece*

Abstract. Currently, medical digital imaging systems are characterized by the introduction of additional modules such as digital display, image compression and image processing, as well as film printing and digitization. These additional modules require performance evaluation to ensure high image quality. A tool for designing computer-generated test objects applicable to performance evaluation of these modules is presented. The test objects can be directly used as digital images in the case of film printing, display, compression and image processing, or indirectly as images on film in the case of digitization. The performance evaluation approach is quality control protocol based. Digital test object design is user-driven according to specifications related to the requirements of the modules being tested. The available quality control parameters include input/output response curve, high contrast resolution, low contrast discrimination, noise, geometric distortion and field uniformity. The tool has been designed and implemented according to an object oriented approach in Visual C++ 5.0, and its user interface is based on the Microsoft Foundation Class Library version 4.2, which provides interface items such as windows, dialog boxes, lists, buttons, etc. The compatibility with DICOM 3.0 part 10 image formats specifications allows the integration of the tool in the existing software framework for medical digital imaging systems. The capability of the tool is demonstrated by direct use of the test objects in case of image processing, and indirect use of the test objects in case of film digitization.

Keywords: Digital test object, Performance evaluation, Image processing, Film digitizer.

1. Objectives

Due to the rapid evolution of computerized systems and telecommunication technology in hospitals, medical digital imaging systems have gradually started replacing conventional imaging systems, providing added value services aiming to improve efficiency of diagnosis [1–5]. In medical digital imaging systems, currently represented in the clinical environment by the Picture Archiving and Communication Systems (PACS) concept, modules such as digital display, image compression, image processing as well as film digitization and film printing are introduced in addition to analogue or digital imaging modalities. The last two modules play an important transitory role as bridges between analogue and digital system parts [6].

These modules as well as the services involving them, introduce additional needs of performance evaluation in a digital imaging system, to ensure high image quality [5,7–11]. Common approaches to performance evaluation of these modules are Quality Control (QC) protocols, using physical test objects, traditionally used in QC

* Author for correspondence; e-mail: panayiot@upatras.gr

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of imaging modalities [12–15]. QC protocols are differentiated with respect to the parameters assessed, dictated by the individual requirements of each module being tested, which in turn specify the characteristics of physical test objects. Recently, digital test objects have been used directly as digital images in performance evaluation of digital display [12, 16–19], image processing [20], film printing [12, 16–19] and indirectly as images on film in case of film digitizers [12, 18–19, 21–24]. The most well known digital objects are the Society of Motion Picture and Television Engineers (SMPTE) [18] and Halpern [21] test patterns. However, no flexibility is provided in the design of these digital test objects with respect to different QC user requirements.

The aim of this work is the design and development of a software tool that enables flexible design of computer-generated test objects, by means of user-driven selection of the set of parameters to be assessed in a QC protocol, according to specific user requirements. The designed test objects can be used directly, as digital images, in performance evaluation of digital display, image compression, image processing and film printing, or indirectly as images on film, in case of film digitizers. In order to demonstrate the capability of the tool, direct and indirect use of test objects is presented in two application paradigms, image processing and film digitization.

2. Methods

The basic communication object between the modules of a digital imaging system is the medical image, as figure 1 shows. For example, following acquisition, the digital image can be subjected to film printing, display, storage, compression followed by storage, decompression followed by display, and image processing followed by display. In a digital imaging system digital images are obtained directly, by communication of the output of the respective imaging modality with the digital imaging system, or indirectly, by digitization of the analogue output (film) of an imaging modality. The Digital Imaging and Communications in Medicine (DICOM) standard dictates the requirements for the exchange of medical images and related information between systems and applications [25–26].

In figure 2 direct and indirect use of computer-generated test objects is indicated, as well as the modules of the medical digital imaging system to which they are applicable.

2.1. *Image quality requirements and test object specifications*

Analogue (film) and digital medical image quality is primarily dictated by imaging equipment characteristics and the examination conditions [7, 10, 27]. In addition, digital image quality is affected by the additional modules of a digital imaging system such as digital display [10, 12, 14, 16–18], image compression [9, 11], image processing [10, 20] and in the case of digitized images, by the digitizer [18–19, 21–24]. For analogue images obtained from digital images by film printing the quality of the analogue image is affected by the film printing module [16–18]. The characteristics of a digital image are pixel size and pixel depth (range of grey levels). The effect of the above mentioned modules on medical image quality can be assessed by application of a QC protocol. Parameters such as input/output response

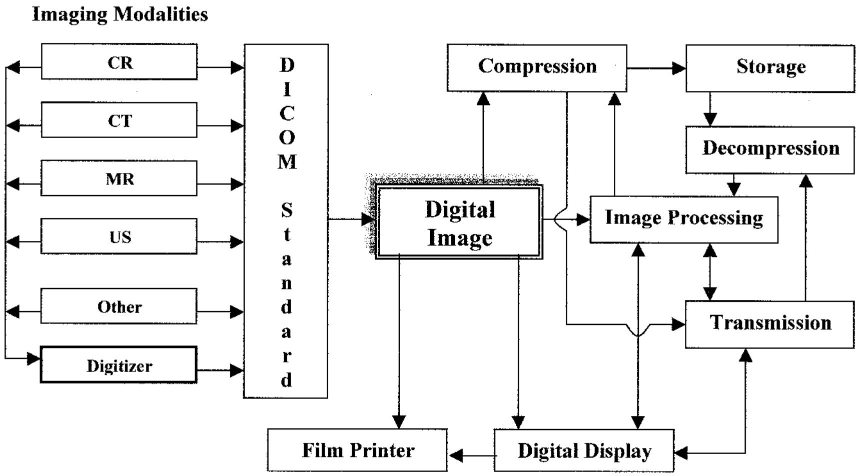

Figure 1. A conceptual framework of a digital image within a medical digital imaging system.

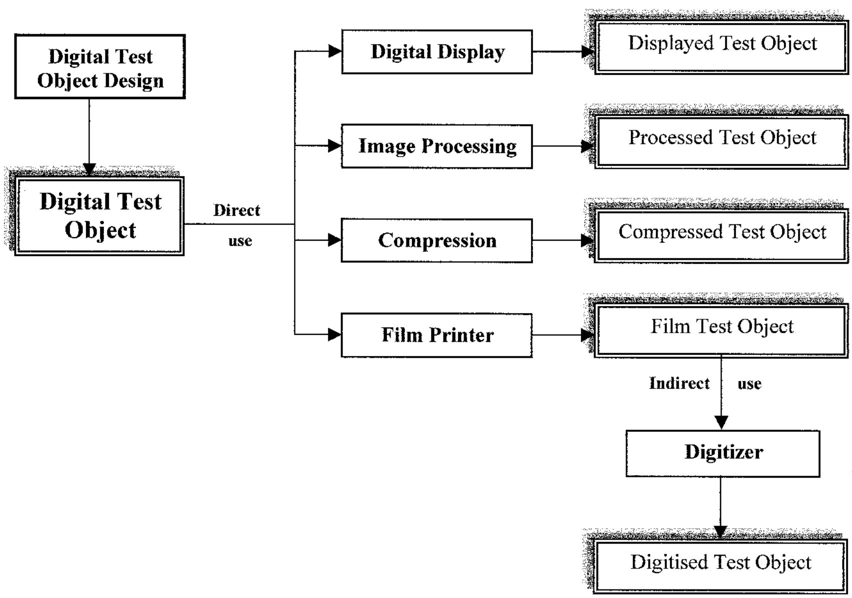

Figure 2. Intended use of digital test objects.

curve, high contrast resolution, low contrast discrimination, geometric distortion, noise, and field uniformity are some of the most important parameters included in most QC protocols [16, 18, 21–22]. Specification of the acceptable value ranges for each of the parameters is also very important, depending on the module or service being evaluated.

The presented tool provides the capability to generate digital test objects to be used in a QC protocol for performance evaluation of the above mentioned modules. The user, according to his/her needs, composes digital test objects in two steps. In the first step, the size (both horizontal and vertical), spatial resolution and pixel

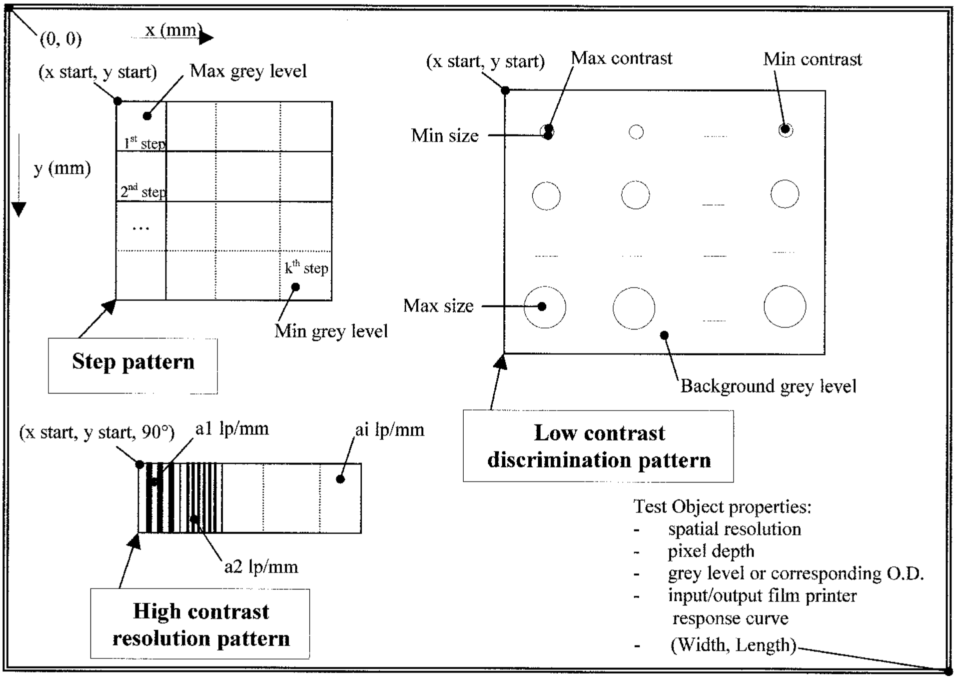

Figure 3. A schematic representation of a test object designed by the tool, indicating its properties and types of test patterns included.

depth of the test object are specified. To facilitate user input, an option is provided to input optical density (O.D.) values instead of grey levels of the test object, as most users are familiar with this characteristic. Input O.D. values are converted to grey level values through a linear function. The O.D. range is considered between 0 and 4.00 O.D. units, and the grey level range between 0 and $2^8 \div 2^{16}$, depending on user selected pixel depth. In the case of designing a test object for indirect use (for digitizer evaluation), the transformation of the test object grey level values to O.D. values must be specified and included as a property of the test object. The actual size of the test object on a display monitor will depend on display resolution. In the second step, the different test patterns that are associated with the QC parameters are designed. Parameters such as input/output response curve, high contrast resolution, low contrast discrimination, noise, geometric distortion, and field uniformity are available. For each pattern, specific parameter value ranges are under user control, as table 1 indicates. A schematic representation of a test object designed by the tool is presented in figure 3.

The input/output response curve of a module has different content, depending on the module being evaluated. For digital display it represents the relationship between grey level values (input) and luminance (output), for film digitizer represents the relationship between O.D. values (input) and grey level values (output) and finally, in the case of film printer, the previous relationship is inversed. The test for input/output response curve is based on step patterns as presented in figure 3. The tool enables the user to create different step patterns, with variable number of steps and variable minimum and maximum grey level (table 1). Selection of the specific values of the above characteristics depends on image quality

Table 1. Test object specifications provided by the tool.

Parameter	Pattern	Characteristic	Range	Comments
Input/output response curve	Step	no. steps	9–36 steps	
		max grey level	$0–2^8 \div 2^{16}$	a
		min grey level	$0–2^8 \div 2^{16}$	a
Noise		x start	—	b
		y start	—	b
High contrast resolution	High contrast resolution	groups of line-pairs	0.59–20.00 pl/mm	The difference of line size between two consecutive groups is 1 pixel.
		orientation	0°, 45° or 90°	
		x start	—	b
		y start	—	b
	Low contrast – variable contrast	background grey level	$0–2^8 \div 2^{16}$	a
		min contrast	1–10%	Step of 1%
		max contrast	1–10%	Step of 1%
		min objects size	0.1–3.0 mm	Step of 0.1 mm
		max objects size	0.1–3.0 mm	Step of 0.1 mm
		x start	—	b
		y start	—	b
Low contrast discrimination	Low contrast – constant contrast	no columns	8–20 columns	
		min background grey level	$0–2^8 \div 2^{16}$	a
		max backgrounds grey level	$0–2^8 \div 2^{16}$	a
		min objects size	0.1–3.0 mm	Step of 0.1 mm
		max objects size	0.1–3.0 mm	Step of 0.1 mm
		x start	—	b
		y start	—	b
Geometric distortion	Grid	grid spacing	5–50 mm	
		background grey level	$0–2^8 \div 2^{16}$	a
Field uniformity	Uniform	grey level	$0–2^8 \div 2^{16}$	a

(a) The range is limited by the pixel depth given as property of the test object under design. In the case that it is chosen to introduce these values as O.D. values, the range is 0–4 O.D. units.
(b) The positioning coordinates are limited by the dimensions of the test object under design.

requirements of a module. For example, for a digitizer, a linear input/output response curve from 0.2 up to 3.5 O.D. units is considered satisfactory for most imaging applications [16, 17, 19, 28] and extended to 4.0 O.D. units in some specific applications [22].

High contrast resolution refers to the smallest size resolved in an image and, in the case of line-pair object is given as the maximum number of line-pairs resolved within 1 mm. The high contrast resolution pattern is designed as groups of line-pairs of high contrast (black and white lines) having vertical, horizontal or diagonal orientation (table 1). A high contrast resolution greater than 3.0 lp/mm (equivalent pixel size less than 0.165 mm) is sufficient for chest x-ray imaging [8, 29–31], while x-ray imaging of the finest structural details in bones requires a spatial resolution of 5 lp/mm [4]. A high contrast resolution of 6 lp/mm (equivalent pixel size 0.08 mm), is considered satisfactory with the exception of mammography [13, 28, 32–34].

Low contrast discrimination is a composite notion, involving both contrast and size of low contrast objects. Figure 3 contains a model of test pattern for low contrast discrimination evaluation. The low contrast discrimination test pattern corresponds to a rectangular area of constant grey level, in which circular objects, having variable size within a column and variable contrast within a row, are embedded (table 1). In addition, low contrast discrimination as a function of grey level values can be tested by an additional low contrast pattern. This pattern corresponds to a rectangular area having a number of columns split into two halves, to test positive and negative contrast. Within each half, columns correspond to varying grey level values, and within each column objects correspond to variable size and constant contrast. A contrast discrimination of 2% for size of low contrast objects between 0.1–3.0 mm imposed by radiographic images is considered as maximum requirement [33, 35].

The noise added by a module or service to a digital image can be approximated by computing the coefficient of variation or the standard deviation of pixel values in a uniform area. If the steps of a step pattern are used for calculation of the coefficient of variation or standard deviation, then the variation of noise as a function of module input values is obtained [17, 21, 23–24, 36]. For geometric distortion the test object is defined as a variable size grid of black lines having a constant background, and field uniformity is checked using test objects having a uniform grey level value (table 1).

2.2. *Software Design and Implementation*

The tool, called Test Objects Design (TOD), has been developed for PC platforms running Microsoft Windows 95 or preferably Windows NT operating systems. Microsoft Visual C++ 5.0 has been chosen as the development environment [37]. The C++ programming language is widely adopted due to its high performance (execution speed) and its advanced object-oriented character (support of classes, encapsulation of data, operator-overloading, inheritance, and polymorphism) [38].

The functionality of the tool is based on the Microsoft Foundation Class Library version 4.2 (MFC 4.2). This hierarchy of classes is an encapsulation of a large portion of the Windows Application Programming Interface (API) in C++ form. These classes provide C++ member function interface to the user-interface items (windows, dialog boxes, lists, buttons, slider bars, etc.) that they encapsulate. The MFC library supplies various classes serving generic functionality to easily generate the ‘skeleton’ of the application source code.

The tool uses the Multiple Document Interface (MDI) model, i.e. documents (images) are displayed in resizable – movable child windows inside the main frame window.

The types of documents that the tool can handle are the BMP, TIF, PAPYRUS (PAP) formats and a type specific to the tool, called TOD. BMP and TIF formats enable the reading and saving of greyscale images corresponding to test objects with up to 16 bits dynamic range. The TOD format enables the reading and saving of tool-type files and is used to enable modification of test objects under design in more than one session. In order to be integrated in a PACS environment, the tool supports the PAPYRUS 3.0, DICOM-compatible image format. Reading and saving a PAP file format is accomplished by calling C routines of the PAPYRUS software toolkit (compiled as a DLL file), provided by the University Hospital of Geneva [39].

The grey scale windowing is used to map the image intensity values (with dynamic range of up to 16 bits) to the pixel grey levels of the display (0–255). Greyscale window width and level adjustments directly affect the image contrast and brightness respectively. The minimum configuration consists of a PC equipped with a 586 processor running at 120 MHz, 32 MB of RAM and a 1024×768 pixel, 24-bit colour display.

3. Results

3.1. *User-driven design of test objects*

The main window of the application is a menu based user interface that includes the usual functionality, like File, Edit, View, Help, and a function for the user-driven design of the test objects (TOD menu command), as figure 4 shows.

In order to create a new test object the TOD Properties menu command is used to define size, spatial resolution, pixel depth, input values option and, if necessary, to input the printer input/output response curve for the new test object. According to these specifications, a working space with these properties is created and provided with appropriate window and level display handling. After this part is completed, the access to the Evaluation Parameters menu command is enabled. The instance from figure 4 shows an already created working space containing a previously created step pattern for input/output response curve evaluation. Upon evaluation parameter selection, the associated test pattern is specified in the status bar, as in figure 4, and a dialog box for additional test pattern specifications is enabled, as shown in figure 5.

Figure 5 presents an instance of a low contrast discrimination test pattern dialog box. The relative positioning of the test pattern under design inside the test object, is specified by its upper left corner coordinates. Input grey level values and contrast values of low contrast objects have to be compatible to the respective requirements for low contrast discrimination test patterns applicable to the module being tested, as mentioned in § 2.1. A preview function enables the user to visually inspect the test pattern under design. Similar dialog boxes control the design of the other test patterns.

Figure 6 shows an instance of the Edit TOD menu command associated dialog box, enabling the user to access any of the test patterns contained in the active test object and to modify/delete them.

Figure 7 presents an example of a test object in final form, containing a group of patterns repeated in the four corners and in the middle, a low contrast discrimination

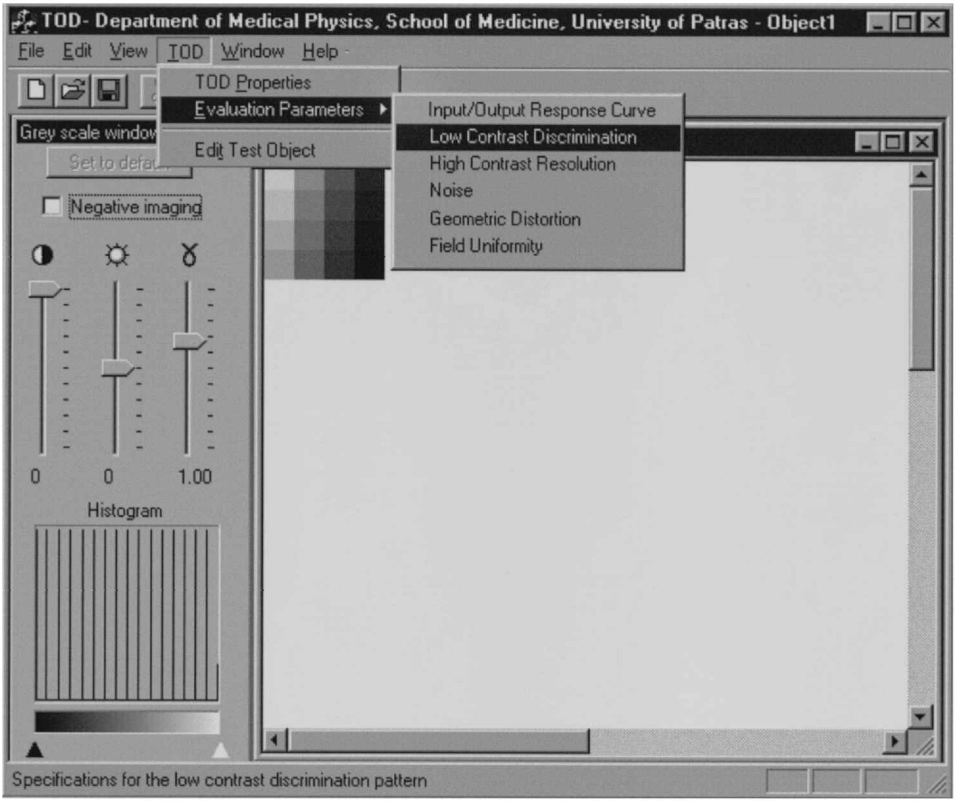

Figure 4. An instance of the tool main window and available evaluation parameters. At present the low contrast discrimination parameter is selected. A test object with the associated grey-scale window/level manipulation functions is shown, containing a previously created step pattern.

pattern of constant contrast in the bottom and a grid pattern covering the remaining area. The group of patterns is composed from a step pattern, two high contrast resolution patterns (horizontally and vertically oriented), and a low contrast discrimination pattern of variable contrast.

3.2. *Direct use of test objects*

The direct use of digital test objects is presented by an application paradigm in the evaluation of an image processing algorithm, the sharpening filter, of a medical image manipulation system (OSIRIS) [40]. For display and measurements on the digital test object before and after the application of the sharpening filter, the Region Of Interest (ROI) operations of another visualization tool were used [41].

In the case of evaluating the effect of an image processing algorithm on a digital image, calculating image histograms of a step pattern has been selected instead of the input/output response curve. By comparing the two histograms (figure 8), before and after the application of the sharpening filter, it is observed that the majority of the pixels inside each step preserve their grey level value. Horizontal and vertical profile lines along the steps demonstrate that a change in grey level value occurs only at step edges, as it is expected from a sharpening filter.

The effect of the sharpening filter with respect to noise was evaluated using a step pattern to which gaussian white noise has been added. Measurements of the mean

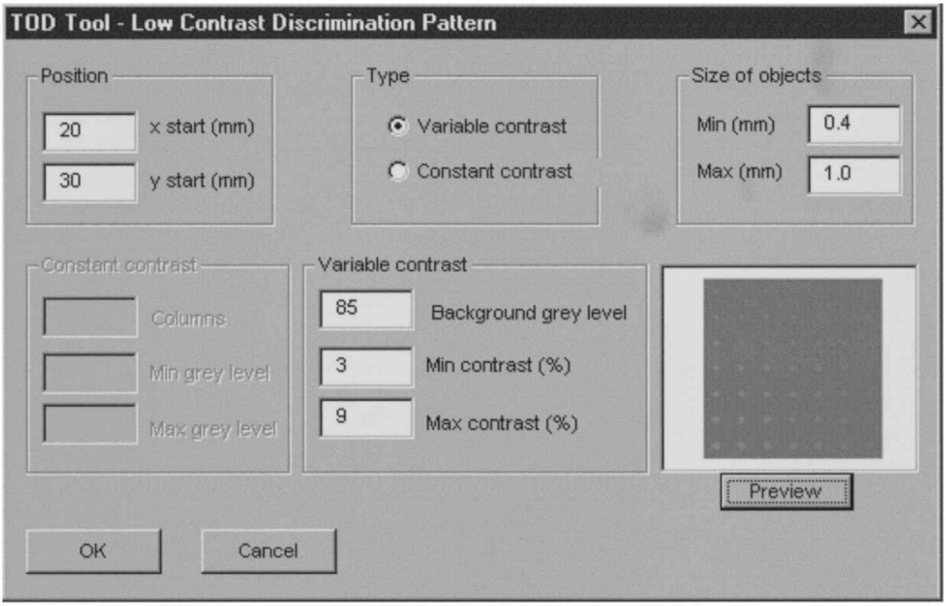

Figure 5. The test pattern specifications dialog box for a low contrast discrimination pattern. As a variable contrast pattern type is selected, the respective variable inputs are activated. In the left side a preview corresponding to selections made is shown.

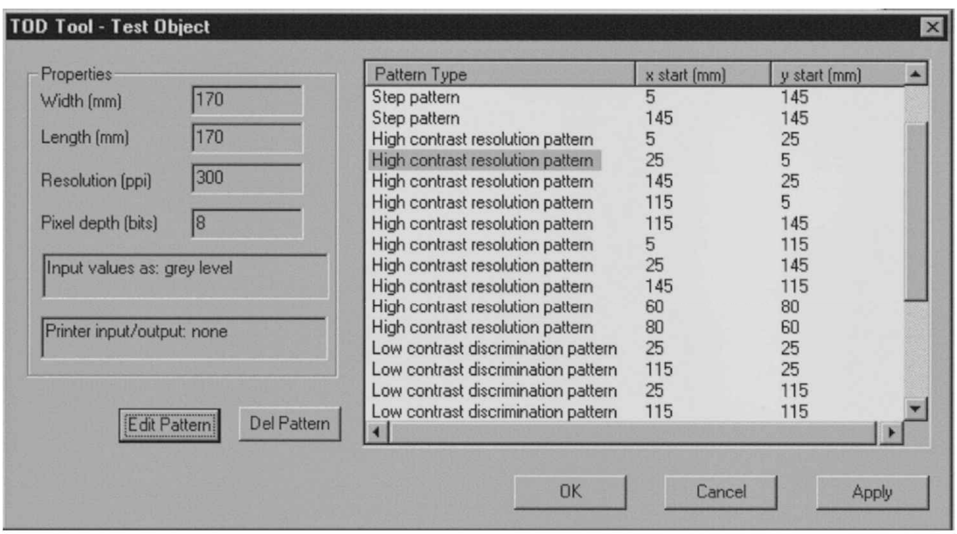

Figure 6. The dialog box corresponding to test object editing (edit/delete operations). In the left side the properties of the test object are displayed, while in the right side patterns types and positioning coordinates are listed.

value and standard deviation in each step, before and after the application of the sharpening filter, show an increase of noise, measured as coefficient of variation (coefficient of variation = standard deviation/mean pixel value), up to 5 times (figure 9).

High contrast resolution patterns, vertically and horizontally oriented, were

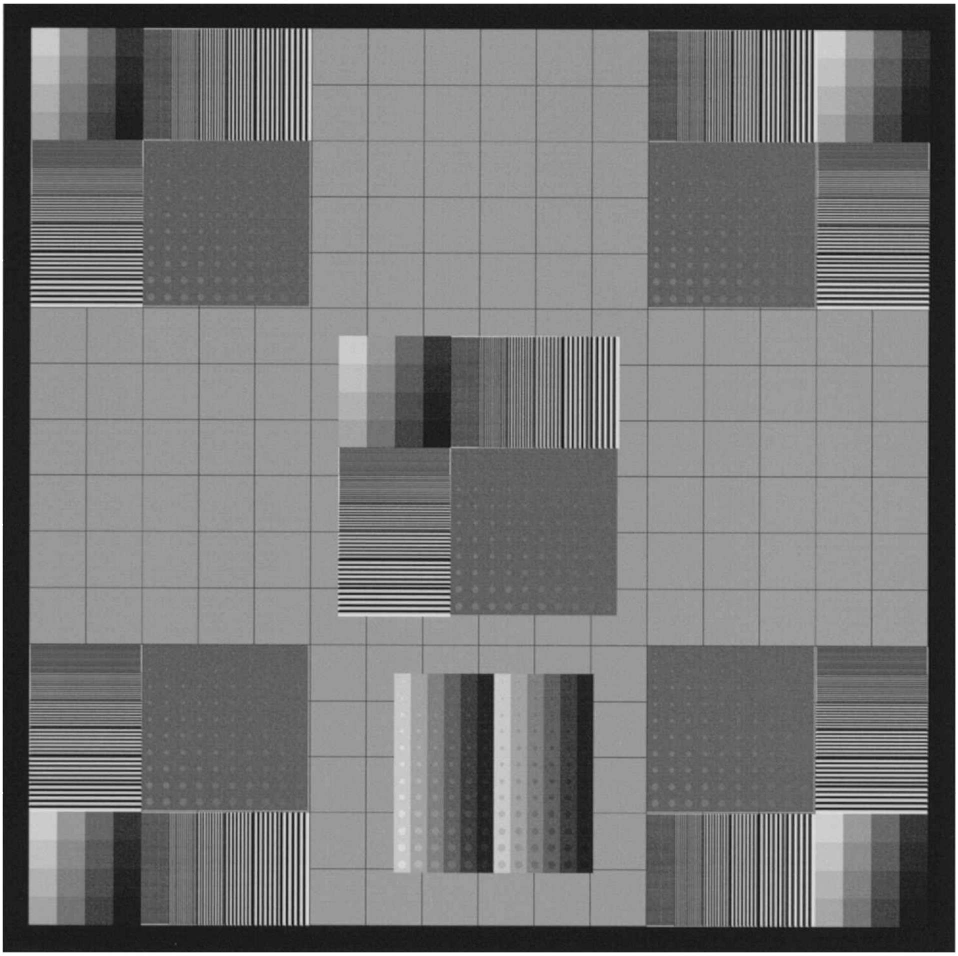

Figure 7. A test object example. A group of patterns (a step pattern, two high contrast resolution patterns, and a low contrast discrimination pattern of variable contrast) is repeated in the four corners and in the middle of the test object. In addition, a low contrast discrimination pattern of constant contrast is present in the bottom of the test object and a grid pattern is covering the remaining area.

processed using the sharpening filter. By comparing the line profile plots before and after the application of the filter it was observed that there are not modifications introduced by the filter with respect to spatial resolution.

A low contrast discrimination pattern was also processed using the sharpening filter. As figure 10 shows, there is an important change in grey level values of the pixels that are located at the edges of the low contrast objects. This results in an increase of the perception of these objects, even if the contrast between objects and background is very low.

3.3. *Indirect use of test objects*

The indirect use of digital test objects is presented by an application paradigm in the performance evaluation of a film digitizer (AGFA DuoScan). The printed on film version of the designed test object is used as input for digitization, as figure 2

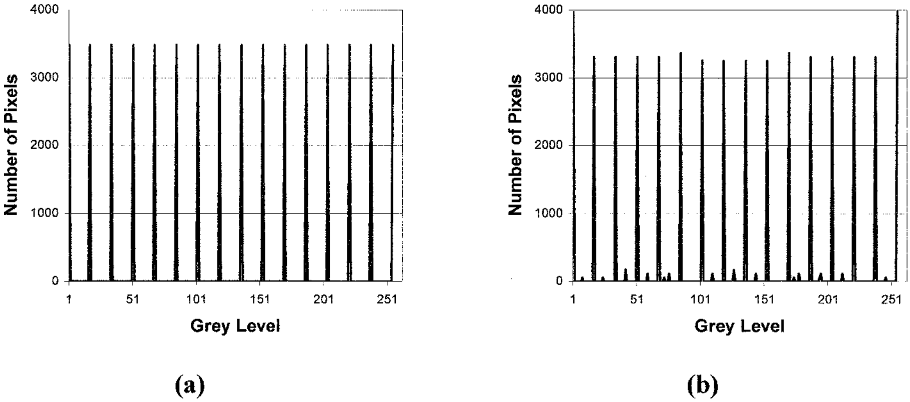

Figure 8. Histograms corresponding to a step pattern (min grey level = 0, max grey level = 255, number of steps = 16) (a) before and (b) after the application of the sharpening filter.

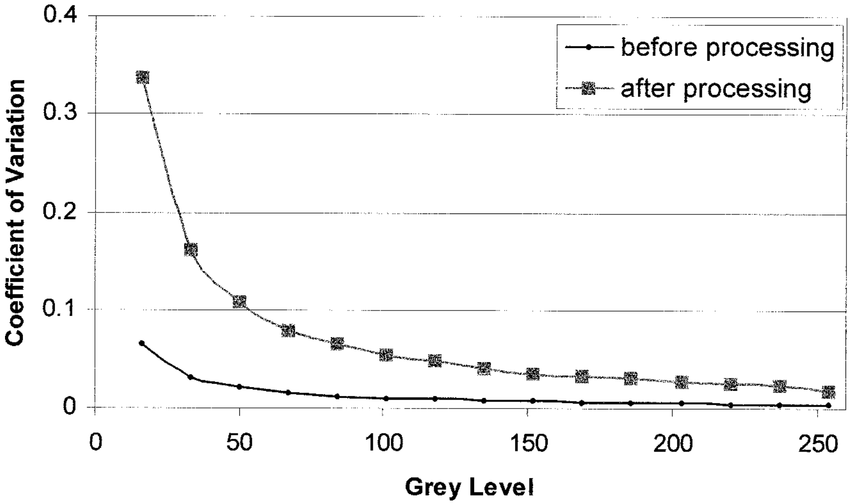

Figure 9. The coefficients of variation before and after the application of the sharpening filter, calculated in each step of a step pattern (min grey level = 0, max grey level = 255, number of steps = 16).

indicates. For display and measurements on the digitized test object, the same visualization tool was used [41].

The input/output response curve, presented in figure 11, was derived by relating the mean grey level inside a square ROI (20×20 pixels) in each of the 36 steps of a step pattern to the corresponding measured O.D. values (measured from the film test object with a densitometer). This curve demonstrates a compression of high O.D. values (from 2.00 to 3.40 O.D. units) to a few grey levels, thus limiting the diagnostic capability of the digitized images.

For noise measurements, the coefficient of variation, presented in figure 12, was calculated in each step of the step pattern used for the derivation of the input/output response curve.

The high contrast resolution was evaluated by observing line profiles perpendicular to the orientation of two high contrast resolution patterns (horizontally

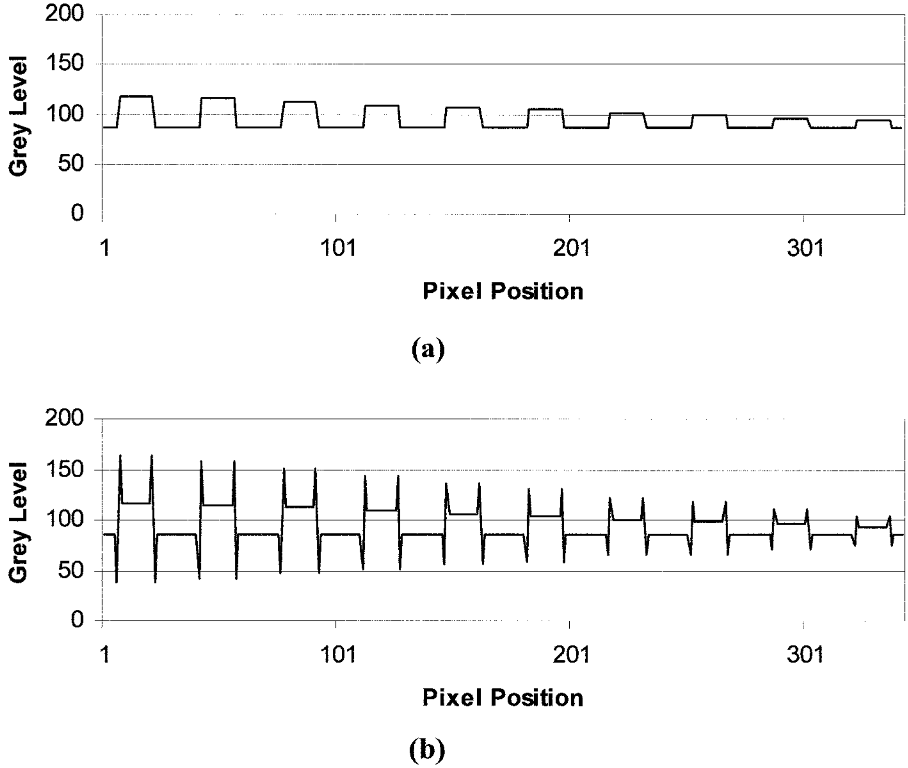

Figure 10. Line profiles for the 1.3 mm row of objects of a low contrast discrimination pattern of variable contrast (background grey level = 85, min contrast = 1%, max contrast = 10%, min size = 0.4 mm, max size = 1.3 mm) (a) before and (b) after the application of the sharpening filter.

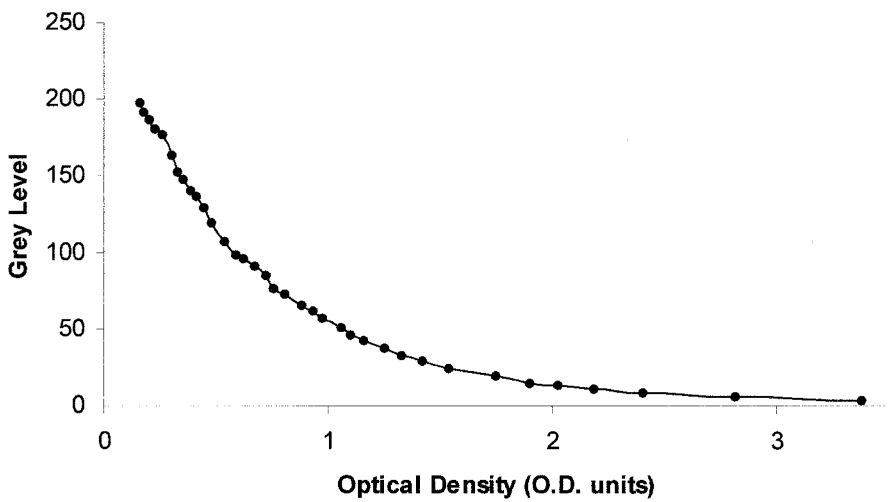

Figure 11. The input/output response curve of the film digitizer derived on the basis of a step pattern (min O.D. = 0.18 O.D. units, max O.D. = 3.40 O.D. units, 36 steps).

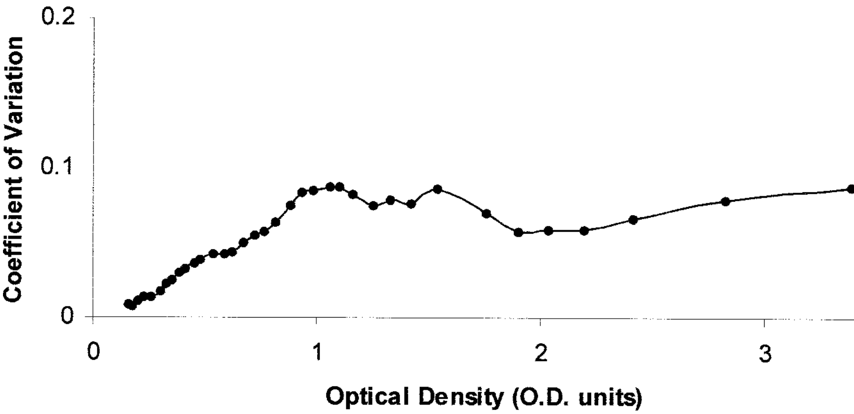

Figure 12. The coefficient of variation as a function of O.D. for the film digitizer, calculated in each step of a step pattern (min O.D. = 0.18 O.D. units, max O.D. = 3.40 O.D. units, 36 steps).

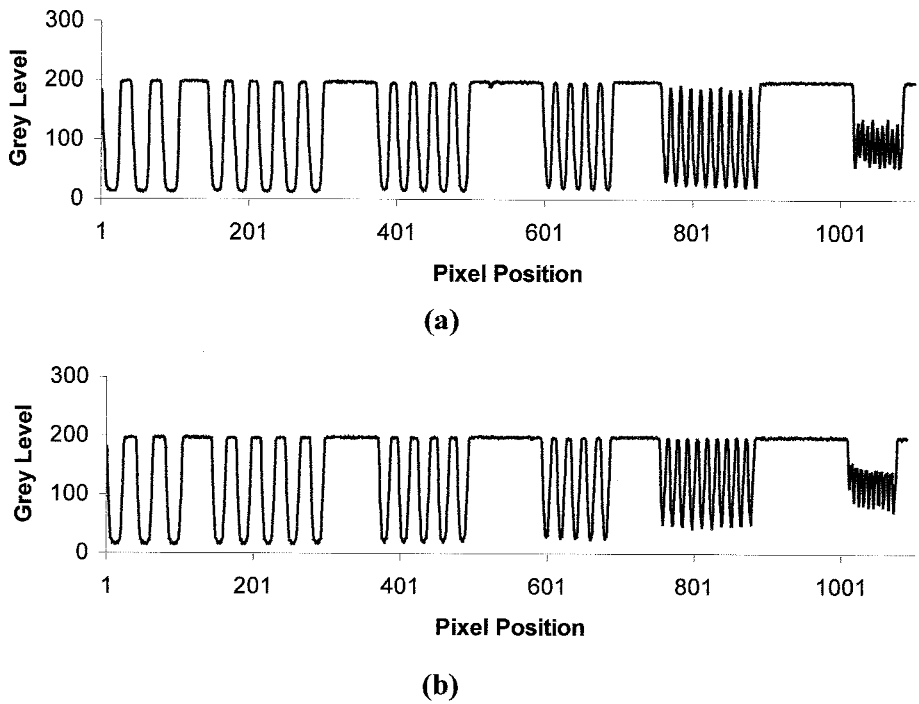

Figure 13. Line profiles for two high contrast resolution patterns with line-pairs oriented (a) vertical (90°, groups 1.00, 1.18, 1.50, 2.00, 2.95 and 5.90 lp/mm) and (b) horizontally (0°, groups 1.00, 1.18, 1.50, 2.00, 2.95 and 5.90 lp/mm).

and vertically), as figure 13 presents. The selected spatial resolution of the digitizer was 1000 ppi. In both line profile plots the 5.90 lp/mm line-pairs group is considered unresolved according to a profile amplitude criterion [21].

Low contrast discrimination was evaluated by deriving the low contrast threshold curve using a low contrast discrimination pattern of variable contrast (min contrast = 1%, max contrast = 9%, min size = 0.1 mm, max size = 1.0 mm, background O.D. = 1.00 O.D. units). For each column of low contrast objects an

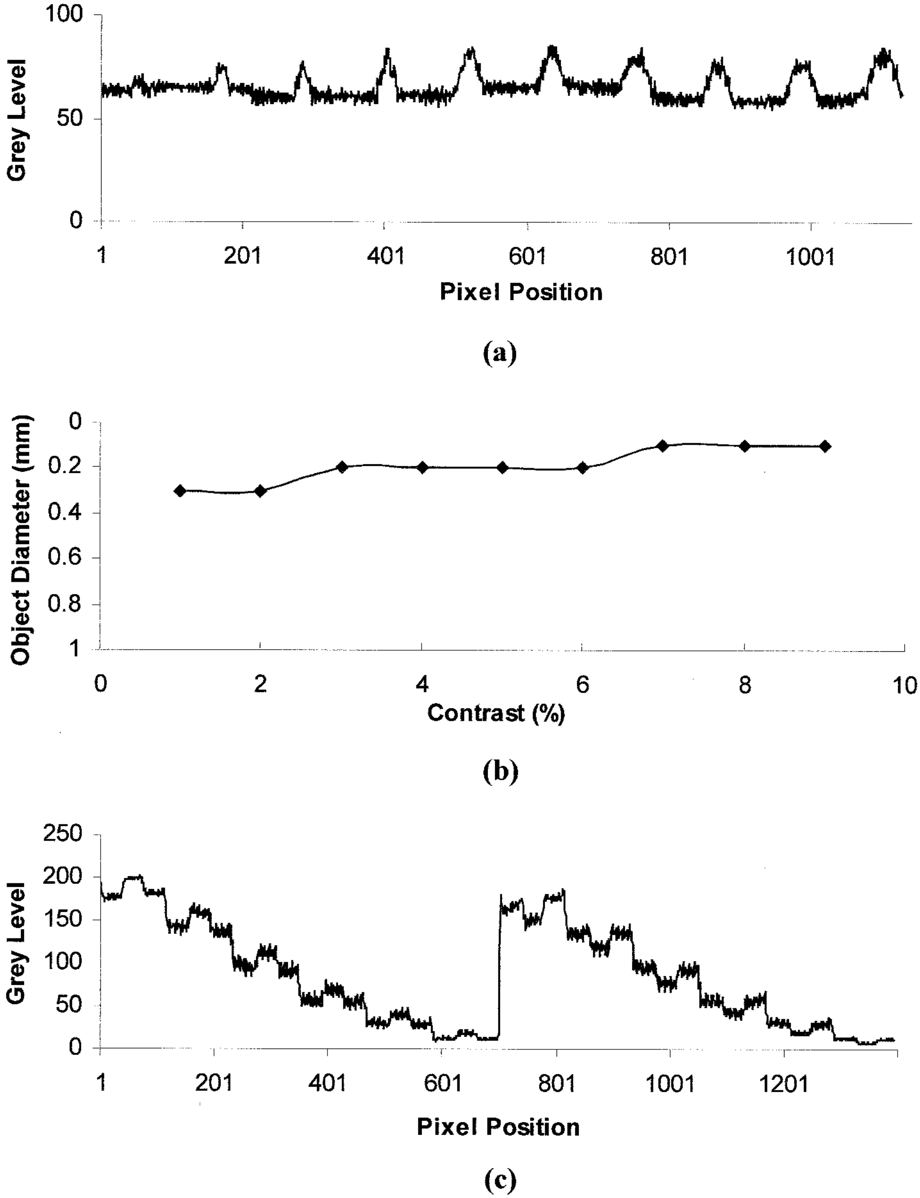

Figure 14. Low contrast discrimination. (a) Average line profile for the 6% contrast column of a low contrast discrimination pattern of variable contrast (background O.D. = 1.00 O.D. units, min contrast = 1%, max contrast = 9%, min size = 0.1 mm, max size = 1.0 mm). (b) The contrast threshold curve derived using the average line profiles for all the columns of the previously specified low contrast discrimination pattern. (c) Line profile for the 1.0 mm objects line of a low contrast discrimination pattern of constant contrast (no columns = 12, min O.D. = 0.18 O.D. units, max O.D. = 2.80 O.D. units, min size = 0.1 mm, max size = 1.0 mm).

'average' profile plot (figure 14a) of a set of three lines passing through the centre of the low contrast objects was used to identify the minimum size of the low contrast objects that can be discriminated for a specific background contrast. From this 'average' plot, the smallest detectable object size (0.2 mm) is identified, according to the above mentioned profile amplitude criterion. By repeating this for all columns the contrast threshold curve is derived (figure 14b). This curve demonstrates the dependence of object detectability (size) on contrast. Figure 14c shows a line profile for a low contrast discrimination pattern of varying background O.D. and constant objects contrast in each column. A decrease in signal detection, corresponding to line profile amplitude decrease, is observed for low grey levels (i.e. high O.D. values), in agreement with the derived input/output response curve.

In addition to the above parameters, geometric distortion and the digitizer specific parameters, light leakage and film slippage, have been evaluated by visual inspection of corresponding patterns. Geometric distortion is evaluated by a grid pattern. Light leakage refers to entrance of light in the periphery of the digitizing area. It is tested by adding into the test object a black border of 5 mm. Film slippage refers to the movement of the film during digitization, or to any problems with the stepping motor of the digitizer. It is tested by adding in the test object diagonally oriented high contrast resolution patterns. For the film digitizer used in this paradigm no problems of geometric distortion, light leakage or film slippage were identified.

4. Discussion

The main advantage of the presented tool is the user-driven design of test objects to be used in performance evaluation of modules (digitization, display, film printing, compression, and image processing) and services (e.g. teleradiology) of a digital imaging system. The user-driven design provides test objects that are flexible in dealing with the requirements of the various modules of a digital imaging system. Test object flexibility is inherited by their soft character, which enables the selection of performance evaluation parameters, as well as pattern specifications with respect to positioning, contrast and spatial resolution. The integration of the tool in a digital imaging system is permitted by the capability of the tool to handle DICOM compatible image formats, specifically PAPYRUS, 3.0, and by window width/level display adjustments of image dynamic range of up to 16 bits.

Using those digital test objects, performance evaluation can be carried out by quantitative measurements or by visual inspection. At present, the tool does not provide evaluation functionality, as the ROI operations of another visualisation tool [41] were used in the present evaluation paradigm. However, enhanced ROI operations are necessary for quantitative measurements on the test objects, such as an 'average' plot profile for a rectangular area for the high contrast resolution test patterns, a multi-square ROI for quick extraction of data for the input/output response curve plot, and Wiener spectra computation for more accurate noise evaluation [42].

Use of digital test objects to evaluate image processing algorithms can be a preliminary step in the integration of an algorithm in the clinical environment, as the final acceptance will be driven by performance evaluation studies involving clinical images. For the evaluation paradigm of the film digitizer the test object must be in a hard-form (film copy of the digital test object) and this introduces the printer in the evaluation chain. The limits imposed by the printer are limiting the design of film test objects. For example, a printer spatial resolution of 300 lpi results in a maximum high contrast resolution of 5.90 lp/mm. Thus, although higher resolutions can be contained in a test object (e.g. up to 20 lp/mm) these can not be obtained and subsequently evaluated using line profiles in a film test object. An alternative approach to evaluating such a high resolution would be to find the resolution limit of the film digitizer by calculating its modulation transfer function (MTF) [36]. Another problem related to the film test objects is that GL to O.D. transformation function of the printer should be known before designing the test object, as the inverse transformation function has to be used as a property of the test object.

Future work will be focused on improving the positioning facility of the test patterns inside the test object, that is now keyboard-based, to mouse drag and drop operations. In addition, the evaluation functionality will be embedded into the tool, based on enhanced ROI operations, including point spread function (PSF) and MTF for high contrast resolution measurements, and Wiener spectra for noise measurements. Finally, the tool will support database communication for follow-ups in time, or comparative performance evaluation studies.

5. Conclusion

Medical digital imaging systems are characterized by the introduction of modules such as digitization, display, film printing, compression, and image processing that require performance evaluation to ensure high image quality. A tool for designing computer-generated test objects applicable to QC protocol based performance evaluation of these modules is presented. The tool enables the selection of parameters of a QC protocol and the user-driven design of digital image test objects to be used, directly or indirectly, in such a protocol. Test object design is flexible, due to the soft character of the tool, which offers to the user control of test pattern specifications. The object oriented design and implementation of the code make the tool expandable and the compatibility with DICOM image formats allow the integration of the tool in the existing software framework for medical digital imaging systems. The capability of the tool has been demonstrated by direct use of the test objects in case of image processing, and indirect use of the test objects in case of film digitization.

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