Free software for performing physical analysis of systems for digital radiography and mammography

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Purpose: In this paper, the authors present a free software for assisting users in achieving the physical characterization of x-ray digital systems and image quality checks.

Methods: The program was developed as a plugin of a well-known public-domain suite ImageJ. The software can assist users in calculating various physical parameters such as the response curve (also termed signal transfer property), modulation transfer function (MTF), noise power spectra (NPS), and detective quantum efficiency (DQE). It also includes the computation of some image quality checks: defective pixel analysis, uniformity, dark analysis, and lag.

Results: The software was made available in 2009 and has been used during the last couple of years by many users who gave us valuable feedback for improving its usability. It was tested for achieving the physical characterization of several clinical systems for digital radiography and mammography. Various published papers made use of the outcomes of the plugin.

Conclusions: This software is potentially beneficial to a variety of users: physicists working in hospitals, staff working in radiological departments, such as medical physicists, physicians, engineers. The plugin, together with a brief user manual, are freely available and can be found online (www.medphys.it/downloads.htm). With our plugin users can estimate all three most important parameters used for physical characterization (MTF, NPS, and also DQE). The plugin can run on any operating system equipped with ImageJ suite. The authors validated the software by comparing MTF and NPS curves on a common set of images with those obtained with other dedicated programs, achieving a very good agreement. © *2014 American Association of Physicists in Medicine.* [http://dx.doi.org/10.1118/1.4870955]

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1. INTRODUCTION

The increasing sophistication and resolution of modern medical imaging devices leads to increasing difficulties in managing the assessment and the quality assurance of the clinical systems. The quantitative assessment of image quality is an important consideration in any type of imaging system. Researchers and equipment vendors need to work collaboratively to develop the quantitative protocols and robust analytical software that will lead to the routine inclusion of quantitative parameters, such as spatial resolution, noise spectra, detector's efficiency, in order to assess image quality for equipment performance. Existing guidelines for using and controlling the new technologies do not attain either the specific level for each appliance or the proper insight needed in most of practical situations.[1,2] In such a state, the day to day job of applying guidelines (whenever they exist) is very demanding, even for the qualified personnel in the health services. Besides, the *Digital Era* entails the need of staff with new skills, not always available in many hospital departments. In fact, the achievement of measurements in accordance to the most common standards[3,4] requires skills for the development and implementation of image processing techniques and software tools. These skills are not so common among the hospital departments and there are very few software programs available to make these quantitative measurements for clinical units, such as IQWorks (Ref. 5) and Saunder's software.[6]

The aim of this work is to present a free software developed by our group for assisting users in achieving a physical characterization of an x-ray digital imaging system (i.e., the assessment of its spatial resolution, noise analysis, and detection efficiency), and in performing some of the most common image quality checks. For all the parameters whose description is covered by IEC standards, their evaluation is achieved by following those standards. The software has been

implemented as an ImageJ plugin. In this way, all the functionalities of the ImageJ suite (such as, among others, importing DICOM and raw images, i.e., images with no header, zoom, window/level, drawing of ROIs, plotting data, etc.) can be used with our software. Furthermore, users are facilitated, since the plugin is integrated in a suite widespread and familiar for most of the physicists of the medical imaging community. We believe that this software may be useful for those concerned with assessing the imaging performance, quality control, and quality assurance of medical imaging equipment, such as physicists working in hospitals, and more in general, for the staff working in radiological departments, as medical physicists, physicians, engineers. The availability of such software will allow the radiological departments and the technical correlated departments to benefit of a freeware, accurate, and flexible set of software procedures. These procedures could help to avoid that people from each radiological departments spend a lot of time to produce by themselves similar tools. In addition, also departments with no expertise in some specific procedures or lacking human resources able to implement such software can access to these tools for free. Finally, this could help to spread out a sort of standardization of all the procedures and techniques for most of the quality assurance checks.

Our group previously developed software for achieving some image quality checks for systems for digital imaging. The main difference of the presented plugin with that program, named QC_DR and developed in IDL,[7] is that in that case users can calculate only a part of the parameters that can be calculated with our plugin (image quality checks and response function). In fact, with that software it was not possible to estimate modulation transfer function (MTF), noise power spectra (NPS), and detective quantum efficiency (DQE).

2. MATERIALS AND METHODS

The software can be used with images coming from different modalities (x-ray based projection radiography, mammography, angio/fluorography) and assists users in calculating various physical parameters such as the response curve, MTF, NPS, and DQE. To assess the image quality of an imaging system, spatial resolution and noise properties can be evaluated using metrics, such as MTF and NPS, respectively. These factors contribute for the measurement of the DQE, which is well established as the most suitable parameter for describing the imaging performance of an x-ray digital imaging device.[8] The DQE is the measure of the combined effect of the noise, spatial resolution, and contrast performance of an imaging system, expressed as a function of the object detail. The MTF can be estimated both with the slit and the edge techniques.[9,10] Some parameters, such as detector uniformity, dark and lag analysis, and defective pixels, can also be estimated for achieving an image quality control of the investigated system. Results can be displayed as text and graphical plots and can be exported for further processing. All the operations related to the software can be realized in strict interconnection with the ImageJ framework.

The software was designed in conformity of the following strategies:

– platform independence: the software can run on any operating system, this guarantees an easier and wider distribution;

– modularity: it means that essential parts of the project are independent and can be easily replaced by another implementation. For instance, if a different method is available for estimating the defective pixels (or any other parameter we can calculate with the plugin), the implementation of this new method can replace the current one and the rest of the software will not be affected from this change. This will help upgrades and/or personalization of the program. At this stage the possibility of upgrading the software with different modules is reserved to the developers;

– configurability: it means that a user can configure many parts of the software to better fit his/her needs (e.g., changing the number and the size of the region of interests for evaluating the contrast-to-noise ratio).

The software was implemented in Java and is freely available as ImageJ plugin. It can be found online (www.medphys. it/downloads.htm) and does not require any licensed software. It can be easily installed, as the majority of the ImageJ plugins: it is sufficient to copy the .jar file in the ImageJ plugin folder, restart ImageJ, and the plugin label "COQ" will then appear on the list of the plugins. Figure 1 shows the main window of the graphical user interface (GUI): the window covers the entire screen and can be divided into three sections. The first one (upper left) contains the buttons for choosing the operations that the user would like to perform. The second one (right) displays the image (or images stack) used for achieving the results of the chosen operation. The third one (lower left) shows the results obtained, both in textual and graphical way.

Users can configure some options, such as the possibility of opening multiple images at the same time, using data from external files for computing some parameters (e.g., the linearization function, the MTF, and the NPS for computing the DQE), importing raw images (i.e., images with no header) instead of the typical images in DICOM format, changing the default size of the ROIs, and others, by using the *Config* button, as shown in Fig. 2.

The main functions implemented in the plugin can be divided in two classes: physical characterization parameters and image quality checks. The physical characterization of a digital system consists a set of tests for measuring parameters such as spatial resolution, noise properties and detection efficiency that can be measured at the time of commissioning. Technical image quality checks usually include a series of testing procedures that can be achieved periodically in very short time. These checks can be used for monitoring the system and ensuring that the high image quality remains in place over time. Five different classes of functions are implemented in the software, as a combination of the three analyzed modalities (mammography, general radiography, and angio/fluorography) and two technologies [digital
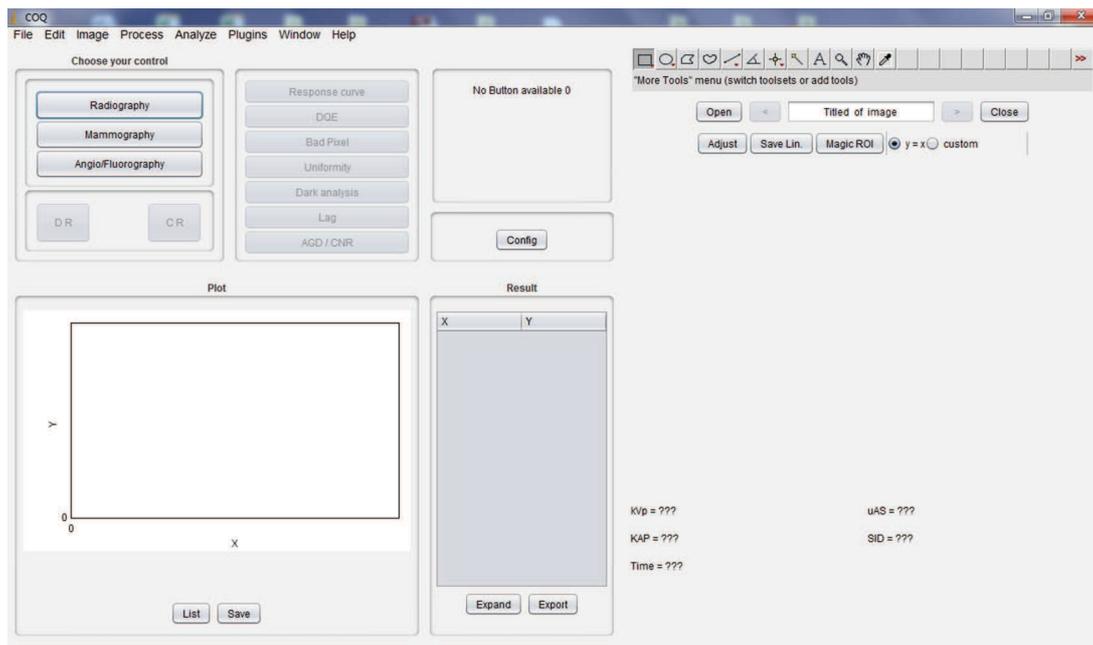
FIG. 1. Main window of the ImageJ plugin developed for performing the physical analysis and the image quality checks.

radiography (DR) and computed radiography (CR)]. Most of the functions are the same for all the five options, whereas some specific issues are considered for each of the option [e.g., the beam spectra tabulated for mammography are different to those used in general radiography, the average glandular dose (AGD) is calculated only for mammography, for CR systems lag and dark analysis are not computed and only the global uniformity is calculated, for angio/fluorography only the additive lag is calculated].

Other software products are freely available for achieving the physical characterization of systems for digital imaging in the medical field. To the best of our knowledge, most of them calculate the MTF and NPS only (or only one of the two metrics), and the user must combine them to extract the DQE. Moreover, those products are available only for some operat-

ing systems, or need virtual machines to run. With our plugin users can calculate all three most important parameters used for physical characterization (MTF, NPS, and also DQE), can run on any operating system and only need the freely available well-known ImageJ suite. In this paper, we considered two of the available free software products: IQWorks (Ref. 5) and one developed by Saunders and Samei at Duke University.[6] In Sec. 3, we validate our plugin through a comparison on the same set of input data, in terms of MTF and NPS.

2.A. Physical characterization

The first outcome that can be achieved is the response function of the system (also termed signal transfer property). To this end, one image for each exposure level shall be acquired,
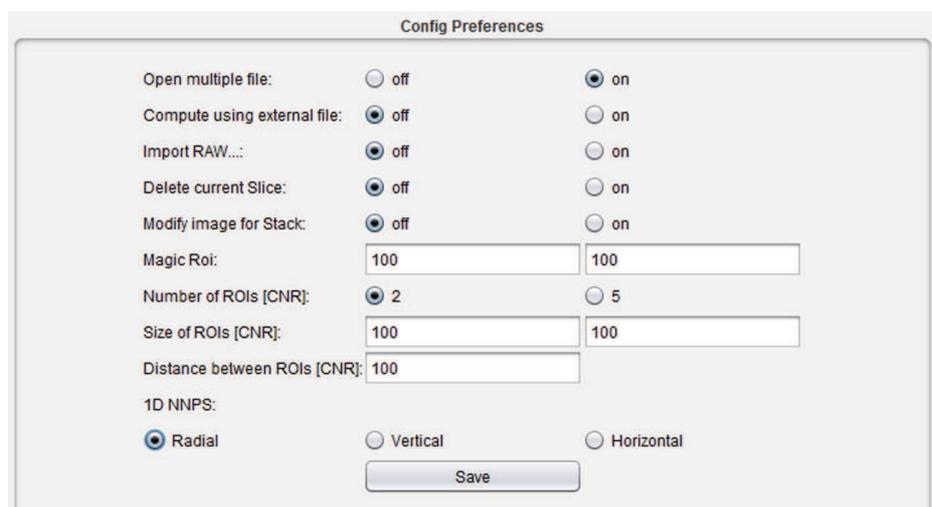

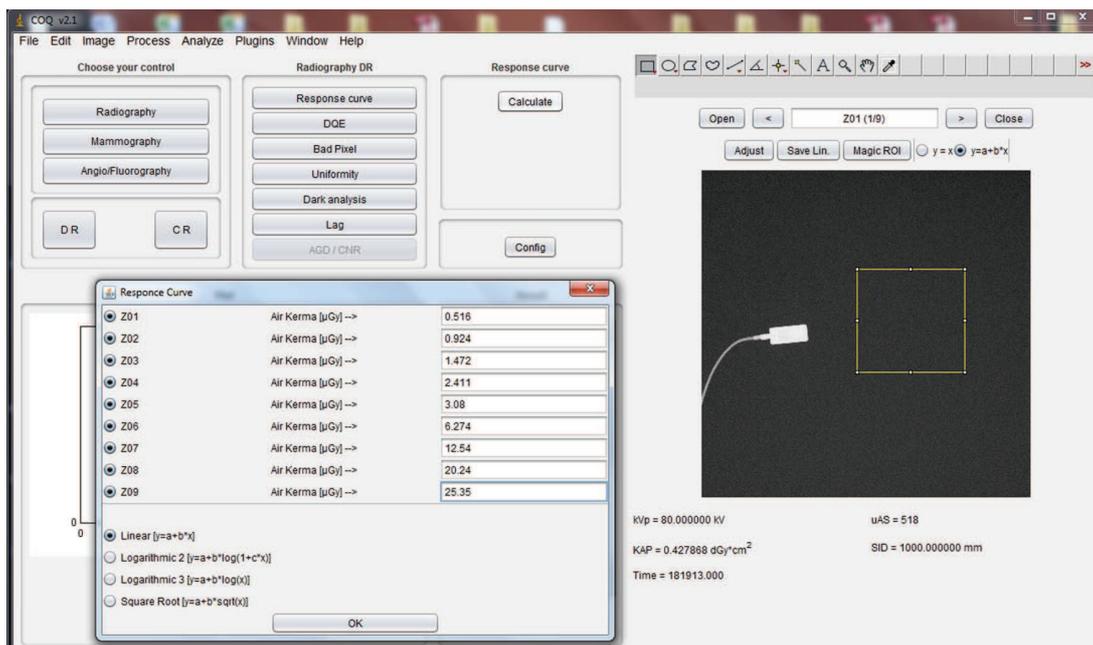FIG. 2. Window showing the Configuration menu available to the users for setting some parameters.

FIG. 3. Example of the calculation of the response curve. Users must provide a set of flood images, and associate to each one the correct exposure value, using the window shown on the left. Here, users can also choose some fitting functions, for fitting the data at the various exposure values.

in a range of exposures compatible with clinical conditions. The number of exposures required shall be estimated in such a way that the maximum increment of logarithmic exposure is not greater than 0.1, as suggested by IEC standards.[3,4] A suitable fitting function can be estimated with the plugin, chosen among the most common ones (linear, logarithmic, or square root based on the response of the digital system, see Figs. 3 and 4). According to the signal transfer theory, the x-ray detector needs to be linear and shift invariant in order to calculate the DQE. Based on this theory, the IEC standards[3,4]

recommend the linearization of the images prior MTF and NPS calculations. This is mainly required for CR detectors that have logarithmic response but can be also applied to DR detectors. When the linearization function is already known, users can directly insert its parameters through a dialog window.

The MTF, NPS, and DQE parameters can be estimated by acquiring and using suitable images, as reported in the literature.[9–11] The MTF can be calculated from both slit and edge techniques. Users just have to select a ROI over the
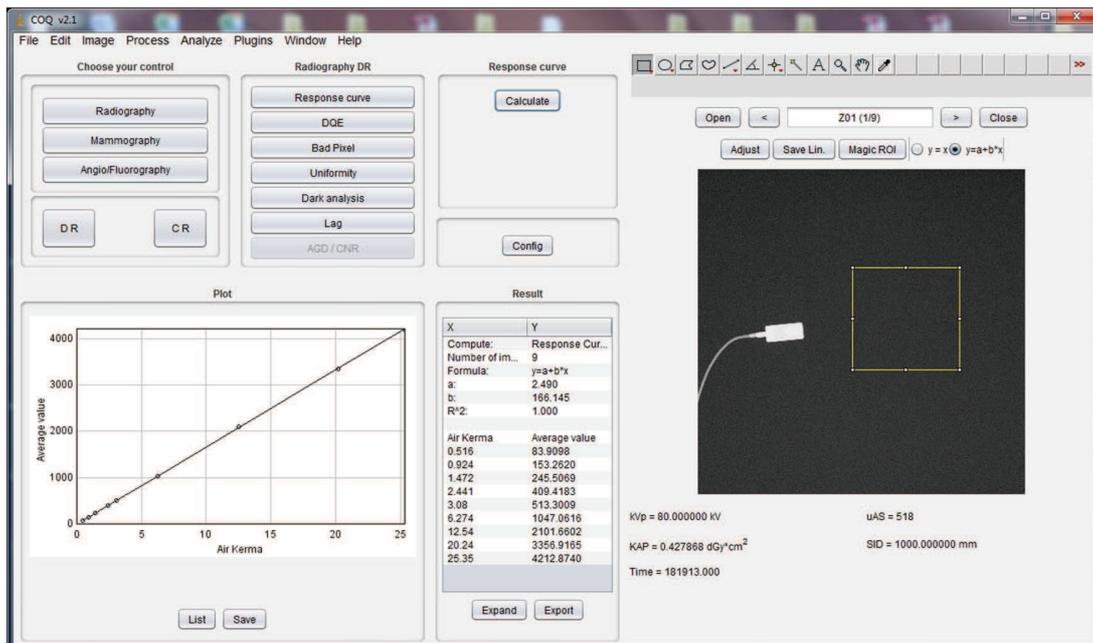

FIG. 4. Example of the calculation of the response curve. The experimental data and the fitted curve are shown on the left.

part of the image which contains the detail useful for estimating the MTF (slit or edge). We extracted the oversampled LSF/ESF to calculate the presampled MTF. The algorithms implemented for deriving the MTF are basically those described in Refs. 9 and 10. For estimating the NPS, a number of flood images at the same exposure shall be acquired to get better statistics (i.e., a greater number of pixels to be considered for the NPS calculation) and opened as a stack. The number of images shall be estimated in accordance to IEC standards[3,4] and is connected to the pixel size of the detector under analysis. The NPS is calculated on windows extracted from the selected ROI and the outcome is available in both 2D image and 1D extracted cuts. The 1D NPS can be extracted from the 2D NPS in four different ways: on the horizontal and vertical directions (each one separately from the other or averaging the two directions), and considering the entire spectrum. Users can choose which option is used for getting the final DQE, by selecting it through the *Config* panel. The DQE is then achieved by selecting properly the x-ray beam used and inserting the correct exposure value: the appropriate SNR_{in}^2 values are already tabulated for standard beams from IEC standards.[3,4,12] Alternatively, users can manually insert SNR_{in}^2, when the correct values are not available. In all cases, results are provided in various ways: as graphical plots or tables, and can be saved as text files.

2.B. Image quality checks

The set of quality control procedures implemented includes the computation of the following features: defective pixel analysis, uniformity (global and local), dark analysis, and lag (multiplicative and additive).

– The first analysis aims to determine the accuracy of the *defective pixels/lines* correction in the preprocessing stage, by counting the defective pixels in a flat image. A defective pixel is defined as an element within a 1×1 cm ROI where its absolute value deviates more than 20% from the mean pixel value of the ROI elements.[13]

– The *uniformity test* is performed for testing the flat-field correction implemented in a digital system, by evaluating a uniform flat image over the entire area of the detector. Local and global analysis of signal and SNR uniformity can be achieved. Local signal (or SNR) nonuniformity is evaluated as the mean signal intensity (or SNR) difference between the considered ROI and the average of the eight-neigborhood ROIs. Global signal (or SNR) nonuniformity is evaluated as the difference between the maximum and the minimum mean signal intensity (or SNR) found in all the ROIs.

– The *dark analysis* has the purpose of assessing the intrinsic noise of the system (electronic noise signal), by acquiring a constant intensity x-ray exposure image with a lead attenuator at the x-ray tube output.

– *Lag* is used for evaluating the artifacts due to previous exposures to the detector; to this end, multiplicative and additive lag effects can be estimated. The additive and multiplicative lag analyses are realized in accordance to IEC 62220 standards.[3,4] For estimating the additive lag two images are required: one irradiated with a test phantom (e.g., the edge used for the MTF calculation) and a nonirradiated image. The additive lag is then calculated as the difference between the mean signal values of two ROIs on the nonirradiated image (one outside and one within the region of the test phantom), normalized by the mean signal value of the ROI positioned outside the phantom on the irradiated image. The multiplicative lag is estimated for measuring a temporary change in the sensitivity of the detector determined by prior exposure history. For calculating this kind of lag three images are required: one image irradiated with a test phantom (image2), and two uniform images with no phantom, one acquired before (image1), and one after the irradiated test image (image3). Also in this case two ROIs are needed: one positioned within the phantom area (ROI1) and one outside the phantom (ROI2). The multiplicative lag is then determined as

$$\left| \frac{(\text{image1}_{ROI1} - \text{image1}_{ROI2}) - (\text{image3}_{ROI1} - \text{image3}_{ROI2})}{(\text{image1}_{ROI2} + \text{image3}_{ROI2}) \cdot 0.5} \right|.$$

– The *AGD/CNR* can be used for estimating the AGD and the contrast-to-noise ratio (CNR) in mammography. These metrics aim to correlate image quality to patient dose in mammography. The AGD is computed from the incident air kerma by applying conversion factors which take into account the object absorption dependence on its thickness and composition, and characteristics of the x-ray beam used. The CNR is related to human capability of detecting large objects with given contrast in a noisy background and can be estimated from the difference between the mean pixel values of background and

aluminum detail, divided by the standard deviation of the background where the detail is embedded.

For most of the estimated parameters a threshold can be set, for assessing whether the system response is acceptable or not. More details about the image quality procedures implemented in the plugin can be found in the literature.[7]

In this paper, we report a case study consisting of a complete set of measurements realized with the plugin for a system for digital radiography (GE Revolution XR/d, GE Healthcare, Milwaukee, WI).
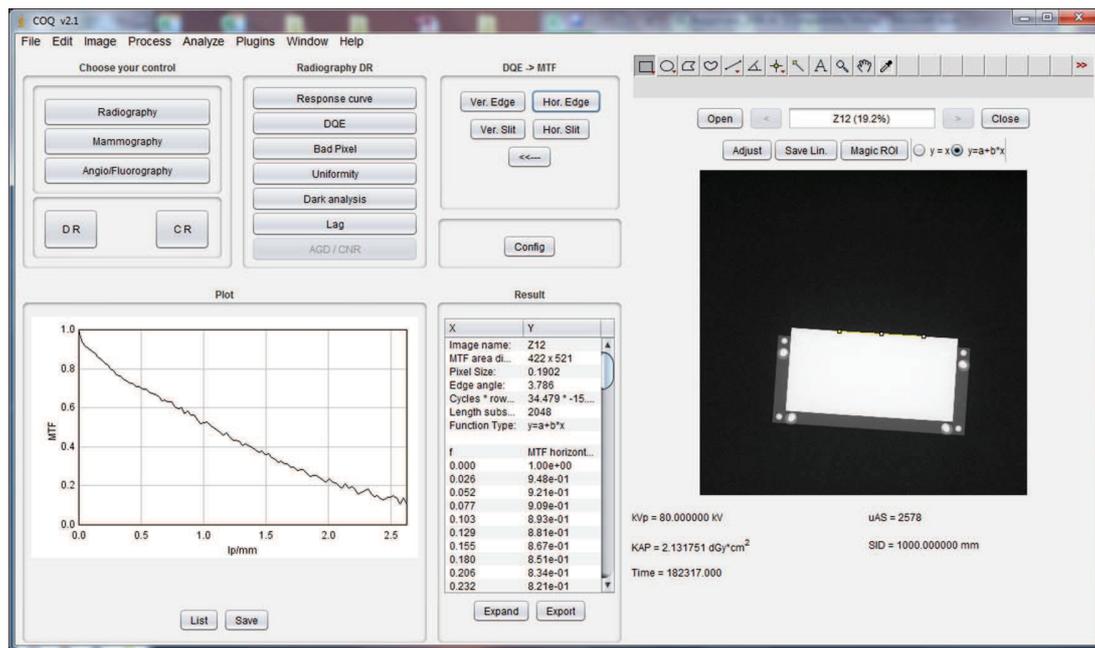
FIG. 5. Example of MTF calculation with a tungsten edge phantom (image on the right), and with the MTF results shown as a plot (MTF curve on the left) and in a textual way (table in the middle part of the GUI).

3. RESULTS AND DISCUSSION

Figure 5 shows the MTF calculation realized with an edge phantom. In this case, users must select a ROI which contains a part of the edge. This operation can be facilitated by using the usual ImageJ tools for zooming and changing the window/level of the image. Once selected the edge, users must also provide the pixel pitch (a default value is read from the DICOM header when available and presented to the user). The MTF can also be achieved with a slit technique (usually adopted in mammography), and in this case users have to select a ROI containing the slit. The MTF is then estimated and presented both as an ImageJ plot and as a text table. By means of the *Save* and *Export* buttons, one can save the points of the graph as .txt file, and the results shown on the table as .csv file (the .csv file contains a header with more information, with
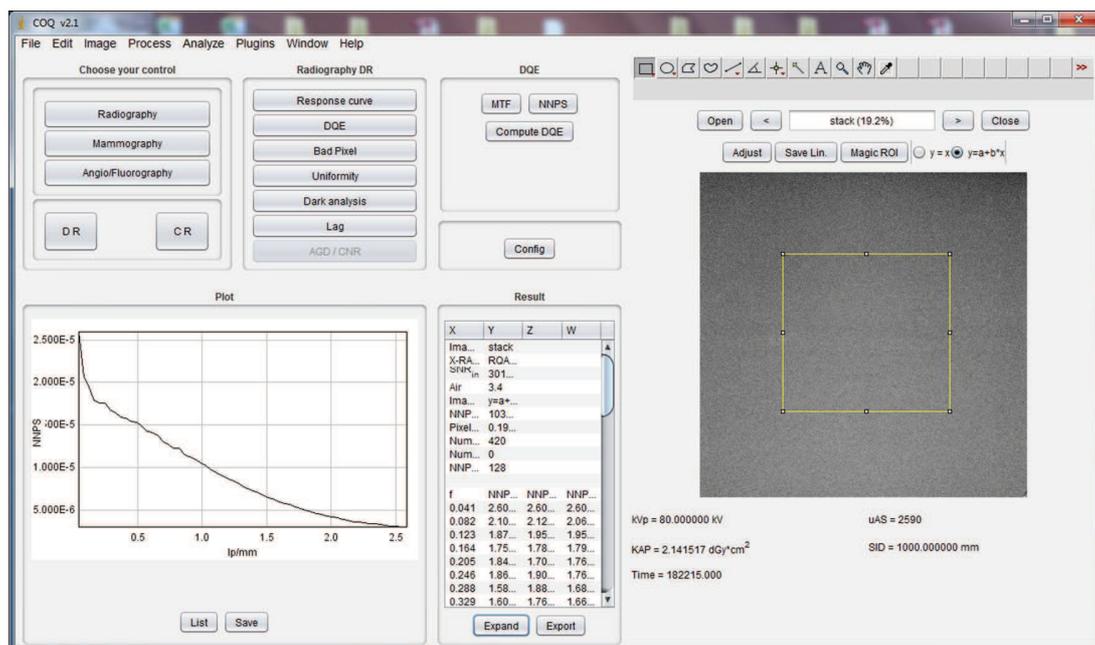

FIG. 6. Example of NPS calculation with a ROI selected on a flood image (on the right), and with the NPS results shown as a plot (NPS curve on the left) and in a textual way (table in the middle part of the GUI).
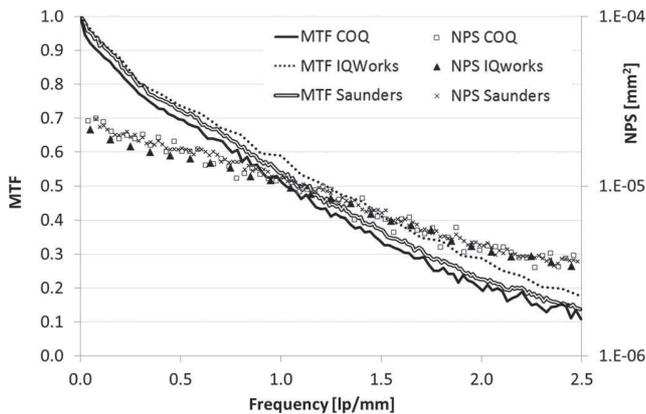
FIG. 7. Comparison of the MTF and NPS achieved on the same images with our plugin (COQ) and two other programs freely available (IQWorks and software developed by Saunders and Samei). The comparison shows a very good agreement among the three programs.

respect to the .txt file, such as parameters connected to the acquisition conditions or to the processing used for achieving the stored outcomes). The outcomes can also be copied directly from the result table and pasted to another application.

In Fig. 6, we reported the 1D NPS estimated for the same system through the analysis of flood images.

In Fig. 7, we show a comparison of the MTF and NPS outcomes achieved with our plugin and two other programs freely available on internet.[5,6] The validation has been realized on the same set of images acquired with the GE Revolution XR/d system. It is worth noting that there is a very good agreement among the three outcomes, both in terms of MTF and NPS. Keeping the outcomes of our plugin as reference, the maximum relative difference is around 2% and 6%

for MTF, 5% and 4% for NPS, for IQWorks and Saunders' software, respectively.

In Fig. 8, we reported the DQE as resulting from the MTF and NPS previously calculated, and from the x-ray beam and exposure values inserted by the user. The DQE values estimated with the plugin agree well with data from the literature for the same or similar systems.[14,15]

The bad pixel analysis revealed that for the investigated system all the pixels have a deviation from the mean pixel value of the neighbor ROI that is always lower than 20%, therefore there are no defective elements. That means that the correction and calibration procedures operated by the manufacturer and the staff of the hospital are effective. In case of pixels considered as defective, the plugin shows the list and the coordinates of all of them.

Figure 9 shows an example of the uniformity test. In this case, a table with the four outcomes (global and local signal and SNR uniformity) is presented to the user, together with the prefixed limits which define the pass/fail criteria. Also in this case we can note that the investigated system shows all the four parameters below the thresholds, therefore the uniformity test can be considered passed.

The dark analysis is realized by means of an irradiated image with a lead attenuator in place at the output of the x-ray source. The mean value and the standard deviation on five ROIs (one at the center and four at the corners of the image) are estimated and reported, as shown in Fig. 10. These values can be used for achieving the dark analysis in different ways, there is not a unique way to realize the dark analysis. For instance, the user can estimate for each ROI the ratio between its mean values and the average level of the same ROI at a reference exposure (typically 2.5 uGy). Alternatively, the variation as a function of time of the mean values can be monitored, or
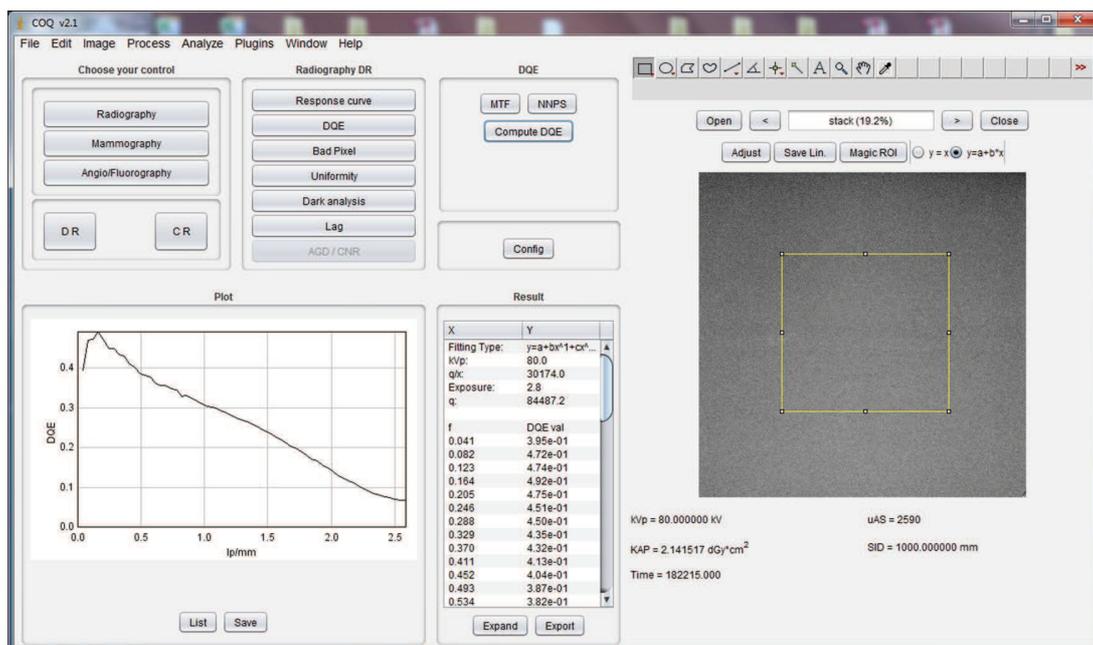

FIG. 8. Example of DQE calculation starting from the MTF and NPS previously shown, and with the DQE results shown as a plot (DQE curve on the left) and in a textual way (table in the middle part of the GUI).
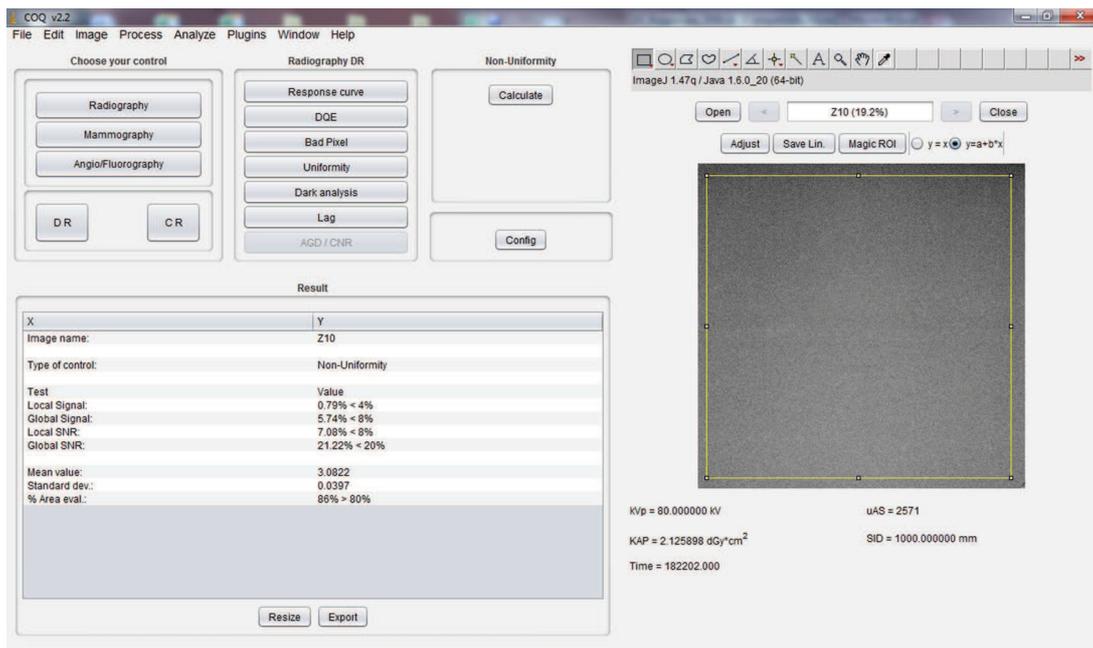
FIG. 9. Example of calculation of the "uniformity" quality check. To this end a uniform flat image is considered and visualized on the right. Local and global uniformity (both in terms of mean signal and SNR) are estimated and compared to prefixed thresholds derived from error propagation applied to data available from IEC 62220–1, as described in Ref. 7 (table in the left-middle part of the GUI).

the percentage nonuniformity can be considered, by comparing the mean value of the central ROI with the respective of the other four ROIs.

Figure 11 shows the outcome of the additive lag analysis. To this end, two images are necessary, one acquired with an irradiated test phantom (the same edge used for the MTF in our case), and one nonirradiated images acquired immediately after the first exposure. The user is requested to select two

ROIs, one inside and one outside the phantom. The additive lag for the investigated system resulted to be 0.004%, well below the prefixed threshold. A similar outcome was achieved for the multiplicative lag, showing very good performance of the system, with respect to lag properties.

The estimation of all the other parameters not mentioned here can be achieved in a similar way: basically users must open one (or more) suitable DICOM (or raw) images, select
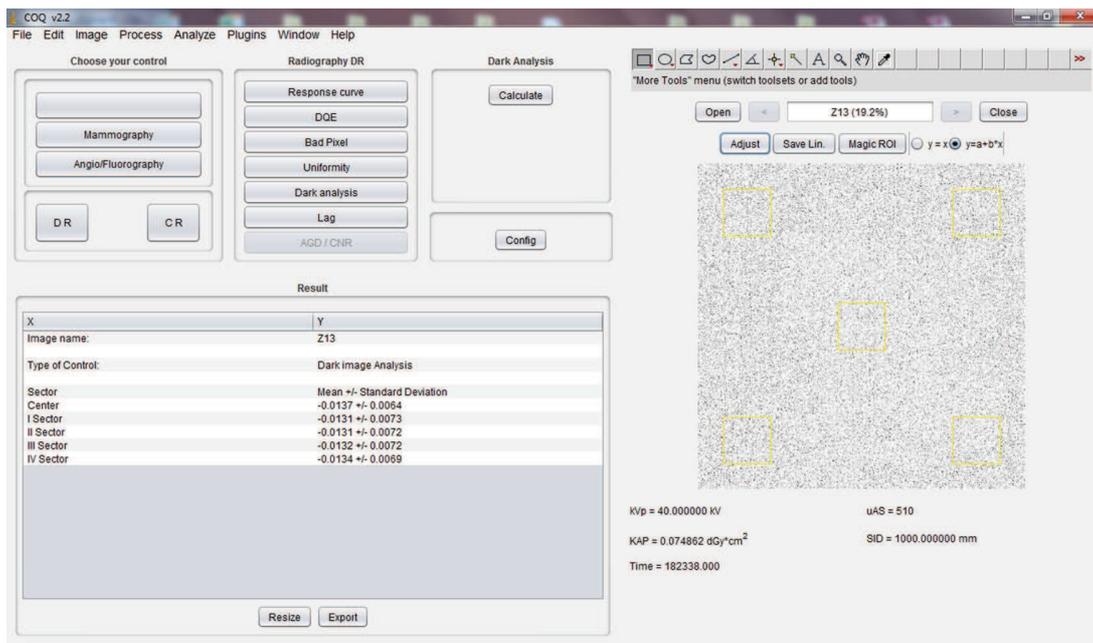

FIG. 10. Dark analysis: in this case an image is acquired with the beam stopped by an appropriate lead attenuator. Five ROIs are considered: one at the center of the image and the other four at the four corners.
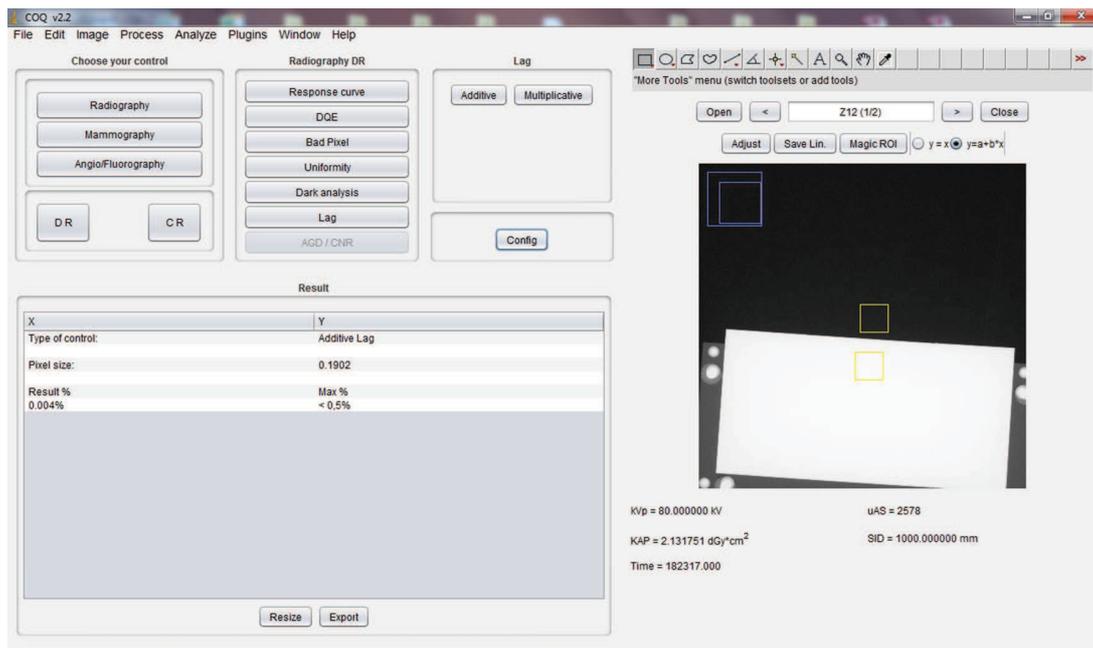
FIG. 11. Example of the additive lag analysis. In this case two images are used: one with an irradiated test phantom (shown on the right) and the second one is a nonirradiated image. The additive lag is calculated by means of two ROIs: one inside and one outside the phantom.

a ROI over the image, choose the parameter to be computed, and eventually save the outcomes. Results saved as external files can be used for both further analysis with other software tools (e.g., a spreadsheet), and subsequent examination with our plugin.

The software has been downloaded and perhaps, used by more than 100 users from more than 30 countries around the world. The outcomes of our plugin have already been used in various published papers for achieving the physical characterization of several computed and digital radiography systems both for general radiography and for digital mammography.[15–19] A brief user manual is also available on the aforementioned website (www.medphys.it/downloads.htm) for helping users in realizing the basic operations with the software ("COQ: an ImageJ plugin for the physical characterization and quality checks of digital detectors").

4. CONCLUSIONS

We developed an inhouse software for assisting users in performing physical characterization and image quality checks in x-ray digital imaging systems. The software was implemented as ImageJ plugin, in order to exploit the full functionalities of the well-known suite. The plugin has been used for realizing the physical characterization and image quality check of various clinical systems for digital radiography, mammography, and fluoroscopy. In this paper, a complete set of measurements obtained for a clinical system for digital radiography is presented. The comparison achieved by calculating some of the parameters (MTF and NPS) with our plugin with those obtained with other software programs on the same images provided a very good agreement.

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