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Intelligent Imaging Sensors for Industry, Health and Security

Preliminary Analysis Report and Proposed Design

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Abstract

Quality assurance and resulting image quality in modern mammography are known to be directly related to X-ray exposure parameters. Current state-of-the-art detector technologies and architectures, even in the case of digital mammography, suffer from various non-trivial quality deterioration factors, including spatial resolution, contrast and noise. Although proper selection of the exposure parameters by an expert radiologist can minimize these problems, automatic control can greatly increase the quality and the reliability of the system. Current automatic exposure control techniques like automatic exposure control (AEC) and automatic brightness control (ABC) can only be employed in the context of automatic timers, while still associated with typical global image quality measurements. A new innovative approach is proposed in this report, including a content-oriented quantitative feature analysis of tissue-related discriminative information in the case of digital mammographic images. The final processing module is to be used as an intelligent controller in future radiographic systems, effectively improving the quality of the resulting image via accurate and content-related automatic image quality evaluation, while at the same time optimizing the exposure parameters versus minimum radiation dose and extending the adaptability of the system to case-specific patient attributes.

Keywords: Digital mammography, automatic exposure control, image quality enhancement, intelligent controller design, adaptive controllers.

1. Introduction

In modern X-ray radiography, an attenuation profile of a human body part is projected onto a two-dimensional detection device, using the focus of the X-ray tube as a point source, effectively producing a detailed representation of the internal structural content. In mammography, radiological imaging enables the expert physician to conduct a thorough investigation of the anatomical image of the resulting mammogram, effectively reviewing all the required information for a complete clinical evaluation.

In order to assert the quality and effectiveness of the radiographic procedure, modern X-ray devices employ advanced detector technologies and image processing, mostly based on the radiologist's expertise and in lesser extent on automatic exposure control. New innovative approaches should be able to automate much of the processing, adapting it to case-specific characteristics and optimizing the radiographic exposure profile, while at the same time minimizing the overall cost and patient dose by limiting repeat rates and exposure time.

2. Material

2.1 Quality assurance

In accordance to modern quality assurance (QA) programs employed for diagnostic equipment in radiology, it is necessary to maintain optimum image quality, while at the same time minimize the patient's radiation exposure and the overall cost of the examination [01]. Thus, it is essential that efficient technological and computational methods be employed extensively in radiological equipment, including both the X-ray detection accuracy and the resulting X-ray image visualization.

Although radiation exposure of the patient is described by typical measurements, including radiographic positioning (RP), loading factors (KV, mA, time, AEC, etc) and entrance-skin-exposure (ESE) parameters, equipment control is fully described by quantitative operational parameters that essentially relate to the quality properties of the final result [02, 01]. The quality of the resulting image itself is directly proportional to the resolution capabilities and quality of the detection system and especially the detector technology, usually evaluated via a set of typical measurements, including detective quantum efficiency (DQE), modulation transfer function (MTF) and noise power spectrum (NPS) [03, 11].

In clinical level, there are some well-defined characteristics of the radiographic images that are evaluated in order to formulate an accurate and complete set of quality acceptance criteria, including contrast resolution (CR), spatial resolution (SR) and noise (N). Except spatial resolution, which is a physical parameter of the projection system, both contrast and noise properties can be effectively controlled by proper optimal control of the basic exposure parameters (voltage, intensity, time), as well as radiographic device calibration by anthropomorphic and test-pattern phantoms, properly selected for the specific attributes and distinct radiological characteristics of the current application and the subject [02, 01].

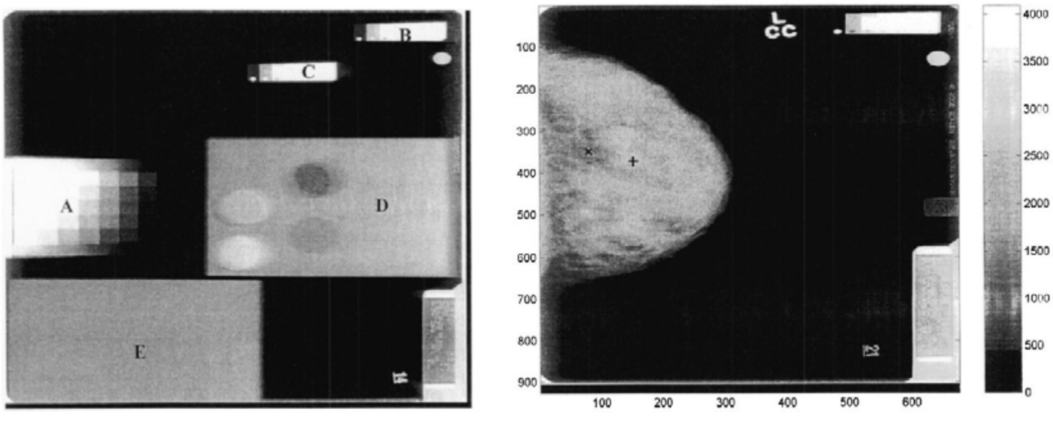

Figure 1: On the left, radiograph on 24x30 cm image receptor illustrating the plastic calibration device (A), two aluminum step wedges, located in positions corresponding to the edge of the image on the large (B) and small (C) receptors, a ''hole'' phantom (D) used for volumetric density estimation and a uniform plastic block (E). On the right, a sample anthropomorphic phantom used for mammographic image quality estimations and exposure profile calibrations. See [02] for further details.

2.2 Equipment and detection technologies

The detection system in modern X-ray devices consists of a composite electronic architecture that essentially collects X-ray quantum radiation at the opposite side of the projector and converts it into electrical signals that can be translated as visual representation of the spatial content of the projected subject [04, 05]. There are two major types of imaging detectors:

- Indirect conversion-detection: a collector layer (CsI) is used to convert X-ray radiation into visual light that is sequentially converted into electrical charge by an active layer (TFT/a-Si:H). This composite architecture is implemented in the form of active-matrix flat panel detectors (AMFPI). Other forms of inherent conversion detectors may include phosphor screen CCD arrays and image intentifiers [04, 06, 07].
- Direct conversion-detection: a collector layer (a-Se) is deposited onto an active layer (TFT/a-Si:H) for converting the detected quanta into electrical charge. This composite architecture is implemented in the form of active-matrix flat panel detectors (AMFPI) [04, 08].

In both cases, additional circuitry (A/D converters, amplifiers, TFT arrays, etc) is required to produce a signal of adequate quality and resolution. Inherent structure inefficiencies and additive noise effects generate significant deteriorations in the quality of the final visual result [09, 10].

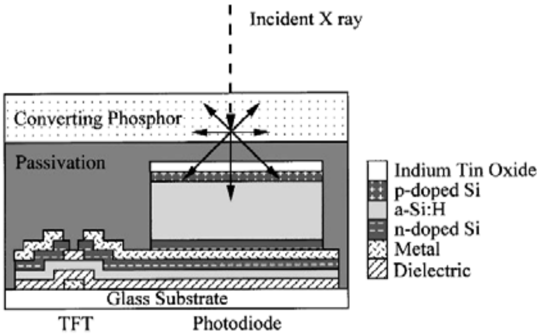

Figure 2: Schematic diagram of a cross section of a single a-Si:H imaging pixel, typical in image intensifier detection systems, used for indirect conversion-detection radiographic imaging (see [11] and [06]).

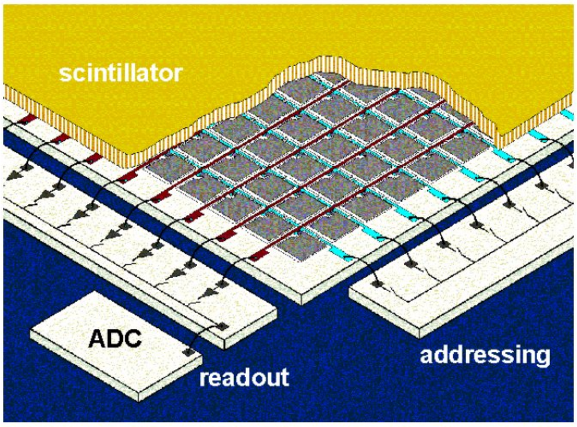

Figure 3: Schematic of a flat-panel detector. An array of a-Si diodes over a glass layer is covered by a scintillator screen of CsI:Tl. Addressing and read-out lines are used to interconnect every imaging pixel with external circuitry (courtesy Philips Research Laboratories, Aachen – see [06]).

A third approach is computed radiography, where phosphor cassettes can be used as direct energy storage layers (storage phosphor arrays) that can later be read using laser sweeps. However, due to the two-stage readout process, on-line control and image quality optimization cannot be applied in a fully automated system.

Digital radiography addresses many of the above problems, effectively digitizing several stages of the overall process [16]. Specifically, the radiation-to-charge conversion is implemented directly, using an amorphous Selenium (a-Se) collector layer, or indirectly, using a phosphor matrix similar to the above description. Without multiple intermediate energy conversion stages, digital detectors improve the quality and noise reduction, however many of the main system inefficiencies still remain.

2.3 Automatic Exposure Control (AEC)

A crucial factor in the quality of the resulting radiographic image is exposure time and control. Using a specific set of operational parameters, including voltage (KV) and intensity, i.e. tube current (mA), the radiologist must correctly estimate the required exposure time in order to produce images of optimal quality with the minimum patient dose. As tissue type and patient-specific characteristics greatly affect the energy absorption and detection by the detectors, careful estimation of the exposure parameters is essential for the creation of an optimally adapted radiography profile in each case [12, 13].

Manual exposure control requires that the radiologist, who is responsible for defining an adequate and efficient timeframe for the projector, sets all the exposure parameters. In contrast to this, many techniques for automatic control of the exposure time have been developed in the general form of automatic exposure control (AEC) for the projection system and automatic brightness control (ABC) for the visualization system [12, 14]. Automatic exposure timers are implemented with photo-timers and more recently with ionization timers (ionization chambers). Both types of automatic timers convert radiation into electrical charge, which is used to automatically terminate the exposure when the film has reached the proper density, as it is preset by specific adjustments (density selector). In terms of minimum response time (MRT) of the automatic control, ionization timers are considered more accurate and robust due to a more sophisticated design [12].

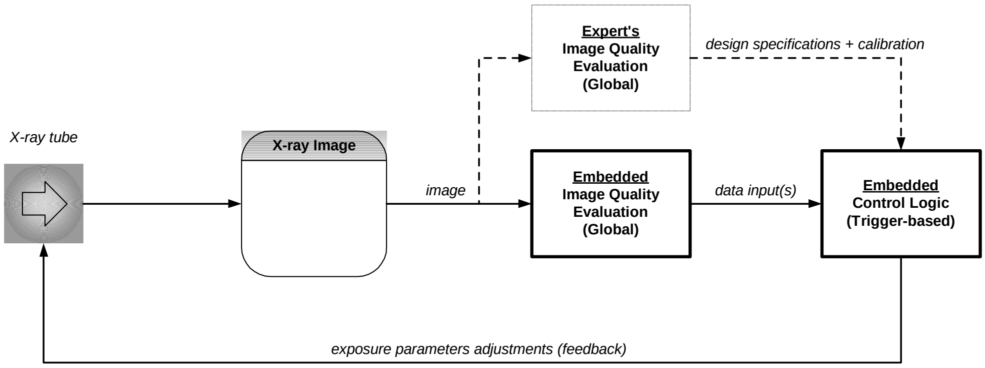

Figure 4: Block diagram of existing automatic control in a typical radiographic system. In practice, the image quality evaluation is integrated into an automatic trigger device, essentially fusing the two depicted modules into one (AEC).

Although the proper use and adaptation of AEC can effectively deal with the issue of exposure time versus the other exposure parameters, it is still bounded to the specific properties of the physical state (patient positioning, tissue type, tissue density), detector technology and limitations, radiologist's density preferences (required density level) and proper film/screen combination for the specific radiographic device [13]. Minimum response time (MRT) is an especially crucial factor, as various adjustments of the exposure parameters in order to compensate its side effects may produce deteriorated image quality. For example, long MRT may be countered by employing lower mA values for longer exposure times, but if lower KV values are used instead (due to hardware limitations) the contrast of the resulting image may be completely different in this case [12, 15]. As MRT is directly related to the efficiency of the design and the implementation of the automatic exposure timer employed, any negative side-effects may evidently counter the advantages of choosing to use it altogether, instead of controlling exposure time manually.

In summary, modern AEC includes of a series of qualitative rules, which assert that the optimal operational envelope is used during the exposure procedure:

- The performance of any automatic exposure timer should be independent of the knowledge and skill of the radiologist.
- Patient positioning is crucial when using AEC devices.
- Density changes should only be made by using the density selector, instead of any other exposure parameter.
- When using AEC, adjustments of KV values should only be made to vary the contrast.
- In order to decrease the density of dark films due to long MRT, employ mA adjustments (instead of KV).

When used properly, AEC can greatly assist the radiologist in producing an optimal exposure profile, decrease repeat rates and decrease overall cost for both the procedure and the patient dose. As the exposure time is the only target of the automatic control process, the AEC model can be considered as a simple open-loop control system. However, there is still a great level of dependency from the specifications of the device operator, despite the first requirement in the above list.

3. Proposed System Specifications

The complexity of the overall problem of choosing the exposure profile for each specific case, in terms of optimally adapting the exposure parameters with minimum effects and patient dose, makes the design of an automatic control model a challenging issue.

Modern automatic exposure control is limited to automatic timers, while still depending on the radiologist for high-level adjustments and adaptation to each patient’s characteristics. Thus, it is crucial to investigate the ability to design and implement a new efficient model for a “smart” system that integrates much of the higher-level control logic of the radiologist, effectively making the overall radiographic procedure much more robust and autonomous [17].

The core issues related to the initial requirements and specifications of a new system design are related mainly to the subject (application & tissue type), the data analysis (input & output) and of course the specific goals (control target) of the final system.

3.1 General application & design goals

The target application is the general problem of automatic exposure control in mammography. Using the current detector technologies and specifications, investigate the ability to create new and innovative computational models for improving resulting image quality and optimize the exposure profile in case-specific level.

The goal of this project is the design and implementation of a high-level “smart” controller, employing much of the expertise and adaptability of the expert radiologist. The final system should be able to adapt to patient-specific characteristics and optimize the exposure profile, in order to produce the best possible level of image quality for the enhancement of discriminative content and clinical information.

3.2 Application-specific material

The raw material for the design and implementation of a high-level “smart” AEC controller is digitized mammographic images, as retrieved in crude quality during the first few fractions of total exposure time (5-20μs). In order to produce a highly adaptive content-based approach, it is essential that the data analysis process is focused on the various aspects and properties of the clinical content of these images, i.e. mainly the distinct characteristics and attributes of the mammographic tissue types. Some basic categories of recognizable tissue types in mammographic images, related to clinical appearance and pathological indications, may be skin tissue, fatty tissue, dense tissue, mammary gland, fibro-granular tissue, micro-calcifications, cysts, veins, ducts, etc.

The final system should be able to successfully recognize various tissue areas in relation to spatial data information, extract content-specific features from various image regional zones, exploit tissue-related discriminative information to specify image quality assurance requirements, and finally translate these requirements into on-line quantitative feedback for the control logic. While standard AEC systems control only the time frame of the profile, evidently ensuring correct appearance of the overall image, the new “smart” AEC system should be able to enhance the informative content of the image, in relation to the correct representation of the various tissue types recognizable in the mammographic image. The final system is expected to operate on-line in real time, similarly to the standard systems that are integrated in modern X-ray devices.

4. Methods

The complete analysis and implementation of the smart control system constitutes of several development phases that include:

- Construction of a complete list of medical properties regarding objective image quality evaluation by the expert physician, as well as a systematic formulation to translate them into a compact image quality vector.
- Construction of a thorough list of analytical quantitative feature functions, describing the textural and structural properties of the underlying tissue, which may be useful in the creation of descriptive content-rich signatures for the medical images.
- Evaluation and selection of optimal feature sets directly related to both overall image quality and tissue-specific discriminative content, as assessed by the expert.
- Design of a smart controller logic, exploiting high-level discriminative information content to optimize image quality.
- Clinical evaluation of the final system by application-specific physician.
- Profiling, optimization and integration of the final system into an operational-level module.

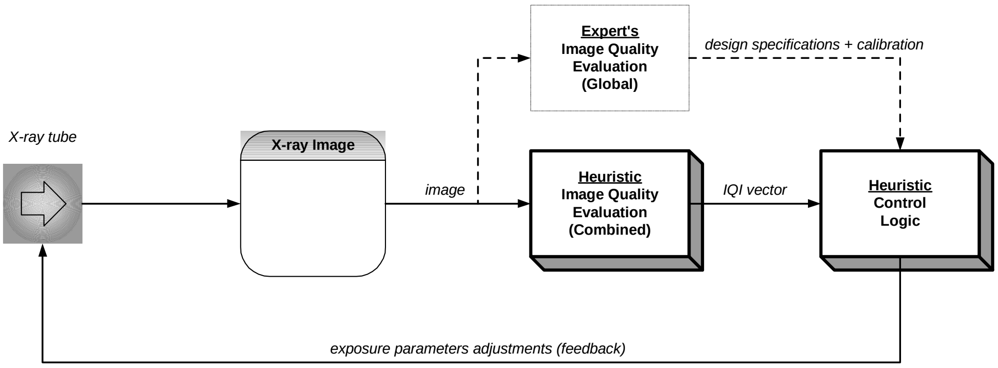

Figure 5: Block diagram of the proposed heuristic automatic control in an intelligent radiographic system.

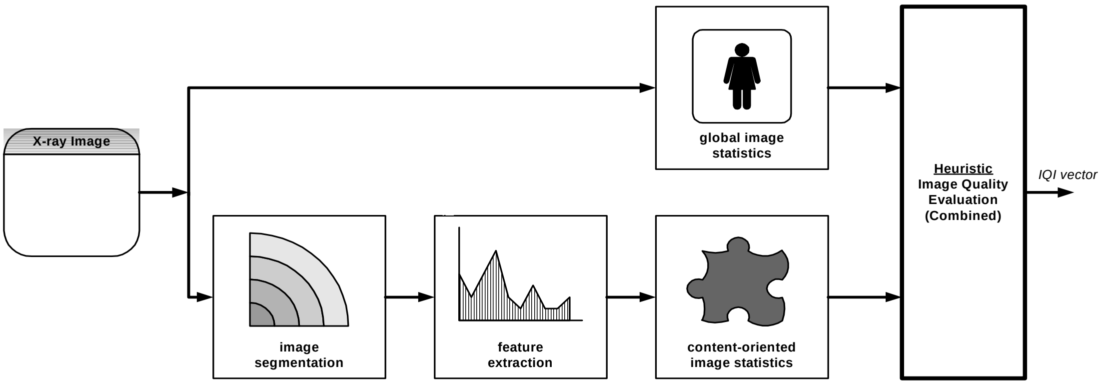

Figure 6: Block diagram of the heuristic image quality evaluation module of the proposed controller design.

4.1 Preliminary analysis, data acquisition, input design

The first phase of the development process is focused on the core medical and computational issues addressed by the new system. Image quality improvement is mainly considered in relation to tissue-specific discrimination properties, as well as textural and structural fine details present on the underlying image. The preliminary and final improvement of image quality is to be provided by the expert physician in detail for every available case, while robust image feature extraction algorithms are to be categorized, exploited and evaluated in correlation with the required tissue discrimination and overall image quality improvement. In short, these steps are:

1. Acquire all tissue-related clinical details, provide a thorough list of various tissue properties, and verify informative content and completeness in close cooperation with the expert physician.
2. Research and enumerate all feature extraction algorithms fit for medical image analysis and the construction of content-rich data signatures for the various tissues.
3. Construct an analytical model for compact image quality evaluation, especially for different types of tissue-related areas of the image.
4. Create a detailed mammographic image database with complete image quality descriptions by the expert physician, used for the content-oriented image quality optimization analysis.

5. Create a detailed test-pattern (anthropomorphic phantom) image database with complete X-ray device resolution and scaling parameters, as well as image quality descriptions by the expert physician, used for the final controller design.

The completion of this phase will produce and organize the required base framework for the data analysis and system evaluation in all of the development stages that follow.

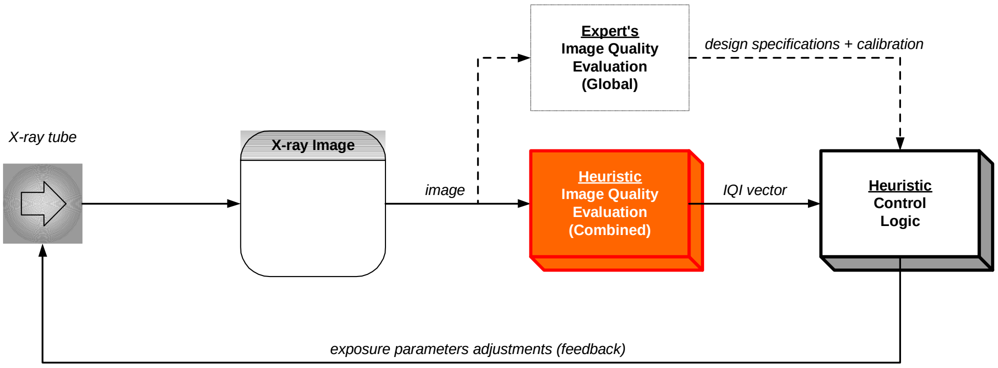

Figure 7: Heuristic image quality evaluation, using combined global and content-oriented image statistics to produce a compact image quality vector (module 1).

4.2 Content-oriented image quality evaluation

In order to acquire the effectiveness and informative content of the high-level datasets introduced by the constructed feature sets, it is essential to relate the values of these quantitative properties and the objective clinical evaluation of the image quality provided by the expert physician.

As the exact model of the expert's evaluation process is generally not known or it is too complex to formulate analytically with acceptable accuracy, a heuristic self-organizing approach is more prominent for this goal. A prototype approximation scheme can be created by employing various types and architectures of non-linear function approximators, including neural networks, fuzzy sets, SVM, etc.

In contrast to the estimation of typical image quality parameters like contrast resolution (CR), spatial resolution (SR) and noise (N), that take into account the overall image properties, content-oriented quality estimation should take into account the improvements or deteriorations of the quality when focused on the core issue of correct tissue type characterization and clinical evaluation. The introduction of content-rich informative features, extracted locally at the various areas of interest on the underlying image, along with robust and fast methods to automatically segment and identify these areas, are the key issues for translating the global quality estimation process into a localized content-based estimation approach.

The segmentation stage is considered equally important to the feature extraction stage, as it focuses the analysis in the most prominent areas of interest and improves the discriminative quality of the extracted information. Thus, it is essential that it is employed effectively with regard to the specific properties and constraints of the application at hand (i.e. mammographic images), and at the same time satisfy strict limitations in resources and complexity in order to apply to real-time response requirements. The most prominent solutions include adaptive regional zoning of the complete X-ray projection into 2-3 suggestive areas of different tissue type, combined with full or partial sampling of each distinct zone, in order to construct a robust and complete profiling procedure for content-oriented image quality analysis. The exact values of the number of separation zones, as well as the sampling resolution used for each zone, constitute a significant part of the overall heuristic architecture and thus are to be exploited during the design process.

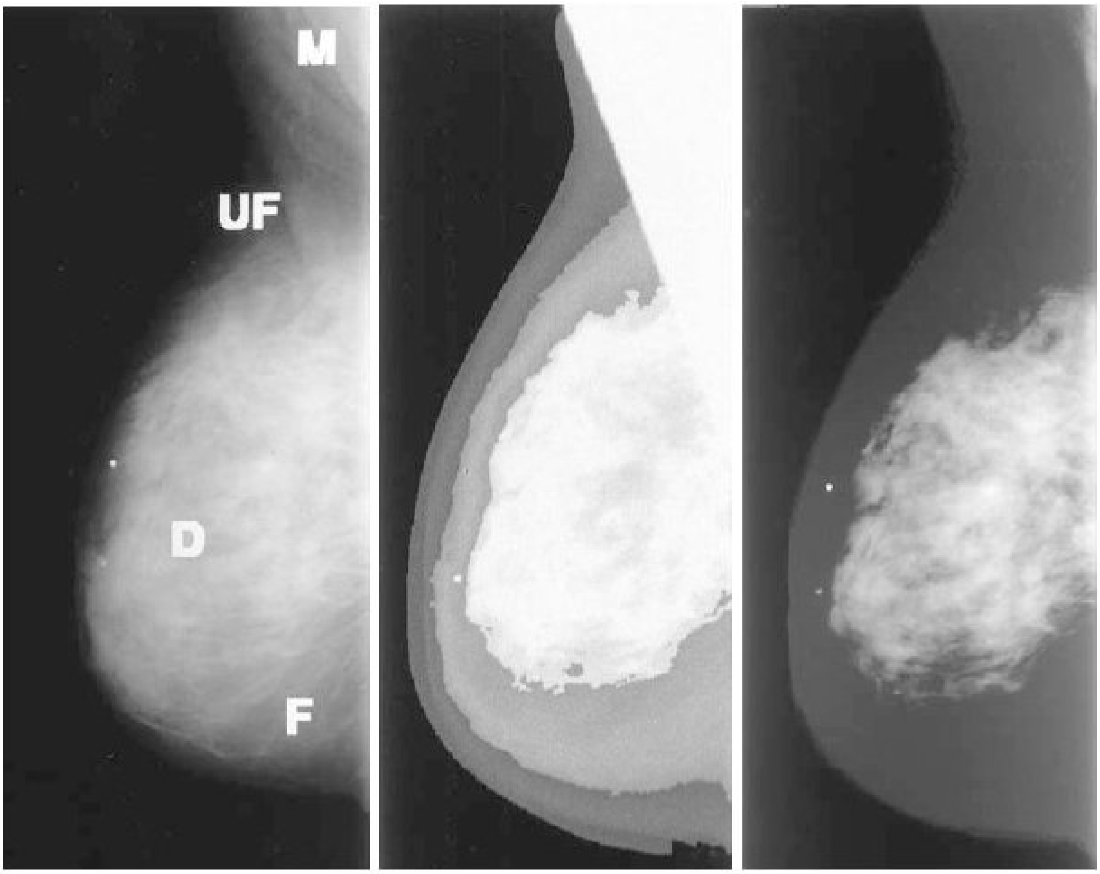

Figure 8: Application of mixed-model intensity windowing processing to digital mammograms. In the left section, the mammographic image shows dense tissue (D), fat (F), pectoral muscle (M), uncompressed fat (UF) and the background represented as homogeneous black area. In the middle, same mammographic image is segmented and cropped, highlighting the muscle, dense tissue, compressed fat, and uncompressed fat, with portions of the various tissue types represented with different greyscale values. In the right, mixed-model intensity windowing processing has been applied in the original mammogram for the final tissue discrimination and representation. For further details, see [10].

Using a complete and robust heuristic architecture, the expert's clinical evaluation of image quality can be effectively approximated and extrapolated with maximum accuracy over any unknown case. This potential, not only links the various extracted image features with the clinical evaluation of the image itself, but also produces the necessary means for the design of the control logic for the final system.

Content-oriented optimization of the image quality comprises the following steps:

1. Employ a fast adaptive segmentation technique to dynamically acquire areas of various tissue types, effectively focusing the quality analysis to content-rich feature datasets.
2. Apply all the available feature extraction functions on every image of the mammographic image database, in order to create a complete set of image feature descriptors (content signatures).
3. Analyze and exploit data correlations between image feature sets and content-oriented image quality vectors, as provided by the expert physician, using:
    a. Statistical methods (univariate & multivariate)

    b. Fractal analysis (dimensionality, self-similarity)
    c. Heuristic methods (advanced filtering, pattern recognition)

4. Create an optimized set of content-oriented image feature descriptors that relate best to the expert's image quality evaluation, focused mainly on the best visual distinction of the various types of tissue areas on the underlying image.

When this phase is finished, an optimized set of content-oriented image feature sets will be available for determining the extent and payoff of using this higher-level data input for estimating the quality of the image, in relation to the quality estimation provided by the expert.

4.3 Global image quality evaluation

High-level content features have thus far been identified, optimized for content-oriented discrimination over various tissue types, and exploited through a heuristic architecture to correlate with clinical image quality evaluation, as it is formulated by the expert physician empirically. In order for these feature datasets to be used as raw input for the final controller design, it is necessary to further investigate the underlying interrelation between the effects of modifying the exposure parameters (KV, mA, sec) of the X-ray system and their resulting improvement or deterioration of the clinical image quality evaluation of the expert.

Although content-based features are optimized for the expert's preferences regarding tissue discrimination and clinical evaluation, an additional set of global image properties, such as overall contrast, density and noise, have to be supplied as additional input to the quality evaluation process. Thus, the combined image quality vectors (n-IQI) will contain quantitative information related both to the empirical estimation of the expert and the typical image statistics used in the existing controller designs (AEC).

Existing image evaluation models exploit automatic measurement or prior adjustment of global image attributes, including X-ray projection density (density selector), spatial resolution (SR, film-specific physical property), overall image contrast (CR) and overall noise profile (N). The same or similar set of parameters can be employed in the new system as global image quality identifiers, in order to provide additional input feed for the heuristic evaluation process, as well as provide the means for a common base of reference when comparing the performance of new design with existing controllers. However, the significance of this set of global parameters still remains limited for the final control logic, as content-based feature sets are expected to provide more accurate input in terms of quality evaluation and tissue-related discriminative information.

The combined image quality vector, a heuristic approach in the form of a universal approximation model can be created, employing various types and architectures of non-linear pattern-based classifiers, including neural networks, fuzzy sets, SVM, etc. This type of "smart" control logic can generally satisfy the most complex system specifications and constraints, effectively integrating the existing global image quality evaluation and a new sophisticated approach for simulating the expert's high-level evaluation in relation to the specific content of the image.

4.4 Control system design

At this stage, the value and quality of the optimized feature sets in improving the image quality should be evident, both for typical (global) image improvement and for content-oriented discrimination and characterization of the various types of tissue areas. The overall problem of controlling the X-ray exposure envelope by using directly the high-level feature data as raw input is now decomposed into two sequential procedures. Using the heuristic image quality evaluation developed in the previous stages, the clinical image quality evaluation of the expert can now be directly linked to the X-ray exposure parameters.

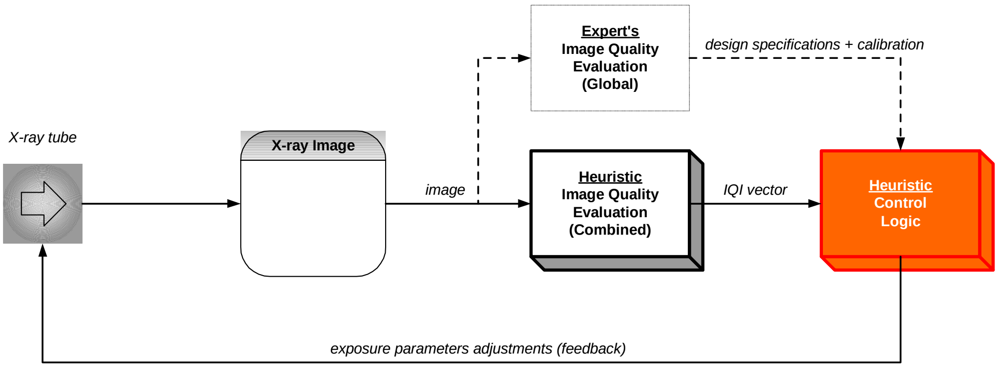

Figure 9: Heuristic automatic exposure control, using the image quality vector as a compact and content-rich input for the controller (module 2).

The final control system can be effectively combined into a modular architecture by linking the two sub-systems sequentially, using the clinical image quality evaluation as the interconnection link between them. The initial image is segmented into several regional zones of different tissue types, the optimized feature functions set is applied using full or partial sampling over these distinct regions, and the first analysis stage (module 1) is used to create a good estimation of the image quality index, in terms of clinical evaluation as it is provided normally by an expert physician. This estimation is then passed to the second analysis stage (module 2) as input, in order to identify the related optimal system response and produce a new set of adjusted X-ray exposure parameters, essentially creating a content-rich feedback for the X-ray controller device. In this case, the process of designing the final control logic is simply a task of optimally approximating the required interactions between the image quality vector (IQI vector) and the appropriate adjustments for the exposure parameters (KV, mAs).

While the 2-stage approach is an acceptable solution for the original problem of “smart” optimal control, it may be preferable to integrate the two related heuristic modules into one combined architecture. However, the correlation between the new input type, i.e. the high-level data feature vectors, and the desired output type, i.e. the X-ray exposure parameters (KV, mA, sec), cannot be directly extracted by examining the heuristic modules themselves, due to the nature and complexity of these architectures. Thus, a similar heuristic approach must be employed for designing the combined system itself, exploiting the potential of various types and architectures of non-linear pattern-based classifiers, including neural networks, fuzzy sets, SVM, etc, to approximate the high complexity of the required system response. As these architectures are known to be very efficient in terms of wide applicability, generalization on the input space, noise resistance and overall stability, they are more prominent and fit for implementing a high-level control model than any other typical linear or non-linear automatic control architecture. This high-level control logic can only be embedded in state-of-the-art ASIC circuitry in the form of neural controllers, fuzzy controllers, etc, in combination with integrated on-line control interconnections with the X-ray tube, similar to the one used today in the form of simple automatic time-triggering mechanisms.

In the case of designing one combined module for implementing ”smart” control logic, the final phase of the design process constitutes of the merging of design steps of each separate module, adjusted to the required sensitivity and specificity final control system:

1. Employ a fast adaptive segmentation technique to dynamically acquire areas of various tissue types, effectively focusing the quality analysis to content-rich feature datasets.
2. Apply all the available feature extraction functions on every image of the mammographic image database, as well as the test-pattern

(anthropomorphic phantom) database, in order to create a complete set of image feature descriptors (content signatures).

3. Analyze and exploit data correlations between image feature sets and both global & content-oriented image quality vectors, as provided by the expert physician, using:
    a. Statistical methods (univariate & multivariate)
    b. Fractal analysis (dimensionality, self-similarity)
    c. Heuristic methods (advanced filtering, pattern recognition)
4. Create an optimized set of image feature descriptors that relate best to the expert's image quality evaluation, estimated both on content-oriented visual discrimination of the various types of tissue areas and the overall image quality.
5. Apply robust universal approximators to construct an effective model for the control logic of the final system.
6. Inspect and analyze the constructed control logic to identify, extract and simplify any evident reduction rules and inherit relations between input and output, essentially profiling and optimizing the final system.
7. Develop a prototype of the (optimized) system and consult the expert physician for a complete and thorough clinical evaluation with new cases, not previously used during system development.
8. Improve system performance, resources requirements and deployment level, in order to produce an application-level module that is ready for the final integration with compatible embedded hardware of X-ray devices.

On step 5, a combined 1-stage control logic can be formulated into a robust and coherent system by using a heuristic approximation self-organizing model, i.e. some form of machine learning and pattern recognition as described above. After an effective model is constructed in terms of fulfilling the required specifications for image improvement, it is relatively easy to examine the internal infrastructure and knowledge representation inside this model and decide whether a reduction on its complexity is feasible without losing its acquired base effectiveness and accuracy. The final (reduced) model of any of these types of soft-controllers can be integrated directly into modern DSP hardware, such as neural or fuzzy ASIC controllers, and linked directly to the X-ray tube exposure control circuitry. In this case, the ability to use inherit image quality measurements as input for on-line estimation of the efficiency of the exposure profile introduces the typical characteristics of a closed-loop control model, improving the overall efficiency and autonomy of the X-ray system.

With the completion of this phase, the development process of the system is essentially over. The final "smart" control module employs the required application specifications for using high-level image feature descriptors, specialized both for global image enhancement and tissue-related characterization at the required specificity level, to improve the quality of the medical image.

5. Discussion

5.1 System design prototyping

The design approach that was analyzed earlier addresses the core problem of developing a control system for the image quality assurance system of the X-ray device, in relation to the automatic control model. However, the final image quality and thus the overall result of the system should be measured against current designs and practices, which means that additional comparison & control lines should be added to the basic design. In the case of modern clinical-level X-ray devices, expert technical personnel and physicians conduct extensive tests and pilot measurements on well-defined calibrating procedures, in order to optimize the X-ray device parameters to its full capabilities. In effect, this process constitutes an additional control feedback for the system, "external" to the inherited automatic controller's logic, yet necessary for system initialization and validation before it can be put into clinical use.

For quality assurance and verification purposes, the proposed system design will include two additional feed-forward lines, in accordance to current practices in modern X-ray devices:

- Objective clinical image quality parameters estimated by the expert physician through visual inspection, both for test patterns and for real clinical images.
- Global image characteristics and statistical properties, according to current state-of-the-art automatic exposure control (AEC) and automatic brightness control (ABC) protocols employed in modern X-ray devices.

These two additional factors are essential for the first stages of the development, in order to create a robust and compact input interface for the controller input, as well as to validate early in the process the actual convergence of the design towards the intended goal. As the design progresses onto more a detailed pattern, the system is expected to become more and more autonomous in terms of operational effectiveness, while at the same time becomes less and less dependent on these additional input feeds. The final system is still expected to require some initialization and validation procedures, but it should exhibit at least the same degree of autonomy as the control systems currently employed in modern X-ray devices.

5.2 Dimensionality and module interconnection

As it was described earlier, the proposed design approach includes a 2-stage implementation of the controller, effectively employing two interconnected non-linear modules that incorporate different aspects of the complete system model. Using multiple modules as part of combined control logic enables the different self-organizing heuristic architectures to focus on smaller, simpler and more specific aspects of the problem at hand, without sacrificing the stability and robustness of the system. However, interconnected modular architectures inherit some additional degree of internal structural and functional complexity that should be investigated thoroughly during the design of the complete system.

The second stage of the control logic includes feedback adjustment to the main X-ray exposure parameters (KV, mA, sec), thus the output state-space is multi-dimensional. Most heuristic architectures (neural / fuzzy controllers, etc) require a well-defined discriminative input vector, in order to successfully segment the input parameters state-space. This usually means that the input space exhibits at least the same degree of dimensional complexity as the output. Thus, in order to successfully design and implement a multi-parameter output space for the X-ray exposure envelope, the corresponding input space should contain at least the same number of distinct and independent quantitative elements.

In order to avoid possible loss of response accuracy and stability of the combined system, interface requirements between the two modules suggest that an image quality vector of dimension at least 2-3 should be used, instead of a single image quality index. In practice, the dimension of this vector might require doubling the actual dimension of the input vector with new independent and analytic parameters, if preliminary analysis should suggest that this would benefit the design and training of the heuristic architecture in terms of complexity, stability and robustness. Typical dependencies of exposure parameters, like the common practice of combining intensity (mA) and exposure time (sec) into one linear abbreviation (mAs) [14, 17], should be used to further reduce the dimensional complexity of the search space without sacrificing the effectiveness and accuracy of the final system.

Although the exact details and infrastructure of the internal module interconnectivity is of no relevance to the actual input and output specifications of the complete system, it is evident that the implications of the internal system organization are especially important to the final system's quality and actual efficiency.

6. Summary

The problem of optimal adaptive control of the radiographic exposure profile in mammography constitutes of various properties with non-trivial inherit dependencies. Modern radiography and mammographic imaging systems employ several exposure parameters for effectively controlling the overall radiographic procedure, however they are still strongly bounded to the operator’s skill and expertise in order to produce quality results, even in the case of some automation in the exposure control (AEC).

The goal of the proposed design is to produce a new control system with embedded innovative capabilities and improved efficiency, employing higher-level “smart” logic that enables a greater degree of automation and accuracy in the radiographic procedure.

The quality of the resulting image is directly related to the exposure parameters used, as well as the quality characteristics of the X-ray projection system, the radiation-to-charge conversion and the visualization system. While the physical properties of the detector system is well defined and fixed for a given radiographic device at hand, the processing stage of the resulting attenuation profile of the projected subject can be improved in terms of automatic image quality evaluation, exposure parameters optimization and adaptability to case-specific patient attributes.

Using existing detector technologies and architectures, including direct and indirect conversion-detection, as well as digital mammography via storage phosphor arrays, the new system will drastically improve both the overall image quality and the discriminative tissue-related information that constitute the basis for a realistic clinical evaluation of the subject. However, it is expected that this higher-level control logic will require the employment of advanced heuristic approaches, including various self-organizing and pattern-recognition architectures.

Existing state-of-the-art hardware embedded solutions will enable the new “smart” controller to be easily employed and integrated into future X-ray equipment with minimal cost and effort, while at the same time achieving more efficient and safe radiographic devices.

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Index of Abbreviations

ABS	Automatic Brightness Control
AEC	Automatic Exposure Control
AMFPI	Active-matrix flat panel detector architecture
CR	Contrast Resolution
DCE	Detective Quantum Efficiency
ESE	Entrance-Skin-Exposure (parameter)
IQI	Image Quality Index (vector)
MRT	Minimum Response Time (automatic timers)
MTF	Modulation Transfer Function
N	Noise (image artefacts)
NPS	Noise Power Spectrum
QA	Quality Assurance
RP	Radiographic Positioning
SR	Spatial Resolution