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Can Image Enhancement Allow Radiation Dose to Be Reduced Whilst Maintaining the Perceived Diagnostic Image Quality Required for Coronary Angiography?

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Shortened title: Can image enhancement allow radiation dose reduction?

Keywords: Coronary angiography, digital image enhancement, image quality, radiation dose reduction, noise simulation.

Abbreviations: Percutaneous coronary intervention (PCI), As Low as Reasonably Practical (ALARP), Body mass index (BMI), Relative dose reduction (RR), Graphical user interface (GUI), Generalised linear latent and mixed models (GLLAMM), Dose area product (DAP), computed tomography (CT).

Word count 219 (abstract), 3744 (main text)

Abstract

Objectives

The aim of this research was to quantify the reduction in radiation dose facilitated by image processing alone for percutaneous coronary intervention (PCI) patient angiograms, without reducing the perceived image quality required to confidently make a diagnosis.

Methods

Incremental amounts of image noise were added to five PCI angiograms, simulating the angiogram as having been acquired at corresponding lower dose levels (10-89% dose reduction). Sixteen observers with relevant experience scored the image quality of these angiograms in three states - with no image processing and with two different modern image processing algorithms applied. These algorithms are used on state-of-the-art and previous generation cardiac interventional X-ray systems. Ordinal regression allowing for random effects and the delta method were used to quantify the dose reduction possible by the processing algorithms, for equivalent image quality scores.

Results

Observers rated the quality of the images processed with the state-of-the-art and previous generation image processing with a 24.9% and 15.6% dose reduction respectively as equivalent in quality to the unenhanced images. The dose reduction facilitated by the state-of-the-art image processing relative to previous generation processing was 10.3%.

Conclusions

Results demonstrate that statistically significant dose reduction can be facilitated with no loss in perceived image quality using modern image enhancement; the most recent processing algorithm was more effective in preserving image quality at lower doses.

Advances in knowledge

Image enhancement was shown to maintain perceived image quality in coronary angiography at a reduced level of radiation dose using computer software to produce synthetic images from real angiograms simulating a reduction in dose.

Introduction

Cardiac interventional X-ray systems allow real-time visualization of the moving heart and coronary arteries to allow for diagnosis and treatment of coronary heart disease, currently the most common cause of death worldwide.[1,2] Percutaneous coronary intervention (PCI) is an image-guided procedure used to treat coronary heart disease. Coronary angiography plays a key role in PCI procedures, and the angiograms must have sufficient image quality for confident clinical diagnosis.

Patient radiation doses from PCI are the highest of any X-ray examination,[3] posing a risk of stochastic and deterministic radiation harm to both patients and staff.[4-10] The number of PCI procedures in the United Kingdom has risen from 45,000 in 2002 to 96,000 in 2014; this increase demonstrates the need to reduce the dose used in PCI procedures as per the 'As Low As Reasonably Practical' (ALARP) principle.[8,11,12] X-ray system settings must be optimized to utilize the minimum possible amount of radiation to form an image of sufficient quality for diagnosis.

The relationship between patient dose and image quality is complex, depending upon the X-ray beam energy spectrum, beam intensity and patient body habitus. Alterations in the X-ray beam energy, through changes in tube voltage (kV) and beam filtration, can have significant effect on the image quality per unit of patient radiation dose.[13,14] By selecting more optimal X-ray beam energy for a given patient size, the patient dose can be lowered whilst maintaining image quality.

The X-ray beam intensity, controlled by the X-ray pulse duration (ms) and tube current (mA), are directly proportional to patient dose. Reducing dose through lowering of the beam intensity increases the level of noise within an image. Given the Poisson nature of X-ray photon statistics, noise is proportional to the square root of the beam intensity. Specifically, increasing the dose by a factor of four will half the level of noise within an image as long as the beam energy is constant, thereby improving image quality.

In recent years, new digital image processing technology has been developed which permits images to be acquired at a lower dose than previous X-ray imaging techniques, whilst preserving the diagnostic quality of the images presented to the user. Advances in high-speed computing allow for real-time processing, thus increasing the sophistication of image processing algorithms used in cardiac imaging systems, which require very low latency image displays. New generations of cardiac interventional X-ray systems have state-of-the-art image processing algorithms which adapt to image content in real-time according to the clinical task selected by the user. These new systems offer dose reductions (50-75%) compared to previous generations of equipment.[15,16] The X-ray dose reduction is achieved through revised radiographic factors for the systems, and potentially the use of additional use of spectral beam filtration. This will alter both the X-ray beam energy profile and intensity incident upon the patient, which will have an effect on radiation dose to the patient and the quality of the recorded image. The use of image processing may then further improve the displayed image quality thus allowing further dose reduction, and the algorithms that are employed in modern cardiac imaging systems are complex. Although the precise details of the algorithms are not revealed by the manufacturers, the main elements of the algorithms are a combination of noise reduction and contrast enhancement (sharpening).Altering the beam energy can have beneficial effects on the quality of the recorded image, and using more optimal beam energies for a given patient size may allow image quality to fall less than may otherwise be expected when lowering dose. None of the previous studies which assessed the overall X-ray dose reduction of these new systems[17-20] have been able to assess the efficacy of the image processing algorithms alone as doing so requires the same image to be processed using different algorithms, a feature not available on end-user systems.

The aim of this research was to quantify the dose reduction that can be facilitated by image enhancement alone for coronary angiography on PCI patients, without reducing the perceived image quality required to confidently make a diagnosis.

Materials and Methods

Patient Images

Patient angiograms were acquired on an Allura Xper FD10 cardiac interventional X-ray imaging system (Philips Healthcare, Best, The Netherlands) during routine PCI procedures in the cardiac catheterisation laboratory at Leeds General Infirmary, United Kingdom. For research purposes, the manufacturer allowed for the capture of angiograms prior to the digital enhancement routinely used in clinical practice. The left coronary 15 frames per second mode was used to acquire images, with 0.1 mm copper and 1.0 mm aluminium spectral beam filtration and the anti-scatter grid in place.

Five PCI patient angiograms were anonymised for this study; the National Health Service Research Ethics Committee approved their use for this research. The patients were selected to provide a range of body mass indexes (BMI) representing adult cardiac patient sizes (BMI 23 to 44 kg m^{-2}). The angiograms were selected to include both left and right coronary arteries, with angulation and rotation angles typically used in clinical practice, as shown in Table 1.

Bespoke software created in-house using MATLAB (The Mathworks Inc., Natick, USA) was used to simulate the effect of having acquired the angiograms at incrementally lower doses (10-89%) by adding corresponding amounts of computer-generated quantum colouredimage noise, frame-by-frame, pixel-by-pixel. The software was calibrated for the imaging mode used to acquire the five patient angiograms, and validated using objective and subjective image quality measurements.[21] Two different image processing algorithms were applied to these images by personnel at Philips Healthcare (Best, The Netherlands), resulting in three sets of images (three processing states): those with no processing, with algorithm A applied, and with algorithm B applied. Algorithm B is that used for angiography on the most recent cardiac interventional X-ray system (or upgrade) available from Philips Healthcare, the AlluraClarity system with ClarityIQ. Algorithm A is that used for angiography on the previous generation cardiac interventional X-ray system from Philips Healthcare, the Allura Xper system. Due to the proprietary nature of the processing methods, details of how the processing algorithms operate were not accessible, but information on algorithm B can be accessed online. Figure 1 shows an example (Patient 2) of the resulting three processing states.

The range of dose reduction increments (10-89%) simulated was divided evenly into four groups, and one increment was randomly selected from each group using Microsoft Excel, with the selected increments as shown in Table 2. Figure 2 shows an example (Patient 5) of the resulting set of dose levels. This was completed to ensure that a reasonable number of angiograms would be included in the image assessment while covering a large range of increments, i.e. a volunteer observer could realistically score all of the images in 20-30 minutes. These increments were the same across all three sets (processing states) of angiograms, to ensure that perceived differences in image quality were solely from the image processing.

The peak tube current (mA) and X-ray pulse duration (ms) used to acquire each of the original five angiograms was extracted from the DICOM header and used to calculate the mAs. The mAs for reduced-dose angiograms was then calculated using the percentage of dose reduction simulated. The mAs was used to calculate the relative reductions (RR) in dose allowed for by the image processing, since mAs is directly proportional to the radiation dose used to acquire the angiogram. The logarithm of mAs (log(mAs)) was used in the statistical models to account for half power law relationship between signal to noise ratio and mAs due to the Poisson distribution of X-ray photons, based on the method by Smedby et al.[22]

Image Assessment

Sixteen observers - four clinical scientists with 2 to 30 years' experience with experience of cardiac imaging, five cardiac radiographers with 10 to 15 years' experience, and seven cardiologists with five to 20 years' experience - participated in the blinded image quality assessment. The University of Leeds Research Ethics' Committee granted approval for the observer study. All of the observers were provided with a participant information sheet and gave written consent, but remained anonymous.

The image quality assessment took place in the reporting room of the catheterisation laboratories, where angiograms are viewed in practice. The angiograms were viewed on an EIZO RadiForce medical grade monitor RX340 (EIZO Corporation, Japan) which was placed one metre away from the observer to simulate a cardiac catheterisation laboratory. A bespoke software program was created in MATLAB specifically for this study to provide a graphical user interface (GUI) with a continuous scale of image quality scores. Every observer scored all of the angiographic sequences in the study, although the viewing order for a given observer was randomly generated. Five of the angiograms from Table 1 were randomly selected for training, to allow the observers to become familiar with the scoring task.[23] Following this, 18 sequences (three each from patients one and four, and four each from patients two, three and five as per table 2) in the three states (no processing, algorithm A and algorithm B), totalling

54 sequences were scored. The angiograms were shown individually with the sequence playing in a continuous loop until the observer scored the image; there was no time limit. Observers were asked to look at the clarity of the epicardial vessels and answer the question, ‘How confidently would you be able to identify a lesion on this PCI patient?’ as though they were the cardiologist making a diagnosis. The continuous scoring scale ranged from ‘not at all’ (0) to ‘enough to make a diagnosis’ (0.5) to ‘very confidently’ (1), and observers clicked anywhere on the entire scale; the numerical values were hidden. The 54 sequences viewed by the 16 observers yielded a total of 864 observations.

Statistical Analysis

Observer scores were analysed using Stata IC 13 (Stata Corporation, College Station, TX). The continuous scale used in the image assessment was categorized to a five-point ordinal scale; an ordinal scale was not used for the scoring task to avoid the limitations associated with this scale format.[24] The scores were converted to categories between one (“not at all”) and five (“very confidently”) at intervals of one fifth of the continuous scale. A visual grading regression framework which utilises ordinal logistic regression with random effects was used to analyse the ordinal scores of the angiograms and obtain a quantitative value of dose reduction allowed for by image processing, as was done by Smedby et al.[22]

The generalised linear latent and mixed models (GLLAMM) programme in Stata was used to conduct the ordinal logistic regression, enabling the observers and patients to be included as random effects, since they were samples from a larger population.[22,25-27] The log(mAs) and image processing state variables were classed as fixed effects.

The relative reduction (RR) in mAs (RR_{mAs}) was calculated using Equation (1), where b and a were coefficients for the processing state and log(mAs) respectively.[22] The resulting RR_{mAs} quantified the dose reduction possible by switching from one image processing state to another, while maintaining perceived image quality and keeping all other X-ray settings constant. The RR_{mAs} was calculated for the three pairwise comparisons of state-of-the-art processing, previous generation processing and no processing.

$$RR_{mAs} = 1 - \exp(-b/a) \qquad (1)$$

The delta method was applied to the GLAMM results to calculate corrected standard errors for the estimate of RR_{mAs}.[22,28]

Results

Compared to the use of no processing both algorithms showed an equivalent image quality at lower radiation doses. These results are summarised in table 3. When switching from no processing to algorithm A, or to algorithm B, the RR_{mAs} (that is the amount of dose reduction that can be applied whilst maintaining equivalent image quality) was significant at 15.6% [9.4%, 21.9%] and 24.9% [18.8%, 31.0%] respectively (the numbers in square brackets are the 95% confidence intervals).

Table 4 shows the regression model and delta method results when comparing the image processing algorithms to one another. For the same input dose level, algorithm B had a higher ordinal score than algorithm A, as shown by the coefficient value of 0.55. The relative dose reduction facilitated by switching from algorithm A to algorithm B was statistically significant at 10.3% [4.4%, 16.2%].

Discussion

Image processing algorithm B was more effective at preserving image quality at lower doses than algorithm A, i.e. it allows for lower doses, and algorithm B is the more recently developed and released of the two algorithms indicating that the manufacturer has improved its image enhancement algorithms over time. Algorithms A and B are (at the time of writng) the most recent and previous generation of algorithm available from Philips Healthcare for cardiac interventional X-ray image acquisition. Unfortunately, the specific operation of the algorithms are proprietary and not available in the public domain or to the authors, and it is therefore not possible to suggest how the improved performance was achieved. .

A previous study showed that switching from full system A to full system B (i.e. taking into consideration all factors involved in reducing dose) provided a reduction in dose area product (DAP) of 76% for angiography of PCI patients, with a slight reduction in displayed image quality as assessed by 75 observers. The current study demonstrates the proportion of this 76% reduction in patient DAP which originates from the image enhancement algorithm alone; the remainder will be from changes in X-ray settings.

This is the first study to quantify the dose reduction permitted by image processing methods alone using patient images in cardiac X-ray imaging, to the authors' knowledge. Previous studies have quantified the reduction in dose permitted by the Philips AlluraClarity interventional X-ray system (which includes algorithm B) compared to the Philips Allura Xper system (which includes algorithm A) in a range of cardiac and digital subtraction angiography applications, demonstrating significant patient dose reduction.[17,18,20,29-31] None of these studies investigated the contribution to dose reduction of individual factors upgraded in the AlluraClarity system, as was completed with image processing here.

The software which added simulated noise to the images enabled this study to utilise patient angiograms as the ethical barrier of repeatedly exposing the same patient to X-rays of different radiation doses was avoided. The alternative would have been to use static, non-clinical images of test objects or phantoms.[32,33] For this study, access to unprocessed image data was required for both the noise simulation software and for the methods. It is clearly important that simulated images accurately represent dose reduced images; a reduced exposure results in lower signal levels at the detector (and increased noise), whereas in the simulated images the noise power was increased in images acquired at higher signal level. The net effect of the two approaches should be the same if the processes are linear, which would be the case if noise is quantum limited (i.e. signal dependent). Extreme levels of dose reduction on a real image could introduce significant levels of electronic or quantisation noise which would not be represented in the simulated dose reduced image. The noise adding algorithm used has been validated using threshold contrast and anthropomorphic phantoms and found to be accurate at the dose reduction ranges used in this study.[22]

The observer (i.e. subjective) image assessments used with patient angiograms provided clinically-relevant results.[34] Observer variability was accounted for in the statistical analysis using random effects. The analysis used was designed specifically for subjective scoring studies and allowed the quantification of RR_{mAs} of image processing alone.[22]

Multiple factors which impact image quality were varied in this study, including patient characteristics, (simulated) dose level, and image processing state. The image assessment was designed to include a range of observers and angiograms, while maintaining a reasonable viewing time. Randomly selected increments within four evenly spaced groups (rather than fixing dose reduction increments which are far apart i.e. 25%, 50%, 75%) assured that both a broad range, and a continuous spread, of dose levels were included. Should an exhaustive list of dose reduction increments have been used, the feasibility of a volunteer observer viewing all of the images for five patients and three processing states during a realistic viewing time would have been miniscule, and consequently a small number of observers would likely have been recruited. Moreover there were 864 observer responses collected in the image quality assessment; a sufficient amount of data to draw reliable conclusions. The choice of five angiograms to be included in this study, combined with a large number of observers, is a compromise limiting the time required for an individual observer to complete the study to a reasonable time period, yet still achieving a large number of observations. The set was selected to include a range of BMIs, projections and both left and right coronary arteries. Rerunning the analysis with the patient as a fixed effect did not alter the results. Whilst the five cases were varied, the limited number of cases meant that it was not possible for us to study the effect of differences in the cases (for example to see if the algorithm performance was different on patients with lower or higher BMI).

Four angiograms (of less than 30% dose reduction) were not available in processed states during this study. As a result there were no angiograms to represent the range of 10-29% dose reduction for Patients one and four. The statistical analyses were repeated without the 10-29% range shown in Table 1 for all patients and the conclusions were unchanged; the reductions in dose were still statistically significant.

Future work could use the methods established here to determine the contribution of image processing alone to dose reduction in fluoroscopy. Also used in PCI, fluoroscopy utilises lower radiation doses and correspondingly lower image quality, generally with different image processing algorithms than for angiography.[35]

Conclusion

Statistically significant dose reduction can be achieved by modern digital image enhancement alone, without loss to perceived image quality, and therefore image processing can play a key role in reducing patient dose. The most recent cardiac image processing algorithm tested in this study was more effective in preserving image quality at lower doses than the previous generation image processing algorithm, however both allowed for statistically significant reductions in dose. The magnitude of dose reduction permitted from processing alone indicates that dose reductions on modern X-ray systems must also be achieved using other factors, for instance the use of more optimal X-ray beam energies, or a reduction in the displayed image quality.

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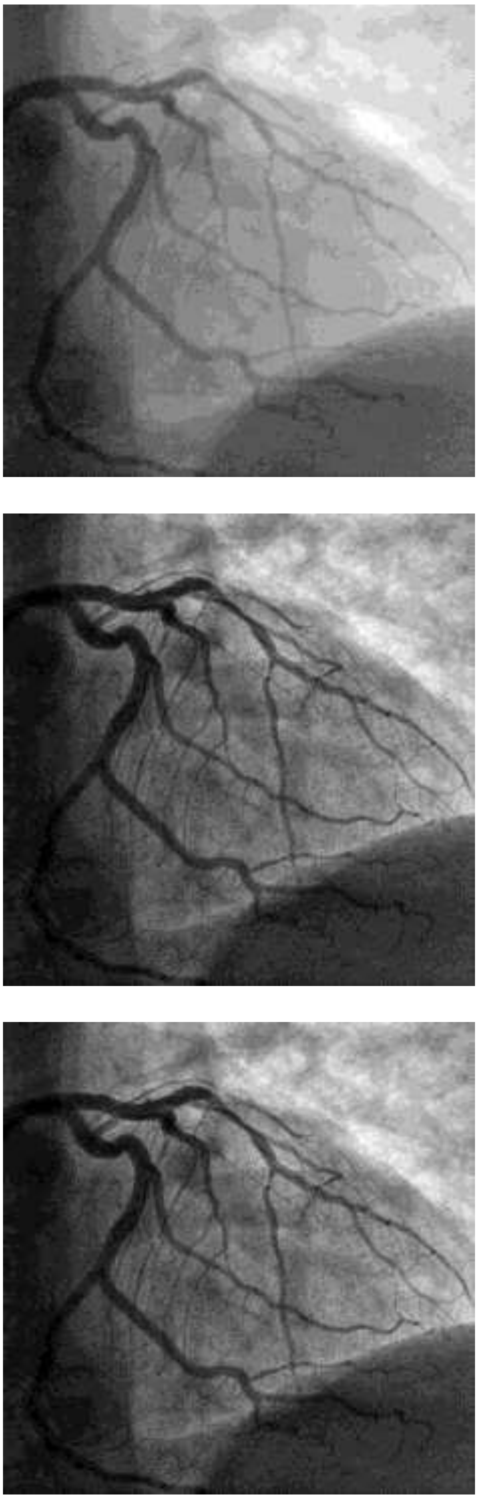
Figure 1: A single frame from Patient 4's angiogram (left coronary artery) with no processing (1a), algorithm A (1b) and algorithm B (1c).

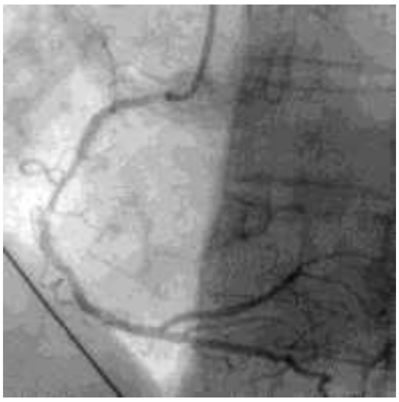


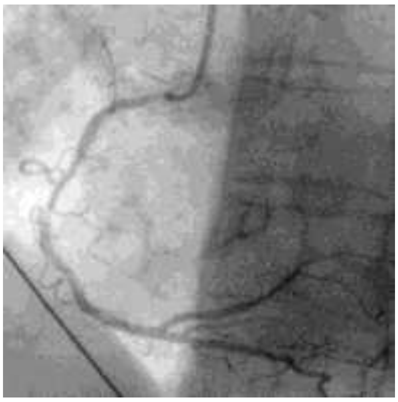
a)

b)

c)

Figure 2: A single frame from Patient 5's angiogram (right coronary artery) with no processing and increments of: 23% (2a), 39% (2b), and 71% (2c) dose reduction simulated by adding image noise.

a) 

b) 

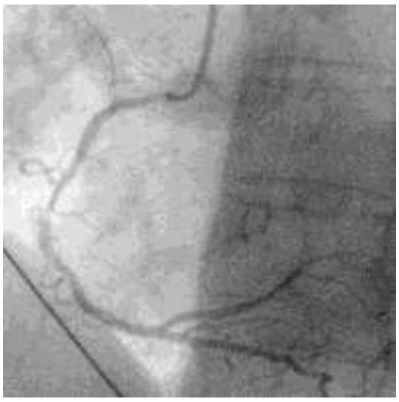
c) 

Table 1. BMI of patients and image projection angles

Patient Number	BMI (kg m^{-2})	C-arm Rotation (°)	C-arm Angulation (°)	Vessel of Interest
1	25.6	RAO[a] 90	Caudal 3	Left circumflex
2	44.1	RAO[a] 35	Caudal 17	Right coronary artery
3	29.4	LAO[b] 37	Caudal 31	Left anterior descending artery
4	36.5	RAO[a] 3	Caudal 20	Left anterior descending artery
5	23.8	LAO[b] 28	Cranial 1	Right coronary artery

[a]RAO; right anterior oblique
[b]LAO; left anterior oblique

Table 2. Increment of dose reduction simulated by adding image noise

Group	Patient1	Patient 2	Patient 3	Patient 4	Patient 5
10-29%	-	26%	28%	-	23%
30-49%	37%	36%	46%	41%	39%
50-69%	61%	60%	63%	50%	65%
70-89%	87%	74%	88%	70%	71%

Table 3. Comparison of the two image processing algorithms with no processing

Regression Model			
	Coefficient	Standard Error	p-value
log(mAs)	4.56	0.35	<0.001
Algorithm B	1.31	0.17	<0.001
Algorithm A	0.78	0.17	<0.001
Calculation of RR			
	RR_{mAs}= 1-exp(-b/a)	RR_{mAs} (%)	Standard Error
Algorithm B	0.249	24.9	0.031
Algorithm A	0.156	15.6	0.032

Table 4. Comparison of two image processing algorithms

Regression Model			
	Coefficient	Standard Error	p-value
log(mAs)	5.10	0.45	<0.001
Algorithm B compared to algorithm A	0.55	0.17	<0.001
Calculation of RR			
	RR_{mAs}= 1-exp(-b/a)	RR_{mAs} (%)	Standard Error
Dose Reduction	0.103	10.3	0.032