Radiation dose reduction capabilities of a new C-arm system with optimized hard- and software

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ABSTRACT

Purpose: To assess the radiation dose reduction capabilities and the image quality of a new C-arm system in comparison to a standard C-arm system.

Method: Prospective, randomized, IRB approved two-arm trial design. 49 consecutive patients with primary or secondary liver cancer were treated with transarterial chemoembolization (TACE) on two different angiography units. 28 patients were treated on a conventional angiography unit B, 21 patients on unit A which provides improved hardware and optimized image processing algorithms. Dose area product (DAP) and fluoroscopy time were recorded. DSA image quality of all procedures was assessed on a four-rank-scale by two independent and blinded readers.

Results: Both cohorts showed no significant differences with regard to patient characteristics, tumor burden and fluoroscopy time. The new system resulted in a statistically significant reduction of cumulative DAP of 72% compared to the old platform (median 76 vs. 269 Gy*cm²). Individually, Fluoro-DAP and DSA-DAP decreased by 48% and 77% (p = 0.012 and p < 0.01), respectively. No statistically significant differences in DSA image quality were found between the two imaging platforms.

Conclusions: The new C-arm system significantly reduced radiation exposure for TACE procedures without increased radiation time or negative impact on DSA image quality. The combination of optimized hardware and software yields the highest radiation dose reduction and is of utmost importance for patients and interventionalists.

INTRODUCTION

Radiation exposure for the patient during image-guided interventional procedures can be considerable, especially due to digital subtraction angiography (DSA), and the implications of radiation are well known [1–3]. In addition, the clinical staff performing the procedures is exposed to radiation as well, and the awareness for the radiation impact on the health of the clinical staff has increased over the last decade, resulting in the development real time dose monitoring systems for clinical staff [4]. Especially for patients undergoing repeated procedures, the cumulative radiation dose is even higher [5]. Transarterial chemoembolization (TACE) for example, is an important and often repeatedly performed treatment option for primary and secondary liver cancer [6–10].

For this reason, continuous research is essential to tackle this issue and to allow for technological enhancement of flat-detector angiography units regarding dose reduction strategies, both hard- and software-based. In this regard, recent advancements have led to several possibilities for dose optimization by modifying X-ray tube potential, current, pulse width, focal spot sizes and filtration thickness [11]. Another possibility is the implementation of advanced real-time image post-processing to reduce the noise caused by low dose imaging [12], allowing to reduce the dose even further. This technique was reported to facilitate a significant radiation dose reduction of both digital fluoroscopy (DF) and digital subtraction angiography (DSA) for various image-guided procedures in the field of interventional radiology.
and interventional cardiology [16,17].

Recently a new angiography unit (Artis Q, Siemens Healthineers, Forchheim, Germany) was released with a completely new developed imaging chain, including a new tube, a new detector and new post-processing algorithms to further reduce radiation dose without rendering the image quality non-diagnostic.

The aim of this study was to compare this new angiography unit with a conventional unit regarding radiation dose and image quality in liver cancer patients treated with transarterial chemoembolization.

1. MATERIALS AND METHODS

1.1. Study Population

49 consecutive patients referred to our department for transarterial chemoembolization were enrolled in this study. The institutional administrative staff, who were not aware of the study, assigned the patients to one of the angiography units based on availability. Thus, 21 and 28 patients were treated on angiography unit A (Siemens Artis Q) and unit B (Siemens Artis zeeqo), respectively.

The study was approved by the local ethics committee, and written informed consent was obtained in all cases. Pregnant patients as well as patients who presented with standard exclusion criteria for angiography (which include subjects with significant bleeding disorders, acute or chronic renal insufficiency etc.) were excluded from the study.

1.2. Angiographic imaging units

The two compared systems show considerable differences in X-ray generation as well as in X-ray detection.

For X-ray generation, the more powerful X-ray tube of unit A utilizes a flat-emitter technology with reduced tube focal spot sizes, i.e. 0.3, 0.4 and 0.7 (for micro, small and large focal spot respectively) vs. 0.3, 0.6 and 1.0 for the tube of Unit B. This allows sharper images at the same dose, which equally converts into lower dose at same visibility level. It is important to note, that very thin structures like fine vessels or wires require a sufficiently small focal spot size for relevant visualization. Otherwise, visibility is technically not feasible. In this regard, the availability of three focal spot is beneficial: The focal spot with minimal spot size is automatically adjusted in respect to the power requirements of the current situation. Usually for abdominal procedures the usage of the large focal spot is quite often indicated in order to deliver the dose requested by the detector. The tube of unit A additionally benefits from the increased maximum pulse power of 90 kWp (vs. 80 kWp). This allows better penetration of thick body parts. In case the pulse power is not needed for tissue penetration, increased copper pre-filtration reduces patient entrance dose at same image quality level by spectral beam hardening.

Due to a different mechanical tube design the continuous power of the tube could be increased to 5000 W (from 2900 W), mainly caused by almost tripling the cooling capacity of the anode to 1520000 Heat units per minute (HU/min), compared to 540000 HU/min. This new capability avoids early reduction of tube power due to extensive tube temperature, which is relevant for treatment of high absorbing body regions, like the abdominal area.

Automatic Exposure Control (AEC) of unit A has been adjusted to the 14-bit resolution of unit B. In addition it employed a thicker scintillator layer of 750 μm (vs. 550 μm) which increased the X-ray detection efficiency (DQE) of 77% (vs. 73%).

Furthermore the new unit A includes improved software components such as enhanced image processing algorithms, similar to those that were previously described [12].

1.3. TACE protocol

All cases were presented at our multidisciplinary tumor board and interdisciplinary consensus for the indication and treatment modality was reached. All interventions were conducted by radiologists with more than 5 years of experience in interventional oncology, following a standardized approach [18]. Drug-eluting Bead chemoembolization (DEB-TACE) was performed in all cases. Furthermore, the same contrast media (Jopamiro 300, Bracco, Milan, Italy) was used for all procedures in order to avoid an influence on the image quality and attenuation of the vessels.

1.4. Radiation Dose Evaluation

A Radiation Dose Structured Report (RDSR) was automatically generated by the system software at the end of each procedure and stored in the Picture Archiving and Communication System (PACS). Such a structured report consists of the number of acquired frames, the corresponding radiation exposure time and the amount of radiation exposure by means of air kerma (AK) and dose area product (DAP) for each radiation event, both DF and DSA (see Supplemental Material 1).

The parameters such as fluoro pulse rate, Source-to-Image Receptor Distance (SID) and collimation settings were similar for all patients so that the DAP obtained is an adequate measure of radiation dose and considered an appropriate specific dose factor to compare the two systems.

The differences in procedure difficulty and therefore radiation time were taken into account by normalizing the obtained exposure values by radiation time, as previously described [13].

The normalized DAP for one second of DSA was calculated as DSA cumulative DAP (Gy·cm²) / DSA exposure time (sec).

1.5. Image Quality analysis

As part of the clinical routine, DSA images were post-processed after the procedure, including stacking, pixel shift and brightness/contrast adjustments. Both unprocessed und post-processed DSA images were archived in the institutional PACS. To avoid bias from post-processing, only the unprocessed DSA images, that were available during the procedure on the operation room monitor, were analysed with regard to image quality. The image quality was assessed in a blinded and randomized setting by two radiologists with at least 8 years of experience in oncologic liver imaging. Using a four-point grading system both readers evaluated independently the visibility of the hepatic artery on the images of the common hepatic DSA run (Table 1).

1.6. Statistical Analysis

SPSS Statistics 22 (IBM Corp., Armonk, NY) was used for statistical analysis. Statistical significance was defined by a p-value less than 0.05. Descriptive statistics were used to summarize the data. Shapiro-Wilk tests were used to assess the distribution of all scale variables. For

<table>
<thead>
<tr>
<th>Score</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Perfect visualization of all hepatic arteries including small intra-tumoral vessels</td>
</tr>
<tr>
<td>2</td>
<td>Good visualization of all hepatic arteries including tumor-feeding vessels</td>
</tr>
<tr>
<td>3</td>
<td>Visibility from the proper hepatic artery to the subsegmental branches</td>
</tr>
<tr>
<td>4</td>
<td>Visibility from the proper hepatic artery to the segmental branches</td>
</tr>
</tbody>
</table>
scale variables with normal distribution, mean, standard deviation, range and unpaired t-tests were used. For scale variables with non-Gaussian distribution, median, interquartile range, range and Wilcoxon rank-sum tests were used. For ordinal variables, count, percentage and Wilcoxon rank-sum tests were used. For the assessment of interobserver agreement, Kendall’s tau coefficient was calculated. Furthermore, image quality ratings of the two angiography units were compared using visual grading characteristics and receiver operating characteristics (ROC)/area under the curve (AUC) analysis.

2. RESULTS

2.1. Patient demographics

Baseline and demographic patient characteristics are reported in Table 2. All patients were affected by hepatocellular carcinoma, the number of liver lesions (and thus the tumor burden) was similar in both groups (p = 0.278). No significant difference was found regarding sagittal abdominal diameter at the level of the portal vein bifurcation (p = 0.377) BMI (p = 0.136) and age (p = 0.459).

2.2. TACE procedures

Procedure characteristics are displayed in Table 3. In the majority of cases, a superselective approach was possible (62% and 71% of group A and B, respectively) and in the remaining procedures a selective TACE was performed (38% and 29%, respectively). The median DF time for group A and group B was 21 min (range, 5-47) and 17 min (range, 6-68), respectively. The median DSA time for group A and group B was 21 min (range, 5-47) and 17 min (range, 6-68), respectively. The total procedure time for study (A) and control (B) groups was 53.3 min (range, 24-276) and 78 sec (range, 41-278), respectively. The total number of liver lesions (and thus the tumor burden) was similar in both groups (p = 0.136) and age (p = 0.459),

2.3. Radiation exposure

The median values (including those normalized by radiation time) of radiation dose Unit A Unit B Reduction p-value

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Unit A</th>
<th>Unit B</th>
<th>Reduction</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cumulative DAP (Gy/cm²)</td>
<td>76.0; 98.1</td>
<td>268.7; 249.1</td>
<td>72%</td>
<td>0.002</td>
</tr>
<tr>
<td>Fluoro DAP (Gy/cm²)</td>
<td>28.5; 32.6</td>
<td>54.9; 74.9 (75.5-106.2)</td>
<td>48%</td>
<td>0.012</td>
</tr>
<tr>
<td>Norm. Fluoro DAP (Gy/cm²/min)</td>
<td>1.43; 1.14</td>
<td>3.33; 2.86</td>
<td>57%</td>
<td>0.003</td>
</tr>
<tr>
<td>DSA DAP (Gy/cm²)</td>
<td>42.2; 88.8</td>
<td>181.9; 184.7 (153.6-246.6)</td>
<td>77%</td>
<td>0.001</td>
</tr>
<tr>
<td>Norm. DSA DAP (Gy/cm²/sec)</td>
<td>0.46; 0.58</td>
<td>2.10; 1.9 (1-7)</td>
<td>78%</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Cumulative RAK (Gy)</td>
<td>0.85; 0.86</td>
<td>1.94; 1.92</td>
<td>56%</td>
<td>0.008</td>
</tr>
<tr>
<td>Fluoro RAK (Gy)</td>
<td>0.32; 0.38</td>
<td>0.54; 0.74</td>
<td>40%</td>
<td>0.063</td>
</tr>
<tr>
<td>Norm. Fluoro RAK (mGy/min)</td>
<td>15.00; 12.8</td>
<td>35.35; 30.27</td>
<td>58%</td>
<td>0.008</td>
</tr>
<tr>
<td>DSA RAK (Gy)</td>
<td>0.37; 0.6</td>
<td>1.13; 1.39</td>
<td>67%</td>
<td>0.002</td>
</tr>
<tr>
<td>Norm. DSA RAK (mGy/sec)</td>
<td>3.2; 4.85</td>
<td>15.2; 10.3</td>
<td>79%</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>

Note: Data represented as median; interquartile range (range).

RAK and the cumulative DAP was statistically significantly lowered by 56% (from 1.94 to 0.85 Gy) and 72% (from 268.7 to 76 Gy·cm⁻²), respectively, compared to procedures performed on the old system. The DAP for DSA and for DF decreased by 77% (from 181.9 to 42.2 Gy·cm⁻²) and 48% (from 54.9 to 28.5 Gy·cm⁻²), respectively. By taking radiation time into account, the DAP for DSA and DF decreased by 78% (from 21.1 to 4.6 Gy·cm⁻²/sec) and 57% (from 3.33 to 1.43 Gy·cm⁻²/min) and, respectively. Fig 1 shows the distribution of radiation exposure for both systems.

2.4. DSA Image Quality

Using the provided four-point grading score (Table 1), both readers rated the DSA image quality of both systems equal (p = 0.43 and p = 0.13, respectively), with a considerable agreement between both readers according to a Kendall’s Tau coefficient of κ = 0.64 (95% CI: 0.01). According both readers, the common hepatic DSA run of most patients showed the intra-hepatic arteries including the tumor-feeding arteries on both systems (score 1 and 2). Only in a few patients, the identification of tumor feeding arteries was not possible on the common hepatic DSA run, but segmental- and subsegmental branched could be assessed (score 3). Using visual grading characteristics, no significant difference was found between the two systems for both readers (AUC 0.612 and 0.571, p >
Both arteriograms were of excellent quality, showing the intra-tumoral vessels and the tumor blush (arrowheads). Focal spots of the X-ray tube of unit A resulting in higher spatial resolution and improved physical contrast. This helps visualizing small objects without motion blur. The increased tube power allows the maximum pulse current increased, resulting in sharper visualization of fine objects without motion blur. The increased tube power allows the automatic exposure control to add additional filtration by inserting more copper before the beam hits the patient, thus reducing the low energy quanta that are increasing the skin dose without contributing to image enhancement.

An additional positive effect of this technology are the small square focal spots of the X-ray tube of unit A resulting in higher spatial resolution and improved physical contrast. This helps visualizing small devices, such as microcatheters, microwires, stent struts and small vessels.

Besides the new X-ray tube, the unit A contains an improved X-ray detector compared to the previous generations. The described increased scintillator thickness of the detector improves the detective quantum efficiency and helps to further reduce radiation exposure. The 16-bit gray level resolution of the detector provides more gray scale information allowing a more sophisticated image processing and with this improved image quality without introducing artefacts. This improved image processing pipeline of unit A allows for better visualization of the objects of interest and could also be partially responsible for the maintained image quality that was found in this study, despite the reduction in radiation dose.

The results in this study are only partially comparable to previous studies using absolute numbers because of the different metrics (e.g. peak skin dose) that were applied. Furthermore most studies only report the cumulative radiation exposure and radiation time without normalisation of the measurements by the number of DSA images or radiation time. A recent study compared the impact of optimized acquisition protocols and advanced real-time image post processing on dose reduction in TACE patients [13]. The authors reported a reduction of total DAP of 66% resulting in a median DAP of 133 Gy*cm². Our study patients had similar BMI and sagittal abdominal diameter, but the median DAP of patients treated with unit A was 76 Gy*cm², which corresponds to further 40% exposure reduction. In addition, the previous study provided radiation exposure values normalized by radiation time, similar to our study, which allows a more detailed comparison. Looking at the DAP for one minute of DF, their advanced system resulted in 3.4 Gy*cm²/min, whereas unit A in this trial required only 1.43 Gy*cm²/min for clinically usable image quality, which is about 60% less radiation exposure during DF. The reason for this seems to be that the angiograph unit in the former study applied only optimized acquisition parameters and several real-time image processing algorithms whereas unit A in our study also incorporates a new X-ray tube and an improved detector, which allows further reduction of radiation exposure. Looking at the DAP for one second of DSA, their advanced system resulted in 0.67 Gy*cm²/sec, whereas unit A in this trial required 0.46 Gy*cm²/sec for diagnostic DSA image quality, which is only about 30% less radiation exposure. The difference in dose reduction during DF and DSA between the two new systems presented in the previous and this study might be explained by more advanced post-processing algorithms during DSA compared to DF of the other system, whereas the dose reduction in unit A in this study was achieved by a combination of optimized hard- and software. In spite of the relatively small number of patients included, which is a limitation of the study, a statistically significant reduction of radiation exposure could be accomplished without trade-offs in image quality.
quality.

In conclusion, the new C-arm system (unit A) significantly reduced radiation exposure for TACE procedures without increased radiation time or negative impact on DSA image quality.

The combination of optimized hardware and software yields the highest radiation dose reduction and is of utmost importance for patients and interventionalists.

Guarantor

The scientific guarantor of this publication is Prof. Dr. Rüdiger Schernthaner.

Fundings

This study has received funding by Siemens Healthineers, Forchheim, Germany.

Statistics and biometry

One of the authors (Prof. Dr. Rüdiger Schernthaner) has significant statistical expertise.

Informed consent

Written informed consent was obtained from all subjects (patients) in the study.

Ethical approval

Institutional review board approval was obtained.

Methodology

prospective randomised control trial performed at one institution

Declaration of Competing Interest

The authors report no declarations of interest.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi: https://doi.org/10.1016/j.ejrad.2020.109367.

References


Fig. 2. The left box plot shows the distribution of radiation exposure (dose area product in Gy·cm²) for the entire procedure, for digital subtraction angiography and digital fluoroscopy for both systems. The right box plot shows the normalized dose area product for digital subtraction angiography (Gy·cm²/sec) and for digital fluoroscopy (Gy·cm²/min) for both systems. Both plots use a power scale on the Y-axis and show the interquartile range (box), 5th and 95th percentiles (outermost bars) and the median (thick horizontal line) of the exposure distribution of each system.