Reduced radiation dose and improved image quality using a mini mobile digital imaging system in a neonatal intensive care unit

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Abstract

This study was aimed to assess the radiation dose and image quality of a mini-mobile digital imaging (mini-DI) system for neonatal chest radiography and compared to conventional digital radiography (DR). A total of 64 neonates were examined and anatomical landmarks were assessed. The entrance surface dose of mini DI and conventional DR was 26.64 ± 0.15 μGy and 49.11 ± 1.46 μGy, respectively (p < 0.001). The mean SNR values for mini-DI and DR were 233.2 ± 5.1 and 316.2 ± 1.2, and 10% MTF values were 131 and 161 μm. A newly developed mini-DI is capable of preserving the diagnostic information with dose reduction in neonates under intensive care.

1. Introduction

Several studies have evaluated the risks associated with radiation exposure during radiographic examinations, such as computed tomography (CT) and digital radiography (DR) scans, in pediatric [1] and middle-age [2] subjects. These showed that an important factor in radiation-induced risk is the age at which exposure takes place, and fetuses and neonates are the most sensitive. Therefore, the age at the time of radiation exposure is critical in the determination of radiation risk.

During fetal development and early childhood, intense tissue proliferation and differentiation take place, and proliferating cells are more likely to develop into cancer [3]. Especially, the smaller body of premature infants places all organs within the useful beam, resulting in a higher effective dose per radiograph than may be the case with older children and adults. Therefore, radiation doses for neonatal X-ray examinations should be minimized.

The World Health Organization (WHO) reported that preterm birth rates are increasing in most countries for which reliable data are available [4]. Preterm birth is one of the most important single conditions in the global burden of disease analysis given the high mortality and the considerable risk of lifelong impairment [5]. In a neonatal intensive care unit (NICU), DR is frequently used in preterm neonates together with bedside chest radiography, because premature infants are born with immature organs, and frequently have complications of severe illness, such as respiratory distress syndrome and patent ductus arteriosus. Therefore, premature neonates are required to undergo a large number of radiographic examinations depending on the birth weight of the infant, gestational age and medical problems [6]. Moreover, repeated follow-up chest X-ray examinations are required to reduce the mortality rate of prematurity after tube and catheter placement and monitoring of health status [7]. In terms of radiation dose safety, reduction of the radiation dose to neonates is an important issue. The guidelines of the European Union (EU) [8] and American College of Radiologists (ACR) [9,10] suggest that the mean entrance surface exposure (ESE) should range from 0.05 to 0.3 mGy per exposure in newborns, infants and children. However, few studies have addressed radiation dose reduction for neonates, including preterm neonates.

In recent years, many DR systems, including mobile digital imaging systems, have been developed for radiographic examinations in operating rooms, emergency rooms and NICUs. Recent advances in DR...
technology have resulted in smaller and lighter systems that are more mobile, and flat-panel detectors are now used [11–14]. Flat-panel detectors typically offer a detective quantum efficiency twofold that of film-screen systems. DR systems with flat-panel detectors exhibit superior imaging performance at a lower radiation dose in clinical radiography due to their relatively high detective quantum efficiency, depending on the detector sensitivity [15–17]. The improved detective quantum efficiency enables dose reduction while maintaining image quality [18, 19]. Recently, we developed a mini mobile digital imaging (mini-DI) system with a flat-panel detector [17]. The imaging system has a number of advantages including small size, absence of spatial distortion, enhanced stability and wider dynamic range. We hypothesized that the system could be used for chest imaging to reduce radiation dose and improve image quality.

Therefore, the aim of this study was to examine the feasibility of chest imaging using our mini-DI system and evaluate the radiation dose received by neonates during radiographic examinations.

2. Materials and methods

2.1. Mini-mobile digital imaging system

A mini-DI system (MX-DRF0815, meteor®, NanoFocusRay Co. Ltd., Jeonju, Korea) with a complementary metal-oxide-semiconductor (CMOS) flat-panel detector was used in this study. The flat-panel detector is based on a high-resolution CMOS sensor-based flat panel with a 2352 × 2944 matrix and pixel size of 49.5 μm. The X-ray source generates 40–80 kVp and 0.25 mA with a focal spot size of 0.033 mm. Also, the source was used pulsed X-ray mode to reduce patient’s radiation dose instead of continuous X-ray mode. The dimensions of the mini-DI system are 324 mm (width) × 470 mm (depth) × 690 mm (height), and the maximum field of view (FOV) is 112 mm (width) × 140 mm (height). The mini-DI system weighed 23 kg and an external interface was designed for portability. The system offers both a radiographic imaging mode and a fluoroscopic imaging mode. The fluoroscopy mode is two options as 2 × 2 binned fluoroscopy mode (at 30 frames per second, fps) and 4 × 4 binned low-dose fluoroscopy mode (at 60 fps). The control panel included basic functions such as browsing, viewing, and control of X-rays. The X-ray control function allows the voltage (kVp) and amperage (mA) values to be controlled (Fig. 1).

For comparison, we used a conventional mobile DR (conventional DR; EFX vision, Shimadzu MobileArt, Kyoto, Japan) with a thin-film transistor (TFT) flat-panel detector with a 2800 × 3408 matrix and pixel size of 125 μm. The X-ray generation conditions in the two systems are as follows: tube voltage of 75 kVp and current of 0.09 mAs in mini-DI and voltage of 60 kVp and current of 1.4 mAs in conventional DR. These parameters are optimized for clinical settings. An automatic exposure control system was used for radiation dose reduction while maintaining image quality in both systems. The protocol was used for radiographic examinations of a line phantom (X-ray test pattern type 18, FUNK, Germany) and neonates. Image post-processing techniques were applied for quality control of phantom images and patient scans using both forms of digital imaging equipment. All images processed noise reduction and contrast enhancements.

2.2. Measurements of radiation dose and image quality

The radiation dose was calculated using the method of the International Commission on Radiological Protection (ICRP) [20]. Entrance surface dose (ESD) is the absorbed dose including the contribution from backscatter [21]. The ESD measurement was performed using a dosimeter (RaySafe Xi, Unfors Raysafe, Sweden). To determine the ESD, source-to-detector distances (SDDs) were as follows: 100 cm for conventional DR and 45 cm for mini-DI. The detector angle was fixed at 90° to the direction of radiation beam. The ESD was measured ten times in radiography mode for conventional DR and in pulsed radiography mode for mini-DI.

Image quality was assessed by determining the signal-to-noise ratio (SNR) and spatial resolution [22]. The SNR is the ratio of measured signal to measured system noise and was calculated as the ratio of the value of a lead bar (0.05 mm thick) to the noise. The mean SNR values of six image sets were obtained for each system. The modulation transfer function (MTF) has been used to evaluate the spatial resolution of imaging systems [23], and in this study was measured using a line phantom (X-ray test pattern type 18) to generate MTF curves. The MTF curve was normalized for each system.

2.3. Patient study

This study was approved by the Institutional Review Board (IRB) at our university hospital. The local IRB classified this study as a prospective, non-interventional trial. The study design was explained to the parents, and patients were recruited only when their parents’ consent was granted. A total of 64 premature patients in a NICU were admitted...
to our hospital from March 2015 to February 2016. All subjects, who were examined for clinical indications, were aged 25–36 weeks (mean, 34.2 weeks). Their mean weight and height were 2.16 ± 0.55 kg and 44.1 ± 3.6 cm.

The inclusion criteria were as follows: premature newborn in NICU born at <37 weeks; and premature newborn requiring at least two follow-up chest X-ray examinations. Premature neonates who underwent chest-imaging examinations without their parents’ consent as emergency procedures were excluded from this study.

Chest radiographs were performed on a routine follow-up basis to monitor health status. The mini-DI system and the conventional mobile DR were used alternately by at least two radiographers. The time delay between image pairs was not longer than 4 days. A short interval was necessary to minimize changes in anatomical and/or pathological landmarks.

2.4. Analysis of clinical chest images

Two radiologists blindly evaluated the chest images of each patient, and reached a consensus regarding the anatomic landmarks [7]. The 11 anatomic landmarks were the aortic arch, azygoesophageal edge, carina, hilus, intervertebral space (T6/7), pulmonary vascularity, retrocardiac lung, paratracheal stripe, subdiaphragmatic lung, unobscure lung and T4&T7 spine pedicle. Each anatomic landmark on chest image data was analyzed according to the radiological diagnosis on a 5-point scale: 1, definitely seen; 2, probably seen; 3, equivocal; 4, probably not seen; and 5, definitely not seen. There were 128 observations from 64 subjects, as each subject was examined using both systems (mini-DI and conventional DR). The 11 anatomic landmarks resulted in a total of 1408 observations.

To evaluate the interobserver variation in the measurements of the anatomic areas two radiologists evaluated the images. They had no access to the readings of the other or their own previous readings. One of the radiologists was an experienced pediatric radiologist (reader A, with 10 years of experience) and the other was an experienced cardiothoracic radiologist (reader B, with 24 years of experience).

2.5. Statistical analysis

All statistical analyses were performed using the Statistical Package for the Social Sciences (SPSS version 20.0 Chicago, IL, USA) software. Coefficient of variance (CV) was calculated for the variability of SNR in each system measurements. Variations in diagnostic scores were analyzed by paired t-test between each anatomic landmark in two different imaging systems. Then, interobserver agreement and reliability were estimated by calculating the intraclass correlation coefficient (r) (and 95% confidence interval (CI)) between the scores for the same subject using the same system [24]. Two-sided p-values < 0.05 were considered to indicate statistical significance.
3. Results

3.1. Radiation dose and image quality

The average ESD, SNR, and 10% MTF values of the two imaging systems are shown in Table 1. The average ESDs for mini-DI and conventional DR were 26.64 ± 0.15 μGy and 49.11 ± 1.46 μGy (p < 0.001, Fig. 2). The mean ESD values of the two imaging systems were <50 μGy (0.05 mGy), giving the EU and ACR guidelines. Regarding image quality, the average SNR values for mini-DI and conventional DR were 233.2 ± 5.1 vs. 31.6 ± 1.2, respectively (p < 0.01). The MTF curve for each system is shown in Fig. 3; their 10% MTF values were 131 μm (3.8 lp/mm) and 161 μm (3.1 lp/mm), respectively.

3.2. Neonatal chest imaging using the mini-DI system and conventional DR

The anatomical landmark scores of the mini-DI system were similar to those of conventional DR (Table 2). Figs. 4 and 5 show neonatal chest images obtained by mini-DI and conventional DR. Fig. 6 shows the mean scores and standard deviation for the two imaging systems. The diagnostic scores of the mini-DI system were not significantly different from those of conventional DR (p > 0.05).

The score indicated as a following 5-point scale: 1, definitely seen; 2, probably seen; 3, equivocal; 4, probably not seen; and 5, definitely not seen.

### Table 2

<table>
<thead>
<tr>
<th>Anatomical areas</th>
<th>Conventional DR</th>
<th>Mini-DI</th>
<th>p-Valuea</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aortic arch</td>
<td>2.81 ± 0.89</td>
<td>2.84 ± 0.80</td>
<td>0.835</td>
</tr>
<tr>
<td>Azygoesophageal edge</td>
<td>3.16 ± 0.98</td>
<td>3.38 ± 0.49</td>
<td>0.090</td>
</tr>
<tr>
<td>Carina</td>
<td>2.25 ± 0.73</td>
<td>2.38 ± 0.72</td>
<td>0.334</td>
</tr>
<tr>
<td>Hilus</td>
<td>2.28 ± 0.45</td>
<td>2.39 ± 0.49</td>
<td>0.193</td>
</tr>
<tr>
<td>Intervertebral space (T6/7)</td>
<td>1.34 ± 0.48</td>
<td>1.23 ± 0.43</td>
<td>0.175</td>
</tr>
<tr>
<td>Pulmonary vascularity</td>
<td>1.84 ± 0.57</td>
<td>2.00 ± 0.64</td>
<td>0.148</td>
</tr>
<tr>
<td>Retrocardiac lung</td>
<td>2.25 ± 0.62</td>
<td>2.44 ± 0.79</td>
<td>0.139</td>
</tr>
<tr>
<td>Paratracheal stripe</td>
<td>2.34 ± 1.03</td>
<td>2.55 ± 1.05</td>
<td>0.271</td>
</tr>
<tr>
<td>Subdiaphragmatic lung</td>
<td>2.58 ± 0.50</td>
<td>2.70 ± 0.63</td>
<td>0.217</td>
</tr>
<tr>
<td>Unobscure lung</td>
<td>1.48 ± 0.50</td>
<td>1.64 ± 0.57</td>
<td>0.104</td>
</tr>
<tr>
<td>T4&amp;T7 spine pedicle</td>
<td>1.44 ± 0.66</td>
<td>1.44 ± 0.56</td>
<td>1.000</td>
</tr>
</tbody>
</table>

DR: digital radiography; mini-DI: mini-mobile digital imaging system.
Scores are presented as means ± SD.

The score indicated as a following 5-point scale: 1, definitely seen; 2, probably seen; 3, equivocal; 4, probably not seen; and 5, definitely not seen.

*The difference in the scores of anatomical landmarks between two systems was analyzed by paired t-test.*

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**Fig. 4.** Chest radiography of a preterm neonate using mini-mobile digital imaging (mini-DI) system showing anatomic landmarks, including the aortic arch, azygoesophageal edge, carina, hilus, intervertebral space, pulmonary vascularity, retrocardiac lung, paratracheal stripe, subdiaphragmatic lung, unobscure lung and spine pedicle (A), which are comparable to those seen by conventional mobile digital radiography (DR) imaging (B).

**Fig. 5.** Chest radiography of a preterm neonate with bronchopulmonary dysplasia using the mini-mobile digital imaging system showing ill-defined reticular markings with interspersed rounded lucent areas in both upper lungs (A), which is comparable to those seen by conventional mobile digital radiography imaging (B).
3.3. Interobserver variability

The average scores and interobserver agreement of the two readers are shown in Table 3. There was no significant difference in the mean scores of the two readers for all anatomical areas. Intraclass correlation coefficients ($r$) for interobserver agreement were $\geq 0.8$ for each anatomical area. The correlation coefficient range was $0.805$–$0.933$. Therefore, the diagnostic scores of the two readers showed good agreement ($p < 0.001$).

4. Discussion

Regarding the detector quantum efficiency, Samei et al. [25] suggested that the high detective quantum efficiency of flat-panel digital radiography systems could be used to decrease radiation exposure to neonates. In the present study, a CMOS flat-panel detector (mini-DI) and a TFT flat panel detector (conventional DR) were compared. The CMOS flat panel detector exhibits high-sensitivity quantum detection.

### Table 3

Interobserver variability.

<table>
<thead>
<tr>
<th>A. Mini-DI</th>
<th>Reader A</th>
<th>Reader B</th>
<th>$p$-Value$^a$</th>
<th>Intra-rater reliability (ICC, $r$)$^b$</th>
<th>95% CI</th>
<th>$p$-Value$^b$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Lower bound</td>
<td>Upper bound</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aorta arch</td>
<td>2.88 ± 0.87</td>
<td>2.81 ± 0.74</td>
<td>0.758</td>
<td>0.922</td>
<td>0.842</td>
<td>0.962</td>
</tr>
<tr>
<td>Azyngeophageal edge</td>
<td>3.41 ± 0.50</td>
<td>3.38 ± 0.49</td>
<td>0.802</td>
<td>0.894</td>
<td>0.783</td>
<td>0.948</td>
</tr>
<tr>
<td>Carina</td>
<td>2.34 ± 0.75</td>
<td>2.41 ± 0.71</td>
<td>0.733</td>
<td>0.903</td>
<td>0.802</td>
<td>0.953</td>
</tr>
<tr>
<td>Hilus</td>
<td>2.31 ± 0.47</td>
<td>2.47 ± 0.51</td>
<td>0.206</td>
<td>0.814</td>
<td>0.604</td>
<td>0.911</td>
</tr>
<tr>
<td>Intervertebral space (T6/7)</td>
<td>1.25 ± 0.44</td>
<td>1.22 ± 0.42</td>
<td>0.772</td>
<td>0.854</td>
<td>0.701</td>
<td>0.929</td>
</tr>
<tr>
<td>Pulmonary vascularity</td>
<td>1.91 ± 0.69</td>
<td>2.09 ± 0.59</td>
<td>0.246</td>
<td>0.827</td>
<td>0.635</td>
<td>0.917</td>
</tr>
<tr>
<td>Retrocardiac lung</td>
<td>2.34 ± 0.79</td>
<td>2.53 ± 0.80</td>
<td>0.349</td>
<td>0.893</td>
<td>0.769</td>
<td>0.949</td>
</tr>
<tr>
<td>Paratracheal stripe</td>
<td>2.56 ± 1.13</td>
<td>2.53 ± 0.98</td>
<td>0.907</td>
<td>0.933</td>
<td>0.863</td>
<td>0.967</td>
</tr>
<tr>
<td>Subdiaphragmatic lung</td>
<td>2.72 ± 0.63</td>
<td>2.69 ± 0.64</td>
<td>0.846</td>
<td>0.844</td>
<td>0.680</td>
<td>0.924</td>
</tr>
<tr>
<td>Unobscured lung</td>
<td>1.56 ± 0.56</td>
<td>1.72 ± 0.58</td>
<td>0.279</td>
<td>0.869</td>
<td>0.715</td>
<td>0.938</td>
</tr>
<tr>
<td>T4 &amp; T7 spine pedicle</td>
<td>1.44 ± 0.62</td>
<td>1.44 ± 0.50</td>
<td>1.000</td>
<td>0.826</td>
<td>0.640</td>
<td>0.915</td>
</tr>
<tr>
<td>B. Conventional DR</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aorta arch</td>
<td>2.84 ± 0.88</td>
<td>2.78 ± 0.91</td>
<td>0.781</td>
<td>0.841</td>
<td>0.674</td>
<td>0.922</td>
</tr>
<tr>
<td>Azyngeophageal edge</td>
<td>3.19 ± 0.97</td>
<td>3.13 ± 1.01</td>
<td>0.801</td>
<td>0.830</td>
<td>0.651</td>
<td>0.917</td>
</tr>
<tr>
<td>Carina</td>
<td>2.22 ± 0.75</td>
<td>2.38 ± 0.73</td>
<td>0.737</td>
<td>0.871</td>
<td>0.736</td>
<td>0.937</td>
</tr>
<tr>
<td>Hilus</td>
<td>2.28 ± 0.46</td>
<td>2.28 ± 0.46</td>
<td>1.000</td>
<td>0.919</td>
<td>0.833</td>
<td>0.969</td>
</tr>
<tr>
<td>Intervertebral space (T6/7)</td>
<td>1.38 ± 0.49</td>
<td>1.31 ± 0.47</td>
<td>0.605</td>
<td>0.928</td>
<td>0.853</td>
<td>0.965</td>
</tr>
<tr>
<td>Pulmonary vascularity</td>
<td>1.91 ± 0.64</td>
<td>1.78 ± 0.49</td>
<td>0.384</td>
<td>0.896</td>
<td>0.780</td>
<td>0.950</td>
</tr>
<tr>
<td>Retrocardiac lung</td>
<td>2.25 ± 0.62</td>
<td>2.25 ± 0.62</td>
<td>1.000</td>
<td>0.805</td>
<td>0.598</td>
<td>0.905</td>
</tr>
<tr>
<td>Paratracheal stripe</td>
<td>2.34 ± 1.07</td>
<td>2.34 ± 1.00</td>
<td>1.000</td>
<td>0.847</td>
<td>0.686</td>
<td>0.936</td>
</tr>
<tr>
<td>Subdiaphragmatic lung</td>
<td>2.59 ± 0.50</td>
<td>2.56 ± 0.50</td>
<td>0.804</td>
<td>0.814</td>
<td>0.619</td>
<td>0.910</td>
</tr>
<tr>
<td>Unobscured lung</td>
<td>1.50 ± 0.51</td>
<td>1.47 ± 0.51</td>
<td>0.806</td>
<td>0.899</td>
<td>0.794</td>
<td>0.951</td>
</tr>
<tr>
<td>T4 &amp; T7 spine pedicle</td>
<td>1.47 ± 0.67</td>
<td>1.41 ± 0.67</td>
<td>0.710</td>
<td>0.925</td>
<td>0.847</td>
<td>0.963</td>
</tr>
</tbody>
</table>

Abbreviations: ICC: intraclass correlation coefficient; CI: confidence interval; mini-DI: mini-mobile digital imaging system; DR: digital radiography.

Scores of each reader are presented as means ± SD.

$^a$ The difference in the scores of readers in the anatomical landmarks was analyzed by paired $t$-test.

$^b$ The intra-rater reliability between two readers was analyzed by intraclass correlation test.

Fig. 6. Mean anatomic landmark visibility scores of the two imaging systems. Note that the scores of the mini-DI system were not significantly different from those of conventional DR ($p > 0.05$). Five-point scale: 1, definitely seen; 2, probably seen; 3, equivocal; 4, probably not seen; and 5, definitely not seen.
compared to the TFT flat panel detector [17,26]. The observed results indicated no statistically significant difference in diagnostic quality between two different imaging systems. Also, CMOS detectors have lower power consumption and high image resolution, which facilitates high detectability in medical imaging [27]. Compared with conventional systems, the mini-DI system facilitates high-sensitivity quantum detection in a pulsed X-ray mode with a low X-ray current for patients. Therefore, the CMOS flat panel detector has several advantages for clinical imaging. One advantage is the reduction in contrast loss by internal scattering between the fluoroscopy mode and 60 fps in 4 × 4 binned low-dose fluoroscopy mode.

With regard to diagnostic performance, optimization of the neonatal chest imaging protocol for medical imaging systems according to image quality and radiation dose is essential [22]. In this study, the mini-DI protocol was optimized based on phantom images using conventional DR. As shown in Table 1, the mean SNR for mini-DI was higher than that for conventional DR. Also, the spatial resolution with 10% MTF was better. The optimized imaging protocol of the mini-DI system exhibited better image quality compared with those obtained using the conventional DR protocol. Therefore, the image quality obtained using the optimized mini-DI protocol was clinically acceptable.

In the present study, we evaluated anatomical landmarks for clinical indications within 4 days and minimize the changes in the landmarks on the images. To perform chest radiographic examinations in premature neonates, the patients are accompanied with the image assessment after tubes and catheter placements. There was no significant difference in the scores using the two imaging systems for detection of anatomical landmarks, tubes and catheters. However, although the individual scores did not differ significantly, the overall image quality was likely reduced. There is a discrepancy between the phantom studies, which found both lower radiation dose and higher image quality, versus the clinical studies, which did not show a statistically significant improvement in image quality. We thought that the reason of the discrepancy is caused by difference between the phantom study and scoring system, which could be subjective and insensitive.

The interobserver variability in the diagnostic scores was higher than 0.8, confirming the results for all measurements using both systems. The results for each anatomical area verify this. The detailed analysis indicates that both systems are reliable and/or reproducible. According to the radiation safety guidelines of the EU and ACR [8–10], the entrance surface dose for neonates and infants should be 0.05 to 0.3 mGy per exposure. Comparable images obtained using the two systems were used in alternating order to minimize radiation exposure of neonates in the NICU. Radiation dose reduction in neonates is an important issue for reducing the long-term risk of cancer. At present, cancer induction is a stochastic risk with a linear-no-threshold dose model; therefore, reduced exposure to radiation decreases the risk of development of cancer, such as leukemia, in a young child [28]. To resolve this, ESD must be reduced while maintaining image quality. This emphasizes the importance of the as low as reasonably achievable (ALARA) concept. The risks in children are higher due to increased radiosensitivity and longer life expectancy [29]. Also, the calculated relative cancer induction risk represents the risk up to the age of 15 years, but the life-time risk can be two to four-fold higher [30]. Several studies have argued that such risks cannot be ignored and must be reduced [28,30]. Other actions at the national and international levels should be taken to prevent an increased risk of long-term effects on neonates who undergo multiple diagnostic examinations. All examination techniques in pediatric radiology should be optimized. Establishing local diagnostic reference levels in each department or possibly each X-ray room would enable patient dose to be optimized, and national reference dose levels for newborns should be established [31].

5. Conclusion

A newly developed mini-DI enables maintaining the diagnostic information with dose reduction in neonates under intensive care.

Financial disclosure

No conflict of interests.

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