Application of a colored multiexposure high dynamic range technique to radiographic imaging: an experimental trial to show feasibility

Eppenberger, Patrick ; Marcon, Magda ; Ho, Michael ; Del Grande, Filippo ; Frauenfelder, Thomas ; Andreisek, Gustav

Abstract: PURPOSE: The aim of this study was to evaluate the feasibility of applying the high dynamic range (HDR) technique to radiographic imaging to expand the dynamic range of conventional radiographic images using a colored multiexposure approach. MATERIAL AND METHODS: An appropriate study object was repeatedly imaged using a range of different imaging parameters using a standard clinical x-ray unit. An underexposed image (acquired at 80 keV), an intermediate exposed image (110 keV), and an overexposed image (140 keV) were chosen and combined to a 32-bit colored HDR image. To display the resulting HDR image on a regular color display with typically 8 bits per channel, the Reinhard tone mapping algorithm was applied. The source images and the resulting HDR image were qualitatively evaluated by 5 independent radiologists with regard to the visibility of the different anatomic structures using a Likert scale (1, not visible, to 5, excellent visibility). Data were presented descriptively. RESULTS: High dynamic range postprocessing was possible without malalignment or image distortion. Application of the Reinhardt algorithm did not cause visible artifacts. Overall, postprocessing time was 7 minutes 10 seconds for the whole process. Visibility of anatomic structure was rated between 1 and 5, depending on the anatomic structure of interest. Most authors rated the HDR image best before individual source images. CONCLUSIONS: This experimental trial showed the feasibility of applying the HDR technique to radiographic imaging to expand the dynamic range of conventional radiographic images using a colored multiexposure approach.

DOI: https://doi.org/10.1097/RCT.0000000000000413

Originally published at:
Eppenberger, Patrick; Marcon, Magda; Ho, Michael; Del Grande, Filippo; Frauenfelder, Thomas; Andreisek, Gustav (2016). Application of a colored multiexposure high dynamic range technique to radiographic imaging: an experimental trial to show feasibility. Journal of Computer Assisted Tomography, 40(4):658-662.
DOI: https://doi.org/10.1097/RCT.0000000000000413

Application of a Colored Multiexposure High Dynamic Range Technique to Radiographic Imaging: An Experimental Trial to Show Feasibility

Patrick Eppenberger, MD,† Magda Marcon, MD,† Michael Ho, MD,† Filippo Del Grande, MD,‡ Thomas Frauenfelder, MD, MAS,† and Gustav Andreisek, MD, MBA†*

Purpose: The aim of this study was to evaluate the feasibility of applying the high dynamic range (HDR) technique to radiographic imaging to expand the dynamic range of conventional radiographic images using a colored multiexposure approach.

Material and Methods: An appropriate study object was repeatedly imaged using a range of different imaging parameters using a standard clinical x-ray unit. An underexposed image (acquired at 80 keV), an intermediate exposed image (110 keV), and an overexposed image (140 keV) were chosen and combined to a 32-bit colored HDR image. To display the resulting HDR image on a regular color display with typically 8 bits per channel, the Reinhard tone mapping algorithm was applied. The source images and the resulting HDR image were qualitatively evaluated by 5 independent radiologists with regard to the visibility of the different anatomic structures using a Likert scale (1, not visible, to 5, excellent visibility). Data were presented descriptively.

Results: High dynamic range postprocessing was possible without malalignment or image distortion. Application of the Reinhardt algorithm did not cause visible artifacts. Overall, postprocessing time was 7 minutes 10 seconds for the whole process. Visibility of anatomic structure was rated between 1 and 5, depending on the anatomic structure of interest. Most authors rated the HDR image best before individual source images.

Conclusions: This experimental trial showed the feasibility of applying the HDR technique to radiographic imaging to expand the dynamic range of conventional radiographic images using a colored multiexposure approach.

Key Words: high dynamic range, radiography, exposure

(*J Comput Assist Tomogr* 2016;00: 00–00)

Advances in Knowledge

- High dynamic range (HDR) radiographic imaging is feasible.
- Image post-processing was stable without artifacts.
- For most readers, the colored multi-exposure HDR image showed the anatomy best.

Implication for Patient Care

- The colored multi-exposure HDR technique could potentially be applied to standard radiographic and computed tomography imaging in humans.

From the *Polyclinic Crossline, Medical Services of the City of Zurich; and †Institute for Diagnostic and Interventional Radiology, University Hospital Zurich, University of Zurich, Switzerland; and ‡Department of Radiology, Ospedale Regionale di Lugano, Lugano, Switzerland.
Received for publication November 6, 2015; accepted January 31, 2016.
Correspondence to: Patrick Eppenberger, MD, Institute for Diagnostic and Interventional Radiology, University Hospital Zurich, University of Zurich, Ramistrasse 100, 8091 Zurich, Switzerland (e-mail: patrick.eppenberger@gmx.ch).
The authors declare no conflict of interest.

DOI: 10.1097/RCT.0000000000000413

Summary Statement (Discussion section)

- This experimental trial showed the feasibility of the application of HDR imaging for radiographs

From digital photography, the concept to achieve images with a higher dynamic range by combination of images from multiple exposures, referred to as HDR (high dynamic range) photography, is well known.[1–4] Its advantages over standard photographs are good illumination and control of lighting even with difficult lighting situations, which results in more detail and vibrant colors throughout the whole image. This concept of HDR could also potentially be used to enhance the dynamic range of radiographic images.

In conventional radiography, contrast is generated by x-ray attenuation mainly as a result of the photoelectric and Compton effects depending on the atomic number and the physical density of the irradiated tissue as well as the energy of the radiation used. The photoelectric effect is typically observed below 100 keV, and radiation absorption is primarily associated with the atomic number of the tissue's material. The Compton effect is typically observed above 100 keV, and radiation absorption is primarily associated with tissue density. The hypothesis is that the dynamic range of radiographic images can be enhanced if the images contain attenuation information not only from a single keV but also from a broader range of absorption spectra below and above 100 keV. The human eye is, however, limited in the perception of high range grayscale images. Human observers are able to discriminate between 700 and 900 simultaneous shades of gray for the available luminance range of current medical displays under optimal conditions. Current monochromatic medical displays are typically capable of displaying between 256 and 1024 gray shades (equivalent to a "bit depth" of 8 to 10 bits).[5]

For colored images, the range is much broader and includes electromagnetic radiation from approximately 380 to 750 nm. The human visual system is therefore capable to differentiate up to 10 million different colors.[6] The absorption maxima of the photoreceptor proteins in the human cone cells lie at approximately 426, 530, and 560 nm, which correspond to the blue, green, and red regions of the visible light spectrum. These colors are referred to as the primary colors. In the RGB model currently used by the display manufacturing industry for the last decades, every color pixel in a digital image is created through a combination of these 3 primary colors. Each of these primary colors is often referred to as a "color channel." Current color displays are typically capable of displaying a range of 256 intensity values per channel, resulting in a total of 16.7 million different colors (equivalent to a "bit depth" of 24 bits also referred to as a 24-bit true-color display).[4,7–10] Thus, because of the additional contained information on tissue composition, it seems a reasonable hypothesis that radiologists would prefer colored multiexposure HDR images over conventional radiographic images.

The aim of this experimental trial was to evaluate the feasibility of applying the HDR technique to radiographic imaging

TABLE 1. Acquisition of Source Images for Colored Multiexposure HDR Technique

	mAs		
80 keV	1.68 (underexposed) (Fig. 1A)	3.27 (Fig. 1B)	5.07 (used for HDR) (Fig. 1C)
110 keV	1.71 (Fig. 1D)	3.32 (used for HDR) (Fig. 1E)	5.11 (Fig. 1F)
140 keV	1.76 (used for HDR) (Fig. 1G)	3.37 (Fig. 1H)	5.17 (overexposed) (Fig. 1I)

to expand the dynamic range of conventional radiographic images using a colored multiexposure approach.

MATERIALS AND METHODS

Study Object

No institutional review board approval was necessary for this prospective experimental trial. As study object, a fresh fish (red snapper, *lutjanus malabaricus*) was chosen. The fish provided tissues with a range of densities that typically can be encountered in diagnostic radiographic imaging, including air-filled spaces up to calcifications.[11] No animal was harmed for this study. The fish was bought by one of the authors (P.E.) in a regular grocery store (Globus, Zurich, Switzerland).

There was no financial support from the industry for this study. A patent application was filed to the European Patent Office (Munich, Germany).

Image Acquisition and Selection

The study object was repeatedly exposed using a range of different imaging parameters (Table 1, Figs. 1A-I) using a standard clinical x-ray unit (Polydoros LX-80; Siemens Healthcare, Erlangen, Germany). Images were automatically stored in the hospitals picture archiving and communication system (PACS; Impax 6.0; Agfa-Gevaert N.V., Mortsel, Belgium) using a 12-bit grayscale Digital Imaging and Communications in Medicine (DICOM) format. From these series of images, 3 images were chosen to generate a single HDR image. Two authors (P.E., a radiology resident who was originally trained as an industrial graphic designer; G.A., fellowship-trained, board-certified radiologist with 11 years of experience) selected the images in consensus and based on that the resulting HDR image should contain absorption information from the photoelectric and Compton effect dominating the radiation absorption below and above 100 keV, respectively. Finally, an underexposed image acquired at 80 keV and 5.07 mAs, an intermediate exposed image acquired at 110 keV and 3.32 mAs, and an overexposed image acquired at 140 keV and 1.75 mAs were chosen (Table 1).

Image Postprocessing

Image postprocessing was performed by one author (P.E.) using commercially available software (Adobe Photoshop CS5; Adobe Systems Inc, San José, Calif) running on a standard computer (Mac Pro Quad-Core 2.8; Apple Inc, Cupertino, Calif). The 3 original images, acquired at 80, 110, and 140 keV, were imported into the software and attributed to the 3 standard color channels, red, green, and blue, respectively. A color depth of 16 bits per channel was used, and postprocessed images were stored as individual colored 16–bit per channel Tagged-Image File Format files. The 3 Tagged-Image File Format images were then combined to a single HDR image using the software's dedicated algorithm. The final image had a color depth of 32 bits per channel and was stored as an individual HDR image file, like it is supported by most HDR image editors including Adobe Photoshop CS5 (4 bytes per pixel, 1-byte mantissa for each RGB channel, and a shared 1-byte exponent). The latter format allows preservation of all contained image information per pixel (full dynamic range).

To display the HDR image on a regular 24-bit true-color display with typically 8 bits per channel, a tone-mapping algorithm had to be applied. The Reinhardt algorithm was chosen because it is known from the literature that this algorithm is usually well suited for nonpictorial colored images and that it generates only

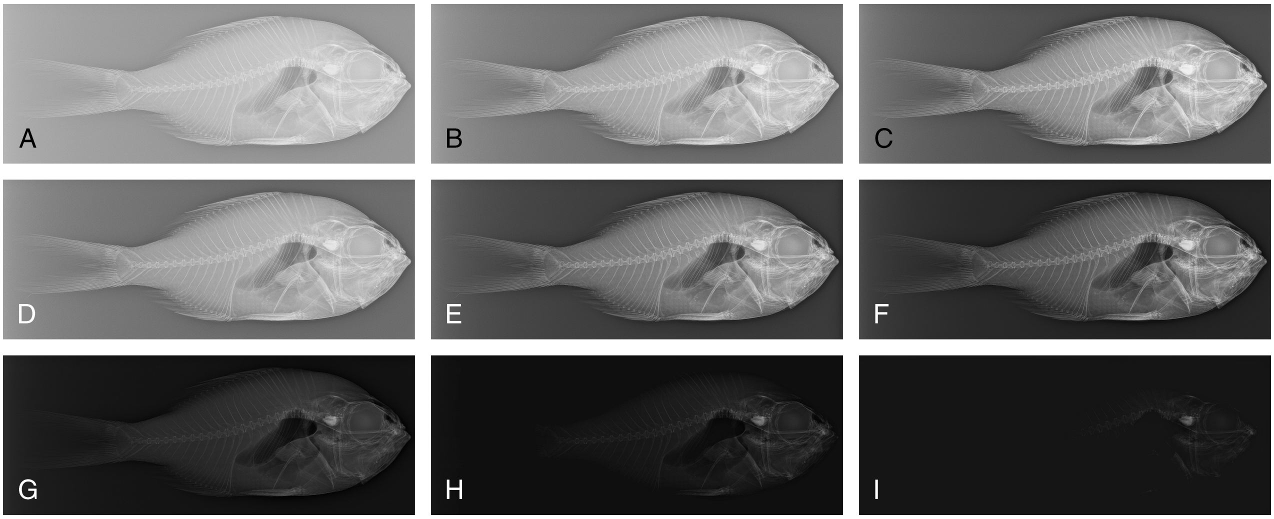

FIGURE 1. Series of source images for colored multiexposure HDR technique using a range of different imaging parameters: (A) 80 keV/1.69 mAs, (B) 80 keV/3.27 mAs, (C) 80 keV/5.07 mAs, (D) 110 keV/1.71 mAs, (E) 110 keV/3.32 mAs, (F) 110 keV/5.11 mAs, (G) 140 keV/1.76 mAs, (H) 140 keV/3.37 mAs, and (I) 140 keV/5.17 mAs. (Please also refer to Table 1.)

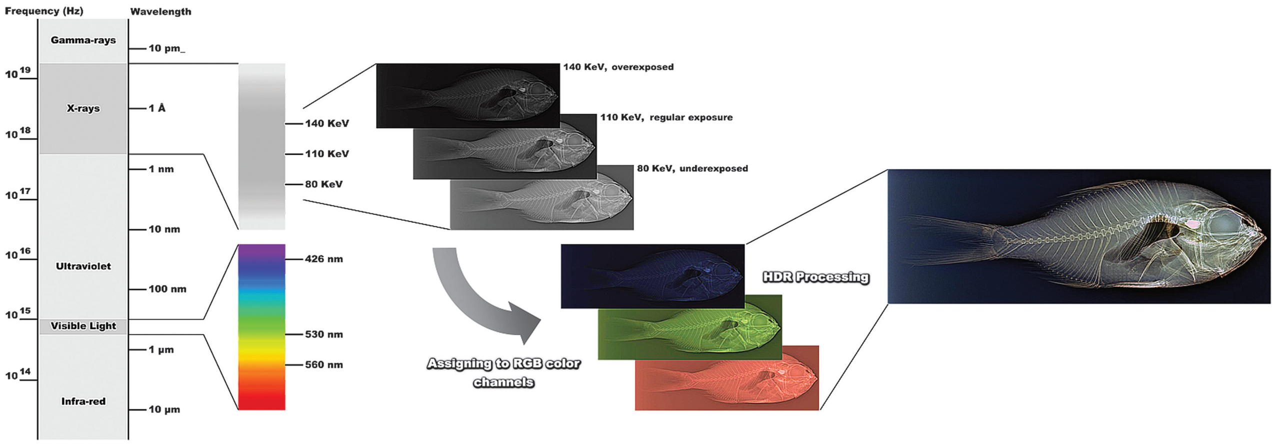

FIGURE 2. Process overview: 3 images acquired at 80, 110, and 140 keV, respectively, were mapped the RGB color channels and combined to a colored HDR image with a much broader dynamic range, which additionally reveals information about tissue properties. Thus, this process allows a differentiated representation of the photoelectric effect (atomic number) and the Compton effect (tissue density) on a single colored image, in analogy to the visible light spectrum.

little artifacts. The function below represents the local dodging-and-burning operator as proposed by Reinhard et al.[2,4,10,12]

$$Ld(x,y) = \frac{L(x,y)}{1 + V1(x,y,sm(x,y))}$$

The luminance of a dark pixel in a relatively bright region will satisfy $L < V1$, so the operator will decrease the display luminance Ld, thereby increasing the contrast at that pixel in analogy to photographic "dodging." Similarly, a pixel in a relatively dark region will be compressed less and is thus "burned." In either case, the pixel's contrast relative to the surrounding area is increased[10] (Fig. 2).

Overall, the postprocessing resulted in an 8-bit color image file that was stored using the DICOM format from within the dedicated image processing software (Adobe Photoshop CS5) (Fig. 3).

Image Evaluation

Images were qualitatively evaluated by 2 authors (P.E. and G.A.) in consensus after each postprocessing step and all artifacts, postprocessing problems, and the file size were noted. The time for postprocessing was noted. The final 8-bit color image was then evaluated along with the source images by 5 radiologists with different levels of experience (1 third-year resident [M.H.], 1 board-certified radiologist subspecialized in breast imaging [M.M.], 1 board-certified radiologist subspecialized in thoracic imaging [T.F.], 1 board-certified radiologist subspecialized in musculoskeletal imaging [G.A.], and 1 general radiologist who is chairman of a large radiology department [F.G.]) with regard to the visibility of the different anatomic structures of the fish using a 5-point grading system (Likert scale) (Fig. 4): 1, not visible (no diagnostic information can be obtained from the images); 2, poor visibility (image quality is heavily degraded due to low contrast and/or artifacts); 3, moderate visibility (image quality is degraded due to low contrast and/or artifacts); 4, good visibility (good contrast and/or slight artifacts); 5, excellent visibility (good contrast and no artifacts). In addition, all radiologists were asked to provide a statement based on their personal experience on the possible strength of the HDR image. Image analysis was performed independently, and readers were blinded to the acquisition parameters of the source images.

Descriptive data are presented; no formal statistical analysis was performed because this is only an experimental trial in a single study subject to proof the concept of HDR imaging for radiographs.

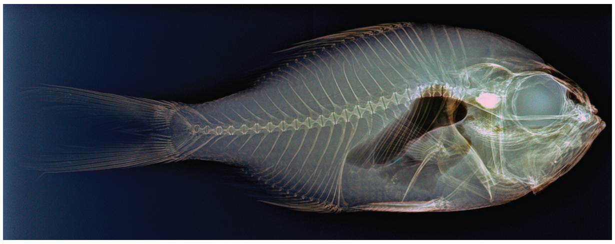

FIGURE 3. Colored multiexposure HDR image of a red snapper. The image was generated from source 140-, 110-, and 80-keV radiographic images using dedicated HDR postprocessing.

RESULTS

The series of images with various imaging parameters could be acquired successfully. After selection of 3 images, HDR postprocessing was possible as described previously without malalignment or image distortion. Application of the Reinhardt algorithm for reducing the images' color depth did not cause image distortion or other visible artifacts. File size (9.55 MB) was small enough to allow smooth postprocessing and data transfer as well as storage to the PACS.

Overall postprocessing time was 7 minutes 10 seconds for the whole process. The first step (loading images, applying color channels, and storing them) took 4 minutes 34 seconds, the second step (calculation of the HDR images) took 1 minute 24 seconds, and the final step (applying the Reinhardt algorithm and storing the final HDR image) took 1 minute 12 seconds.

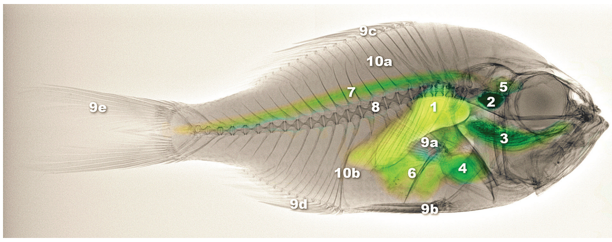

FIGURE 4. Fish anatomy: 1, swim bladder; 2, otolith organs; 3, gills (with cartilaginous lamellae); 4, heart (1 ventricle, 1 atrium); 5, brain; 6, abdominal cavity (liver and viscera); 7, lateral-line organs; 8, osseous structures (including the scull and spine with upper and lower spinous processes); 9, fins (a, pectoral; b, pelvic; c, dorsal; d, anal; e, caudal); 10, musculature (a, epaxial; b, hypaxial).

TABLE 2. Image Evaluation Using a 5-Point Likert Scale (1, Not Visible, to 5, Excellent Visibility)

	HDR					80 keV					110 keV					140 keV				
	R1	R2	R3	R4	R5	R1	R2	R3	R4	R5	R1	R2	R3	R4	R5	R1	R4	R3	R4	R5
Swim bladder	5	5	5	5	5	4	4	5	4	3	4	5	5	4	4	2	4	4	2	2
Otolith organ	4	4	3	4	5	4	4	4	4	4	4	5	4	4	4	3	3	5	4	3
Gils (with cartilaginous lamellae	5	5	5	5	5	2	4	4	1	2	3	5	4	3	3	4	1	5	4	4
Heart (1 ventricle, 1 atrium)	1	2	1	1	1	1	2	1	1	1	1	2	1	1	1	1	1	1	1	1
Brain	1	2	3	1	1	1	1	4	1	1	1	1	4	1	1	1	3	3	1	1
Abdominal cavity (liver and viscera)	5	5	5	5	5	3	4	4	4	3	4	4	4	4	4	3	2	4	2	2
Lateral-line organ	5	5	5	5	5	2	3	5	3	2	3	3	4	2	3	4	3	3	3	4
Osseous structures (including scull and spine)	5	5	5	4	5	3	4	5	3	3	4	4	s	4	4	4	3	4	4	4
Fins (pectoral, pelvic, dorsal, anal, caudal)	5	5	5	5	5	4	5	4	4	4	4	4	5	4	4	3	1	4	3	3
Musculature (epaxial, hypaxial)	3	4	5	3	3	2	3	4	2	2	3	3	3	3	3	2	4	3	1	1

R1 indicates third-year resident; R2, radiologist subspecialized in breast imaging; R3, radiologist subspecialized in thoracic imaging; R4, radiologist subspecialized in musculoskeletal imaging; R5, chairman.

Depending on the source images, some structures were already well appreciated on the 3 differently exposed source image (Table 2). Overall, visibility of anatomic structures was rated best by all authors on the colored HDR image, which contained image information from all 3 source images. However, some structures such as the heart and the brain were not visible or not well visible on neither the HDR nor the source images, which was likely because of the specific anatomy of a fish's heart and brain that both seem to be inherently difficult to delineate. One author stated that he could delineate the brain, but this was likely based on different appreciation of the underlying fish anatomy. In general, all radiologists stated that the delineation of soft tissue structures likely could benefit from the HDR technique, whereas dense structures already can be delineated well on a single (appropriately exposed) source image.

DISCUSSION

This experimental trial showed the feasibility of the application of HDR imaging for radiographs. The HDR technique has been originally developed for digital photography, and its main advantage is to increase the dynamic range of an image beyond what is normally possible.

High dynamic range images are characterized by dense image information, and thus different image specifications are usually used compared with regular images. Because HDR images require a far larger range of values, they are commonly encoded in a floating-point number file format, instead of integer values, to represent the single color channels (eg, 0-255 in an 8–bit per pixel range for red, green, and blue). Floating-point numbers (also referred to as exponential notation) are encoded as a decimal number between 1 and 10 multiplied by any power of 10, such as 6.578×10^4, as opposed to integers (eg, 0-255 for an 8-bit range or 0-4096 for a 12-bit range). This allows the image to contain information that would otherwise even exceed a 32-bit integer range.

We considered it important that the final images could be stored in the widespread DICOM format. Conventional radiographic images are usually stored in a resolution of 2048 × 2048 pixels (4 megapixels) with 12-bit grayscale, corresponding to a dynamic range of 1 to 4096, independent of the energy at which they were acquired. The DICOM standard is based on Bartens model of the contrast sensitivity function so that changes in digital values of the display represent equal perceptual steps in lightness based on threshold differences. The grayscale standard display function is defined for the luminance range from 0.05 to 4000 cd/m^2. The minimum luminance corresponds to the lowest practically useful luminance of cathode-ray-tube monitors, and the maximum exceeds the unattenuated luminance of very bright light-boxes used for interpreting x-ray mammography. For the available luminance range of current medical displays and in optimal conditions, human observers are able to discriminate between 700 and 900 simultaneous shades of gray. Thus, the human eye is limited in the perception of high range grayscale images.

This limitation and the fact that the human visual system is otherwise capable to differentiate up to 10 million different colors were the reasons we believe that a previous report by Kanelovitch et al,[13] who proposed a method to produce grayscale HDR mammograms, falls too short and we were seeking for colored HDR images.[6] The range of electromagnetic radiation that can be detected by the human eye lies in the range of approximately 380 to 750 nm and corresponds to a perceived color range of violet through red. In human cone cells, there are 3 distinct photoreceptor proteins with absorption maxima at 426, 530, and ~560 nm. Their absorbance corresponds to (in fact, define) the blue, green, and red regions of the visible light spectrum. On the basis of the trichromatic nature of the human eye, the standard solution adopted by industry is to use red, green, and blue as primary colors, using an additive color model. Thus, every color pixel in a digital image is created through a combination of the 3 primary colors: red, green, and blue. Each primary color is often referred to as a "color channel" and can have any range of intensity values specified by its bit depth. Overall, colored images can thus contain a much larger volume of information compared with grayscale images. The additionally applied tone-mapping algorithm in our approach allowed us to represent all the contained information on a regular color display with a dynamic range of 8 bits per channel without the need for windowing as it is otherwise often necessary to evaluate radiographic images. Soft tissues in accordance to the predominance of contained elements with a low atomic number are thereby represented in the blue and green color spectrum, whereas mineralized structures such as bones or scales in case of our study object (red snapper, *lutjanus malabaricus*) are represented in the yellow-to-red color spectrum.

Some limitations apply to this colored radiographic multi-exposure HDR technique. First, summation effects remain unchanged and have to be taken in consideration in a similar manner as in conventional grayscale radiographic images. In theory, the HDR technique could also be applied to cross-sectional imaging techniques such as computed tomography (CT) at different keV levels. Currently, however, we are not aware of a study that has been using HDR imaging in CT for medical applications, but own investigations are planned. A few publications geared toward industrial CT applications suggest the use of HDR algorithms to expand the dynamic range, especially when technical objects consisting of dense materials (eg, metals) are scanned.[14] Our study object had a fairly thin diameter of approximately 4.5 cm, which provided optimal conditions for our multiexposure approach. With larger object diameters, however, it need to be expected that photoelectric radiation absorption will significantly increase, that is, for the acquisition or source images with the lowest current (80 keV). This needs to be taken into account, especially when our approach shall be applied to CT imaging, for example, in humans. Second, another limitation is that many monitors have a limited dynamic range, which is inadequate to reproduce the full range of HDR images. Tone mapping addresses the problem of strong contrast reduction to the displayable range while preserving the image details and color appearance important to appreciate the original content. Because the human visual system is more sensitive to relative rather than absolute luminance values (without such an adjustment, small signals would drown in neuronal noise, and large signals would saturate the system), the algorithm proposed by Reinhard et al[10] was applied in our study, which mimics the physiology of the human visual system and is recommended in previous literature.[12] Finally, to be able to use HDR imaging in clinical routine, a full PACS integration of the postprocessing is necessary, if it is not already achieved in-line during image acquisition by, for example, batch processing through a software program. This could be achieved by the different PACS vendors by plug-ins or integrated functionality of the scanner and this is important to reduce postprocessing time for cost-efficient application of the HDR technique to CT examinations.

Potential clinical applications may include detection of breast cancer where slight differences in soft tissue density are present that could potentially be better visible with HDR mammographic images.[13] Another potential application could be detection of abnormal soft tissue density, which is typically seen before soft tissue calcification in crystal deposition diseases such as gout or chondrocalcinosis. In lung imaging, HDR images might improve detection of areas of abnormal lung density as typically seen in lung cancer. Other future perspectives of the HDR technique beyond conventional radiography include the potential applications in dual-energy CT where the anatomy is typically imaged at 2 different voltages,[15] as well as dual-energy x-ray absorptiometry.

In conclusion, this experimental trial showed the feasibility of applying the HDR technique to radiographic imaging to expand the dynamic range of conventional radiographic images using a colored multiexposure approach.

REFERENCES

1. Mann S, Picard RW. Being "undigital" with digital cameras: Extending dynamic range by combining differently exposed pictures. *In Proceedings of the Is&T 46th Annual Conference*; May 1995; Scottsdale, AZ. pp. 422–428.
2. Pardo A, Sapiro G. Visualization of high dynamic range images. *IEEE Trans Image Process*. 2003;12:639–647.
3. Petschnigg G, Agrawala M, Hoppe H, et al. Digital photography with flash and no-flash image pairs. *ACM Transactions on Graphics*. 2004;23: 664–672.
4. Reinhard E, Stark M, Shirley P, et al. Photographic tone reproduction for digital images. *Acm Transactions on Graphics*. 2002;21:267–276.
5. Kimpe T, Tuytschaever T. Increasing the number of gray shades in medical display systems—how much is enough? *J Digit Imaging*. 2007;20: 422–432.
6. Judd DB, Wyszecki G. *Color in Business, Science, and Industry*. 3rd ed. New York, NY: Wiley; 1975.
7. Barten PGJ. Physical model for the contrast sensitivity of the human eye. *Hum Vision Vis Process Digit Display*. 1992;1666:57–72.
8. Indrajit I, Verma B. Monitor displays in radiology: part 1. *Indian J Radiol Imaging*. 2009;19:24–28.
9. Indrajit IK, Verma BS. Monitor displays in radiology: part 2. *Indian J Radiol Imaging*. 2009;19:94–98.
10. Reinhard E, Devlin K. Dynamic range reduction inspired by photoreceptor physiology. *IEEE Trans Vis Comput Graph*. 2005;11:13–24.
11. Johnston J, Fauber T. *Essentials of Radiographic Physics and Imaging*. St. Louis: Elsevier; 2013:80–92.
12. Park SH, Montag ED. Evaluating tone mapping algorithms for rendering non-pictorial (scientific) high-dynamic-range images. *J Vis Commun Image Represent*. 2007;18:415–428.
13. Kanelovitch L, Itzchak Y, Rundstein A, et al. Biologically derived companding algorithm for high dynamic range mammography images. *IEEE Trans Biomed Eng*. 2013;60:2253–2261.
14. Chen P, Han Y, Pan J. High-dynamic-range CT reconstruction based on varying tube-voltage imaging. *PLoS One*. 2015;10:e0141789.
15. Karcaaltincaba M, Aktas A. Dual-energy CT revisited with multidetector CT: review of principles and clinical applications. *Diagn Interv Radiol*. 2011;17:181–194.