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3D Stereoscopic Radiography: New Possibilities in the Digital Imaging Era Using Low Cost, Existing Technology

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Abstract

We present several stereoscopic 3D radiographs, obtained in a clinical setting using a technique requiring minimal operator training and no new technology. Reviewing known perceptual advantages in stereoscopic imaging, we argue the benefits for diagnosis and treatment planning primarily in orthopedics, with opportunities likely extended to rheumatology, oncology, and angiology (vascular medicine/surgery). These advantages accrue with the marginal additional cost of capturing just two or three supplementary radiographs using the proposed method.

Presently, computed tomography (CT) scanning is standard for obtaining 3D imagery. We discuss relative advantages of stereoscopic 3D radiography (3DSR) in imaging resolution, cost, availability, and radiation dose. Further discussion will describe obstacles and challenges likely to be encountered in clinical implementation of 3DSR, to be mitigated through targeted training of clinicians and technicians.

Further research is needed to explore and empirically validate the potential value of 3DSR. We hope to pave the way for this more accessible and cost-effective 3D imaging solution, enhancing diagnostic capabilities and treatment planning, especially in resource-constrained settings.

(All 3D radiographs presented in this paper are in the red/cyan color anaglyph format. 3D anaglyph glasses are commonly available online, or in most comics bookstores. This report's images can also be found in L-R stereo-pair format, suitable for 3D viewing with a 3D screen or stereoscope, at this URL: https://www.starosta.com/3DSR/)

Key Words

Stereoscopic, 3D, 3DSR, imaging, radiography, DR, CT, CBCT, radiation, resolution, anaglyph, LMIC, battlefield, triage, ALARA

Background

The purpose of this paper is to revive interest among medical practitioners into an ancient technique: 3D stereoscopic radiography (3DSR). Despite a complete absence in the 21st century of technology or infrastructure specifically tailored to 3DSR, this author was recently successful in the clinical setting, obtaining useful 3D radiographs that can be displayed on common 3D monitors or via other low-tech or no-tech viewing methods.

The prior art in 3DSR goes back over 100 years, practically to the birth of radiology itself, with the Germans making use of it during World War I and in the inter-war years. But work to develop the method was essentially abandoned during the remainder of the 20th century [1], [2], [3], [4], [5], [6]. As we'll see, until recently stereoscopic radiography was fundamentally impractical, due to the difficulties inherent in the necessary wet-process film imaging that preceded the introduction of digital imaging.

The advantages of 3D imaging to diagnosis and treatment planning are well understood, enabling volumetric visualization and disambiguation of apparently overlapping structures and details typically seen in a simple direct radiograph (DR). There are advantages also in the detection of fine details or hairline fractures, especially in the semi-transparent, structurally cluttered image of e.g. a complex joint [7], [8], [9]. The pursuit of these advantages has led to the development and adoption of Computed Tomography (CT) and Magnetic Resonance Imaging (MRI), among other 3D imaging technologies. Compared to DR, the drawbacks of these newer technologies (especially CT) are not inconsiderable: high doses of ionizing radiation to the patient, lower spatial resolution over a given field of view (correlated with radiation dose), a greater time delay to obtain 3D imaging results, and high capital investment cost in equipment plus high maintenance, staff, and training costs, resulting not least in unavailability in resource constrained settings [10], [11], [12]. 3DSR does not suffer from these disadvantages, yet 3DSR can obtain many of the same 3D imaging advantages of CT. Because it is simply a DR variant, requiring little if any additional technology, if you have DR capability, then you have 3DSR capability.

Given that the advantages of 3D imaging and the technique of 3DSR had been demonstrated as far back as the 1920's, why has 3DSR not become a popular, accessible tool? A description of the method by which 3DSR images are obtained illuminates the difficulties that prevented wider adoption of this technique during the era of wet film processing.

Introduction

Creating a stereoscopic radiograph requires the making of two separate images, with each having the x-rays passing through the patient at a slightly different angle, as if from two different points of view, similar to human binocular vision. Imagine substituting the two eyes of the physician, who is looking at the patient, with two X-ray sources. The optical geometry is the same, whether visible light is flowing from a panel behind, through a translucent patient and into the doctor's eyes, or X-rays are flowing from the doctor's eyes into and through the patient to the detector behind. Thus it follows that a 3D stereograph can be made with X-rays conforming to this optical geometry (Figure 1).

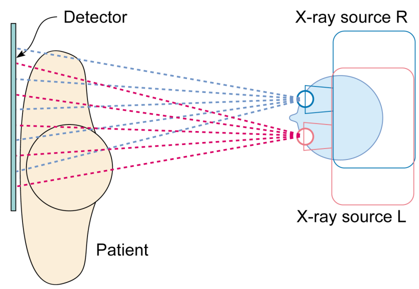

***Figure 1.** Optically equivalent: visible light rays flowing from a light source through a (translucent) patient into the clinician's eyes take the same path as X-rays flowing from an emitter through the patient into the detector .*

Ideally, the stereograph of a live, dynamic subject requires that the two exposures are made synchronously. But with radiographs being shadowgraphs directly onto a single film or detector, a simultaneous exposure of two viewpoints, irradiated from two separate but synchronized X-ray emitters, is not possible using current technology. Thus, the exposures must be made sequentially, translating the X-ray source, while holding the patient as still as possible in the moment of time between the first and second exposures. The shorter that moment of time can be kept, the more likely a useful 3D radiograph will be obtained.

Using the old film technology, such a sequence of exposures would involve a relatively long duration between the exposures. It was very difficult to avoid disturbing the position of the patient, yet such a disturbance would degrade the accuracy of the 3D image, or even disorder the dimensionality, thus destroying its utility completely. In the time between the two exposures, film would need to be swapped out of a plate holder, or even worse, out of the mouth of the patient (in e.g. an oral or dental radiograph), before the second film could be introduced. Then there would be a significant delay in the processing of the films. Most significantly, after processing, stereoscopic display would first require precision alignment and cropping of the two film radiographs, work which in and of itself is a demanding technical specialty. Finally, a suitable stereoscope is needed for viewing the pair of films in 3D. These challenges presented a significant barrier to the adoption of 3D stereoscopic radiography in the era of wet-process films, until now.

Method

In 2021 this author began experimental work with medical 3DSR, working together with his dentist and a willing dental patient to obtain 3D stereographs of a supernumerary tooth that had been discovered in a routine panoramic maxillofacial X-ray. Then, in March 2024, this author was seriously injured in a cycling accident, sustaining numerous skeletal fractures to the ribs, bones in the shoulder and in a hand, as well as a punctured lung. Soon after admittance to the hospital, he recognized the opportunity this presented to obtaining additional experimental stereoscopic radiographs. A selection of these stereographs is reproduced below in anaglyph format. All were made in typical clinical settings, with only minimal instructions (and/or explanatory diagrams) given to the X-ray technician(s). Over the course of numerous visits in 2024 (monitoring his convalescence), this author was able to try three different 3DSR techniques, described below, with almost all exposures producing useful (i.e. 3D viewable) results.

Translating the X-ray Source

When the X-ray source is easily aimed/moved, such as when it is supported by a rail that allows free movement, or it is part of a mobile unit on e.g. a wheeled cart, or it is hand-held as by a dentist, the two viewpoints needed in 3DSR can be obtained by translating the X-ray source laterally between the first and second exposure, with the patient and detector not moving (Figure 2).

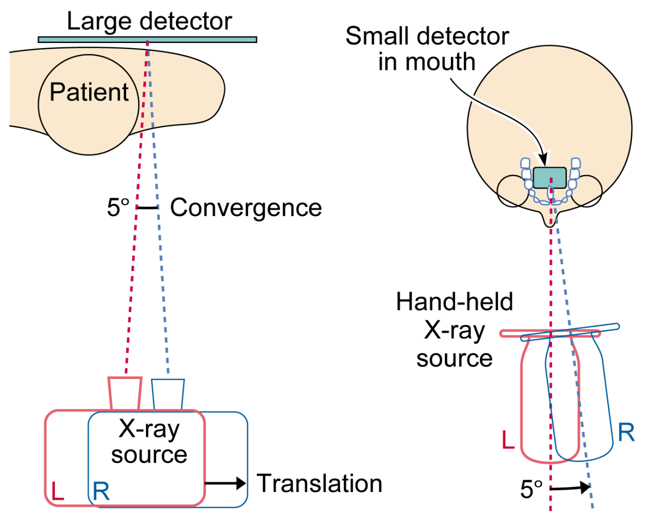

***Figure 2.** Translation of X-ray source with patient and detector unmoving. After the first exposure is made, the source is moved laterally, or orbited around the target, to obtain the desired convergence angle in the second exposure.*

But how much translation is needed? This author relied upon a "rule of thumb" that flows from stereoscopic and human factors theory, that about five degrees of convergence is appropriate for the acquisition of stereoscopic images that are comfortable to view and include a useful 3D effect [6], [13], [14], [31]. Note that for this work, it is useful to refer to a convergence angle, rather than to a distance of translation (or stereobase), because an angular determination is independent of the target size and distance from the X-ray source. Figures 3, 4, and 5 show three such targets, ranging in size from a tooth, to a hand, to an adult human shoulder or torso. All were obtained with convergence angles around five degrees. Given only that one convergence angle, we can easily calculate the best translation distance for any size target or X-ray source distance.

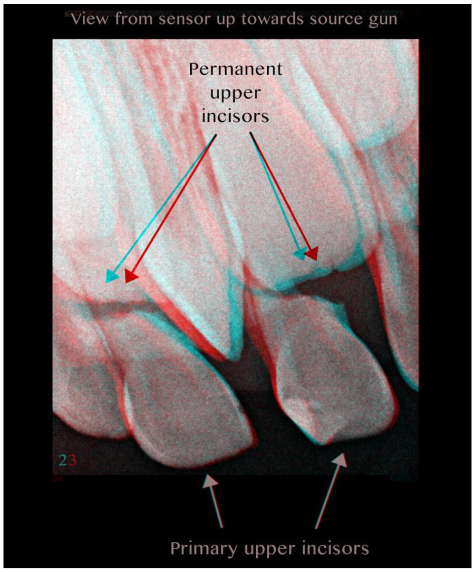

Figure 3. *Dental 3DSR showing a supernumerary tooth between upper incisors, and its spatial relationship to surrounding teeth. The hand-held X-ray source was translated about 1 cm at a distance of 25 cm from the tooth and detector, which was a small wireless device held unmoving in the mouth.*

Figure 4. *The hand was resting on a horizontal detector plate. The X-ray source was about 40 cm above the detector, translated about 3 cm between exposures. Note valuable disambiguation in wrist bones.*

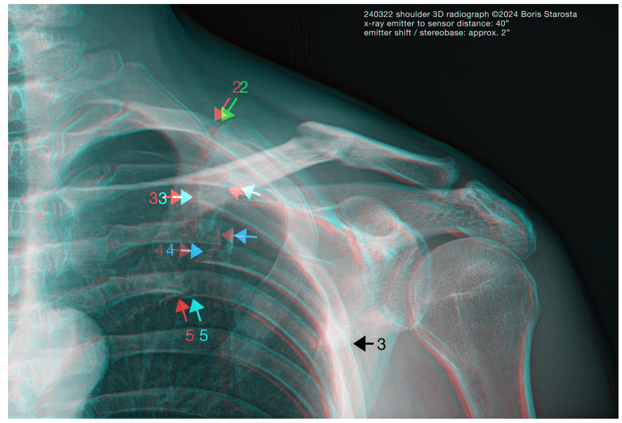

Figure 5. *The X-ray source was translated roughly 6 cm. Distance to sensor was said to be 110 cm. As can be seen, this image is made with a large detector, covering a significant fraction of the upper body. The numbers refer to the ribs. Ribs numbered 2, 3, 4, and 5 sustained fractures, indicated by arrows.*

Translating the Target

When the X-ray source is not easily moved, for example if it is supported by a rail that permits only specific, fixed positions, then the two viewpoints must be obtained by translating the position of the *patient* laterally, moving neither X-ray source nor detector (Figure 6). This became necessary when the author visited a facility where the X-ray source could not be moved the appropriate small distance. As a workaround, the author, standing in front of the detector plate, shifted his weight on his feet. For the first exposure, all body weight was borne on the left foot, then for the second exposure all the weight was borne on the right foot. This weight-shift translated the upper body about two inches, the desired amount. To minimize all other disturbances in the "target," the author held his breath during the time that the two exposures were obtained. The resulting 3D radiograph had some minor 3D flaws, but appears mostly useful (Figure 7).

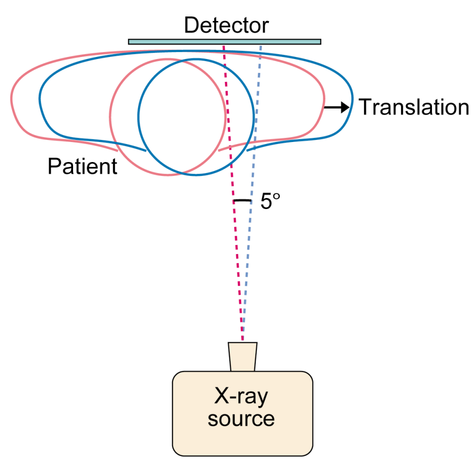

Figure 6. *Translating the patient is necessary, when the X-ray source and detector are not moveable.*

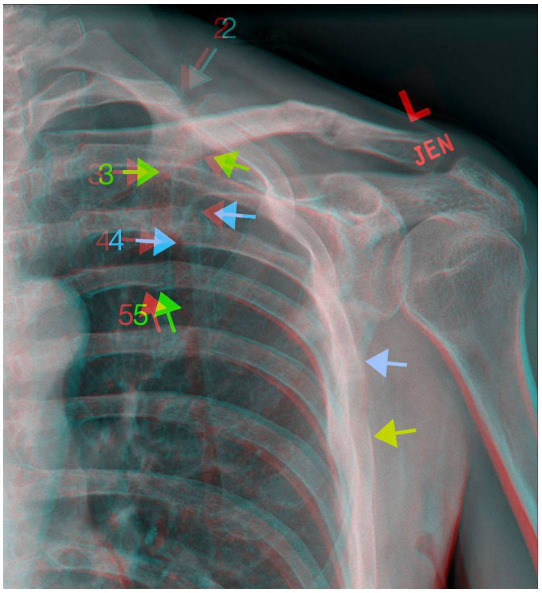

Figure 7. *The patient shifted his weight - thus translating upper body about 6 cm - with the X-ray source and detector unmoving, to produce this 3D radiograph.*

Rotating the Target

In November 2024, the author had another opportunity to obtain a stereoscopic dental radiograph, this time of a molar. Again, the author himself was the patient, and he seized the opportunity to try the third proposed method to obtain a stereo pair image. This method is a work-around for the situation where the X-ray source is not easily moved, for example, as when the X-ray source is not hand-held, instead being supported on an old, creaky, uncooperative mechanical arm, and where the detector is in the mouth (meaning: we cannot translate the target - a tooth - in front of the detector). In this situation, the author instructed the dentist to not bother trying to translate the X-ray source (an estimated) 10 mm, instead electing to rotate his head upon the neck by about 5 degrees, from left to right, with the X-ray source kept stationary for the two exposures (Figure 8). The resulting stereo view shows only a mild 3D effect, because in this first attempt, the rotation was insufficient (Figure 9).

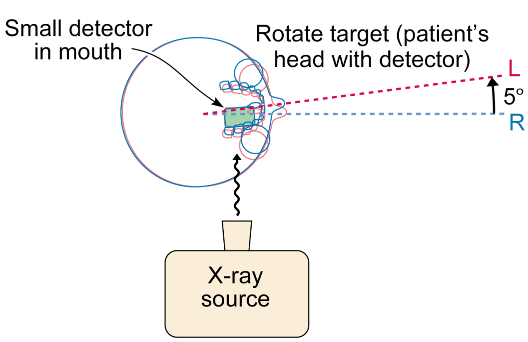

Figure 8. *When X-ray source is not easily moved, rotation of the target - here the head, with detector held in the mouth - can produce a good result.*

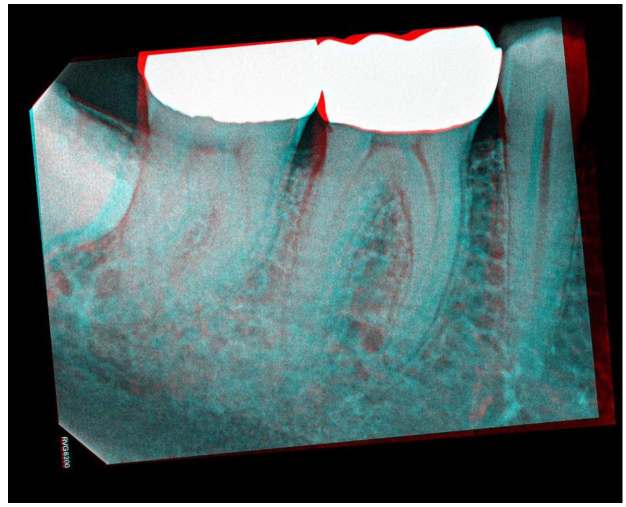

Figure 9. *Stereoview of a pair of crowned molars. The patient rotated his head probably about 3 degrees around vertical axis, though 5 degrees would have been better. The detector was held in the mouth, and the head rotated around vertical axis, with the X-ray source unmoving.*

3D Image Processing

Any stereoscopic images obtained with the three methods here described - translating the X-ray source, translating the target, rotating the target - will inevitably require significant alignment and cropping, before they can be viewed comfortably in 3D. The stereo pair images may be impacted by rotational and other misalignments that introduce distortions into the 3D view. Fortunately, software now exists that can automatically correct for most such misalignments and distortions, as long as the original stereo pair is acquired with reasonable care, close to the parameters described [15], [16]. Ideally, such software would be integrated into existing X-ray machine operating systems.

3D Image Display

Ideally, the clinical setting will include an inexpensive and commonly available 3D monitor, viewed with polarizing glasses. But in the absence of this technology, the imaging software could produce an output in so-called anaglyph format, just like the images reproduced in this paper. Such imagery displays well on standard RGB color monitors, and is viewed in 3D with anaglyph glasses, red lens over the left eye. Finally, simple stereo pair images can be viewed on any monitor, using a stereo lorgnette, or even using a technique called free-viewing, that requires no device at all (Figure 10).

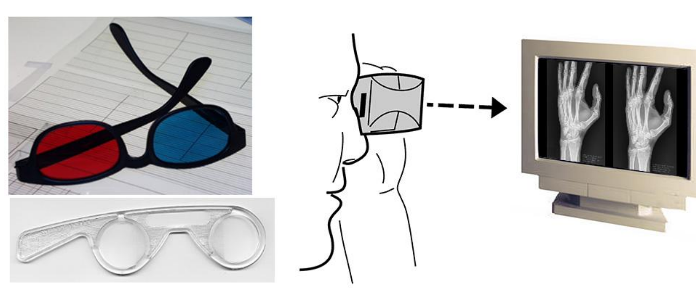

Figure 10. *Common anaglyph glasses, and less common - though inexpensive - stereo lorgnettes or a screen stereoscope.*

What can be gained with 3DSR?

Presently, CT scanning is standard for obtaining 3D imagery in the clinical context. However, 3DSR can offer numerous advantages over CT. 3DSR requires a much lower dose of ionizing radiation even as it produces images of higher spatial resolution. 3DSR images are made more quickly and are easier to read, requiring no additional specialized training. Finally, 3DSR requires less infrastructure, involves less up-front investment, with lower maintenance costs, and no advanced technical staff. Like DR, 3DSR would be broadly available.

Spatial Resolution

On par with DR, 3DSR captures finer details over a wider field of view, using far less radiation than CT. Only with the very narrow field of view of cone beam computed tomography (CBCT), and thus with even more radiation intensity, can CT technology reach the resolution of the much wider fields of view afforded by 3DSR [17].

A traditional direct radiograph has up to ten times better resolution than a typical clinical CT scan, over a comparable field of view: CT == 0.5 to 0.625 mm resolution (1.0 to 1.6 line pairs per mm) vs. DR == about 0.1 mm resolution (3.5 to 5.5 line pairs per mm) [18], [19].

This holds true over any comparable field of view. For example, in the relatively small fields of view in oral / dental radiography the spatial resolution of CBCT images is approximately one order of magnitude less than that of intraoral DR [20]. Based as it is on DR, 3DSR would better enable detection of finer details such as hairline fractures, as well as locating them in a complex 3D space.

Radiation Dose

Best practice in radiology motivates the practitioner to keep the dose of ionizing radiation *As Low As Reasonably Achievable* (ALARA) to reach a clinical goal. This is most important for pediatric patients [17]. 3DSR helps the clinician conform to this practice.

Comparing for example the shoulder imaging reproduced in this work, the typical shoulder CT scan requires a dose of over 5 mSV of radiation, whereas the two radiographs to produce a 3DSR view require a total dose of only 0.02 mSV. That makes the radiation dose from the CT over 250 times greater than the dose for one 3DSR image, covering a comparable field of view [21].

Given the superior resolution of the 3DSR over a wide field of view, along with adequate 3D visualization that fully characterizes the extent and position of the several fractures, in my case a CT scan might never have been needed, had the 3DSR technique been known and applied *first*. For my own medical care, this would have meant lower cost, much lower radiation dose, and likely a comparable course of treatment and outcome.

Speed of Imaging Returns

In my personal experience at a trauma center, direct radiographs, and by extension 3DSR, are much faster and more comfortable than CT. The time to prepare and execute the CT scan took over 15 minutes, with removal to a special facility, and the very painful repositioning of my body onto the patient "bed" of the machine. By contrast, a 3DSR can be obtained in just one or two minutes without even removing the patient from their hospital bed or gurney, using a mobile X-ray system. Not only is acquisition of the exposures much faster, but the post-processing in 3DSR is practically instantaneous: there's no need for specialized analysis of a complex 3D dataset consisting of hundreds of 2D slices [22]. With 3DSR, the clinician can get a nearly instantaneous and naturally understandable visual 3D overview, on a commonly available 3D screen that both the clinician and patient can view.

Resource-Constrained or Battlefield Settings

Battlefield radiography relies on portable digital radiography systems (PDRS) that are compact, durable, and capable of rapid image acquisition even in remote or austere environments. Because 3DSR relies on this exact same technology, 3DSR is envisaged as a unique additional tool in the battlefield scenario. In a battlefield setting, forward positioning of the diagnostic facility is of paramount importance. Poly-trauma is typical in this setting, with triage and/or successful management of multiple patients requiring imaging access, speed, and accuracy [23]. 3DSR enables rapid 3D imaging where CT is unavailable, thereby improving detection and accurate location of multiple fractures, metallic fragments, and diagnoses of other trauma [24].

Cost and Accessibility in LMICs

3DSR is available anywhere where there is an X-ray machine: in local health or urgent care clinics, in rural areas, or in third world settings, in low to medium income countries (LMICs), where the availability of CT imaging is significantly limited due to a combination of economic, infrastructural, and logistical challenges. In LMICs, there are typically fewer than one CT scanner per million inhabitants, compared to around 40 scanners per million in high-income countries [10]. There are numerous reasons for this disparity. The high cost of acquiring and maintaining CT scanners is a major barrier. Many health facilities in LMICs lack stable electricity, water supply, or the physical space necessary to house and operate CT scanners. CT equipment often falls into disrepair due to a lack of spare parts or expertise for maintenance. Many LMICs face a severe shortage of radiologists and radiologic technologists. Finally, there is often insufficient training for healthcare workers on how to use and interpret CT data effectively [11], [12].

In all of these areas, 3DSR provides advantages, as it can rely upon older, less costly, less complicated technology. 3DSR will require less training, less maintenance, and can function with reduced infrastructure. Though with some difficulties, 3DSR can even use the old-fashioned, analog wet-process film technology.

Challenges

Challenges to 3DSR adoption include clinicians with reduced stereoacuity, change management, and training obstacles.

Stereo-acuity

Between 5% to 20% of people are observed to be more or less "stereo-blind," meaning their visual perception may not fuse stereoscopic disparities into the formation of a three dimensional view in the mind's eye. Such visual fusion is called stereopsis and is quantified as stereoacuity [25].

Stereoacuity may be reduced or absent for various reasons. Visual stereo disparities might be unavailable, as when a person has poor or no eyesight in one eye; or because a person has amblyopia or strabismus, where the eyes are physically unable to fuse a stereoscopic image (e.g. they are "cross-eyed"); or because the brain has never learned how to process stereo disparities, because one eye was temporarily blinded during a key childhood visual/cognitive development phase (typically at 2 to 4 years old) [26], [27], [28].

It has been found that even in professions where good stereo vision will confer significant advantages (for example: surgery), stereo acuity is absent or reduced in 2% to 14% of practitioners. This does not mean that stereopsis has nothing valuable to add to visual perception. It is thought that stereo-blind practitioners compensate with the utilization of other depth and haptic cues [29], [30]. Though practitioners with good stereoacuity have much to gain from having access to 3DSR imagery, as described above, the minority of practitioners with moderate or absolute stereo-blindness will suffer *no disadvantage* - they will not perceive any less in a 3DSR image than they would in a regular, "flat" direct radiograph.

Training / Continuing Medical Education

Though the technique is theoretically simple, clinical adoption of 3DSR will require some training. Any training should impart a basic theoretical understanding of stereoscopic concepts, especially the preferred angle of convergence (typically 5 degrees), and how or why one might want to choose more or less convergence. Development of the cost basis, usefulness, procedures, tools and training for 3DSR are a good target for future research.

Conclusions

This work demonstrates that compared to CT scanning, 3DSR can provide a 3D image more quickly and at lower cost, involving a lower radiation dose [31], at the same time improving perception of fine details/textures with its inherently higher spatial resolution.

Our results are from casually obtained 3D stereoscopic radiographs. The author gave cursory, impromptu instructions in clinical settings, demonstrating that 3DSR imagery can be acquired by technicians or clinicians with minimal additional training. With the obtained imagery automatically post-processed for stereo alignment, practitioners can easily view the 3D image using commonly available technology.

3DSR enables 3D imaging in clinical settings where CT and related technologies are ill-advised, impractical, too costly, or simply unavailable.

Conflicts of interest

The author declares no competing interests. This research received no funding.

References

[1] Johan van Ebbenhorst Tengbergen, Lieuwe Evert Willem van Albada, *Die Röntgenstereoskopie. Ihr Wert und ihre Verwertung*. Julius Springer Verlag. 1931.

[2] Albert Hasselwander, *Atlas der Anatomie des menschlichen Körpers im Röntgenbild,* J. F. Bergmann Verlag. 1926.

[3] Hans Köhnle, *Objektive Stereoskopie an Röntgenbildern*, Palm & Enke. 1930.

[4] Werner Teschendorf, Hans Köhnle, *Das Röntgenraumbild*, Urban & Schwarzenberg. 1933.

[5] Wilhelm Trendelenburg, *Stereoskopische Raummessung an Röntgenaufnahmen*, Julius Springer. 1917.

[6] William C. Dolowy MS, DVM, John C. Lind DDS, "Stereoscopic dental radiography: A practical dental office procedure (technique tip)", Oral Surgery, Oral Medicine, Oral Pathology, Volume 68, Issue 3, September 1989, Page 367. https://doi.org/10.1016/0030-4220(89)90226-0

[7] Grunz, JP., Pennig, L., Fieber, T. et al. "Twin robotic x-ray system in small bone and joint trauma: impact of cone-beam computed tomography on treatment decisions." Eur Radiol 31, 3600–3609 (2021). https://doi.org/10.1007/s00330-020-07563-5

[8] Fitzpatrick, E., Sharma, V., Rojoa, D. et al. “The use of cone-beam computed tomography (CBCT) in radiocarpal fractures: a diagnostic test accuracy meta-analysis.” Skeletal Radiol 51, 923–934 (2022). https://doi.org/10.1007/s00256-021-03883-9

[9] Orhan Hakki Karatas, Ebubekir Toy, "Three-dimensional imaging techniques: A literature review," Eur J Dent. 2014 Jan-Mar;8(1):132–140. doi: 10.4103/1305-7456.126269

[10] International Atomic Energy Agency. IMAGINE - IAEA medical imaging and nuclear medicine global resources database. (2019). https://humanhealth.iaea.org/HHW/DBStatistics/IMAGINE.html. Accessed Dec. 29, 2024

[11] Frija, Guy et al., "How to improve access to medical imaging in low- and middle-income countries?" eClinicalMedicine, Volume 38, (2021). https://doi.org/10.1016/j.eclinm.2021.101034

[12] Verduzco-Aguirre HC, Lopes G, Soto-Perez-De-Celis E. "Implementation of diagnostic resources for cancer in developing countries: a focus on PET/CT." ecancermedicalscience. 2019 Jan 31;13:ed87. https://doi.org/10.3332/ecancer.2019.ed87

[13] John P. McIntire, Paul R. Havig II, and Alan R. Pinkus "A guide for human factors research with stereoscopic 3D displays", Proc. SPIE 9470, Display Technologies and Applications for Defense, Security, and Avionics IX; and Head- and Helmet-Mounted Displays XX, 94700A (21 May 2015); https://doi.org/10.1117/12.2176997

[14] Minnich et al., "Three-Dimensional Morphometry in Scanning Electron Microscopy", Journal of Microscopy, Vol. 195, Pt 1, July 1999, pp. 23–33

[15] Gerhard P. Herbig, COrrect Stereo IMages Automatically, *COSIMA*, http://www.cosima-3d.de/index.html

[16] Masuji Suto, *StereoAutoAlign*, an automatic stereo alignment software. https://stereo.jpn.org/stereoautoalign/indexe.html

[17] Edwin T. Parks, Johan K. Aps, Chapter 2 - Radiographic Techniques, *McDonald and Avery's Dentistry for the Child and Adolescent* (Tenth Edition). 2016, Pages 17-38. https://doi.org/10.1016/B978-0-323-28745-6.00002-8.

[18] Lin E, Alessio A. "What are the basic concepts of temporal, contrast, and spatial resolution in cardiac CT?" Journal Cardiovascular Computed Tomogr. 2009 Nov-Dec;3(6):403-8. https://doi.org/10.1016/j.jcct.2009.07.003.

[19] Alim Yucel-Finn, Fergus Mckiddie, Sarah Prescott et al. *Farr's Physics for Medical Imaging* (2023) ISBN: 9780702083655

[20] Brüllmann D, Schulze RK. “Spatial resolution in CBCT machines for dental/maxillofacial applications-what do we know today?” Dentomaxillofac Radiol. 2015;44(1):20140204. doi: 10.1259/dmfr.20140204.

[21] Ming Lei, et al., "The clinical performance of ultra-low-dose shoulder CT scans: The assessment on image and physical 3D printing models," PLoS One. 2022 Sep 26;17(9), https://doi.org/10.1371/journal.pone.0275297.

[22] Karakoyun OF, Kozaci N, Avci M, Uzunay H. “Accuracy of emergency physicians' interpretation of computed tomography for urgent-emergent diagnoses in nontraumatic cases.” Turk J Emerg Med. 2022 Apr 11;22(2):89-95. doi: 10.4103/2452-2473.342804. PMID: 35529030; PMCID: PMC9069923.

[23] Sharma V, Sreedhar CM, Debnath J., “Combat radiology: Challenges and opportunities.” Med J Armed Forces India. 2017 Oct;73(4):410-413. doi: 10.1016/j.mjafi.2017.09.014.

[24] LTC (ret) John Ritter, et al., "Radiology: Imaging Trauma Patients in a Deployed Setting," MILITARY MEDICINE, 183, 9/10:60, 2018.

[25] Michael Wiebrands, Andrew J. Woods, Hugh Riddell, "Incidence of stereo blindness in a recent VR distance perception user study" in Electronic Imaging, 2023, pp 225-1 - 225-5, https://doi.org/10.2352/EI.2023.35.2.SDA-225.

[26] Ciner, Elise B. et al. "Stereoacuity of Preschool Children with and without Vision Disorders," Optometry and Vision Science 91(3):p 351-358, March 2014. | DOI: 10.1097.

[27] Ann L. Webber; Katrina L. Schmid; Alex S. Baldwin; Robert F. Hess, "Suppression Rather Than Visual Acuity Loss Limits Stereoacuity in Amblyopia," Investigative Ophthalmology & Visual Science, June 2020, Vol.61, 50. https://doi.org/10.1167/iovs.61.6.50.

[28] Wajuihian, S., & Hansraj, R., "Stereoacuity and refractive, accommodative and vergence anomalies of South African school children, aged 13–18 years." African Vision and Eye Health, 77(1), 8 pages (2018). doi:https://doi.org/10.4102/aveh.v77i1.400.

[29] Mairiosa Biddle, Sana Hamid, Nadeem Ali, “An evaluation of stereoacuity (3D vision) in practising surgeons across a range of surgical specialities,” The Surgeon, Volume 12, Issue 1, February 2014, Pages 7-10, https://doi.org/10.1016/j.surge.2013.05.002.

[30] Al-Saud LM, et al. "Drilling into the functional significance of stereopsis: the impact of stereoscopic information on surgical performance." Ophthalmic Physiol Opt. 2017; 37: 498–506. https://doi.org/10.1111/opo.12393.

[31] Kai Deng, et al., "Realization of real-time X-ray stereoscopic vision during interventional procedures," Scientific Reports, 26 October 2018, https://doi.org/10.1038/s41598-018-34153-9.

Author Biography

Boris Starosta received his BA in Astronomy and Studio Art from the University of Virginia (1986). For over 35 years he has served education, academia and technical publications as a photographer and illustrator. Since 1997, Boris has pursued stereoscopic imaging using both film and digital tools. His work in this medium draws on a deep fascination with optics, perception and related human factors.