Use of Gamma Correction Pinhole Bone Scans in Trauma

Yong-Whee Bahk · Yong-An Chung · Jung Mee Park

Received: 31 October 2011 / Revised: 21 November 2011 / Accepted: 22 November 2011 / Published online: 5 January 2012
© Korean Society of Nuclear Medicine 2011

Abstract ^{99m}Tc -hydroxydiphosphonate (HDP) bone scanning is a classic metabolic nuclear imaging method and the most frequently performed examination. Clinically, it has long been cherished as an indispensable diagnostic screening tool and for monitoring of patients with bone, joint, and soft tissue diseases. The HDP bone scan, the pinhole scan in particular, is known for its ability to detect increased, decreased, or defective tracer uptake along with magnified anatomy. Unfortunately, however, the findings of such uptake changes are not specific in many traumatic bone disorders, especially when lesions are minute and complex. This study discusses the recently introduced gamma correction pinhole bone scan (GCPBS), emphasizing its usefulness in the diagnosis of traumatic bone diseases including occult fractures; cervical sprains; whiplash injury; bone marrow edema; trabecular microfractures; evident, gaping, and stress fractures; and fish vertebra. Indeed, GCPBS can remarkably enhance the diagnostic feasibility of HDP pinhole bone

scans by refining the topography, pathologic anatomy, and altered chemical profile of the traumatic diseases in question. The fine and precise depiction of anatomic and metabolic changes in these diseases has been shown to be unique to GCPBS, and they are not appreciated on conventional radiographs, multiple detector CT, or ultrasonographs. It is true that MR imaging can portray proton change, but understandably, it is a manifestation that is common to any bone disease.

Keywords Gamma correction bone scan · Bone trauma

Introduction

The gamma correction pinhole bone scan (GCPBS) is a recently developed image-processing algorithm that has been shown to be able to extract fine, specific, and complex morphological changes in various types of occult fractures [1], and the nidus and fibrovascular zone in osteoid osteomas [2], from simply homogeneous or heterogeneous ^{99m}Tc -hydroxydiphosphonate (^{99m}Tc -HDP) uptake in the penumbra. The rationale for such diagnostic performances of GCPBS is that the pinhole bone scan (PBS) produces images with higher resolution through optical magnification with increased photon acquisition [3–6], and added gamma correction (GC) distinguishes occult fractures with higher ^{99m}Tc -HDP uptake from edema, hyperemia, or hemorrhage with lower uptake (Fig. 1). Technically, PBS can be carried out simply by exchanging the collimator assembly from the parallel to pinhole mode, and GC can also be easily performed using an algorithm on a widely available personal computer equipped with a photographic management program such as Photo Editor or Adobe Photoshop. This article discusses the recently introduced GCPBS, emphasizing its usefulness in the diagnosis of traumatic bone diseases including occult fractures; cervical sprains;

Y.-W. Bahk
Department of Nuclear Medicine, Sung-Ae Hospital,
Seoul, Korea

Y.-A. Chung · J. M. Park
Departments of Radiology, College of Medicine,
Catholic University of Korea,
Seoul, Korea

Y.-A. Chung
Institute of Catholic Integrative Medicine (ICIM),
Incheon St. Mary's Hospital,
Inchon, Korea

Y.-A. Chung (✉)
Department of Radiology, Incheon Saint Mary's Hospital,
The Catholic University of Korea,
#665 Bupyeong-dong, Bupyeong-gu,
Incheon, South Korea
e-mail: nm@catholic.ac.kr

Fig. 1 Osteochondral occult fracture depicted by gamma correction. **a** Original anterior DICOM pinhole scan of the left lateral tibial plateau in a 51-year-old man shows poorly defined irregular tracer uptake (arrow). **b** Gamma correction (gamma=81) scan clearly depicts

whiplash injuries; bone marrow edema; trabecular microfractures; evident, gaping, and stress fractures; and fish vertebra.

Technical Methods

GC is a nonlinear image processing algorithm to code and decode the luminance (grey) or tristimulus (color) values in still images or video systems for specific purposes [7]. The nonlinear equation of power-law expression is: $V_{out} = V_{in}^{1/\gamma}$, where the input (V_{in}) and output (V_{out}) values are a non-negative real value and γ is a gamma value. According to Poynton, the equation can be $V_{out} = V_{in}^\gamma$ in the simplest cases [8], but this is not the situation for GCPBS.

GC can reliably extract characteristic and often pathognomonic signs out of featureless uptake of ^{99m}Tc -HDP presented on pinhole scan images of nearly all common bone diseases.

fractures with high uptake in the osteochondral and medullary bones (arrow). Observe washout of low uptake in edema and hemorrhage. **c** Coronal T2-weighted MR image (3,000/33) shows comparable irregularly mottled and streaky areas of low signal intensity (arrows)

For such extraction, the Photo Correction Wizard program of an ACD Photo Editor v3.1 or Adobe Photoshop v7.0 can be used. The gamma value of individual lesional uptake on pinhole scans is manually adjusted so that, for example, occult fractures (Fig. 1), the fibrovascular zone of the osteoid osteoma (Fig. 2), microfractures in osteoporosis (Fig. 3 upper panel), and speckled occult fractures (Fig. 3 lower panel) are distinctly depicted. The level of spatial resolution of an individual microfracture thus attained is less than 0.5 mm in osteoporosis and ± 1.0 mm in speckled fractures (Fig. 3 lower panel), which is equal or close to the 0.5 mm of trabecular fractures measured in macerated trabeculae by Vernon-Roberts and Pirie [9]. The way by which GC renders microfractures as clearly standing out in the featureless uptake is selective subtraction of ^{99m}Tc -HDP, which is presumed to be not chemically but rather loosely bound to the bone cell surface in edema, congestion, or hyperemia, and the resultant

Fig. 2 Nidus and fibrovascular zone (FVZ) in osteoid osteoma depicted separately by gamma correction. **a** Naïve anterior pinhole scan of the right femoral neck in a 14-year-old male shows an oval lesion with intense tracer uptake (arrows). Contour is blurred. **b** Gamma correction (gamma=70) image shows sharply defined central nidus with high tracer uptake and surrounding FVZ with low uptake

(arrows). **c** Gamma correction (gamma=12) radiograph shows calcified nidus and lucent FVZ (arrows). Inset is a pre-gamma correction radiograph not distinguishing anything. **d** Coronal T2-weighted MRI (3,000/99) shows the nidus with low and intermediate signal intensity and FVZ with low signal (arrows)

Fig. 3 Measurements of pinpoint trabecular injuries and speckled occult fractures presented on size-normalized gamma correction pinhole scans and radiographs of the knees. *Top panel* Microfractures of osteoporosis in a 25-year-old woman with steroid-treated SLE. **a1** Anterior gamma correction pinhole scan shows numerous pinpoint fractures (± 0.5 mm in size). This size is the same as that of trabecular microfractures measured

by light microscopy [22]. Aggregates are considered to be due to hemorrhage (arrows). **a2** Anteroposterior radiograph of a normal patient shows trabeculae measuring 0.5 mm in thickness. *Bottom panel* Speckled occult fractures of the left femoral condyle in a 38-year-old man. **b1** Gamma correction scan shows speckled hot areas (1–3 mm). **b2** Anteroposterior radiograph is negative

preservation of the tracer incorporated in repairing bone in fractures, osteoporosis, and osteolysis. For description's sake, 'subtracted' and 'preserved' are arbitrarily referred to as 'washed out' and 'unwashed,' respectively.

GC can be processed by clicking the tool bars on the monitor screen in the following order: Exposure $\rightarrow$ auto-

exposure to maximize uptake intensity $\rightarrow$ done and save with a new name $\rightarrow$ exposure $\rightarrow$ image-brightness control by increasing gamma value to best visualize fracture $\rightarrow$ done and save the finished image with another new name (Fig. 4). Starting from 50 (the default value in Photo Editor), the gamma value is increased continuously until the lesions

Fig. 4 Diagram of gamma correction procedure. *Top panel:* (Left) Naïve pinhole scan shows a large area of intense homogeneous tracer uptake in the tibial tuberosity. (Right) Post-gamma correction image shows characteristic latticework occult fractures with pinpoint and rod-like components. *Bottom panel:* (Left) Naïve pinhole scan shows a small mottled hot area at the medial femoral condylar edge. (Right) Post-gamma correction image depicts a small linear occult fracture. Central panel is the sequence of correction-editing tasks

with high uptake are extracted and left after the washout of the admixture of high, intermediate, and low uptake of fracture, hemorrhage, and edema, respectively. This means subtraction of low and intermediary uptake. In our series, gamma values for the best result ranged from 70 to 95 depending upon the quality of the original naïve scan. In general, a pinhole scan with low photon acquisition (tracer uptake) needs a low gamma value increment, and a scan with high uptake needs a high increment. Importantly, the use of the original naïve scan provided by the digital information and communications in medicine (DICOM) system without modification is mandatory (Fig. 5). It needs to be mentioned that a control study on the comparative efficacy of GC in paired parallel collimator and pinhole collimator scans showed that the latter scan yields by far superior results. Such a difference is generally considered to be due to that scan image resolution being much higher and photon acquisition being approximately 2.0 times greater in the pinhole scan.

Clinical Applications

Occult Fractures

Occult fractures are defined as posttraumatic breaks of the articular cartilage, cortex, and subcortical cancellous bones that are invisible on conventional radiographs. Also called bone bruise or trabecular microfracture, it is an intricate, potentially incapacitating disease occurring in any bone, but most typically in the knee bones. Prior to the era of magnetic resonance (MR) imaging and multidetector computed tomography (MDCT), occult fractures were diagnosed using

conventional X-ray tomography, which is now obsolete. The clinical application of ^{99m}Tc -diphosphonate bone scans for diagnosing occult fractures dates back to the early 1980s [10]. Its high sensitivity was well appreciated and has been utilized as a basis for triage in the imaging workup of traumatized patients after negative CRs [11]. Nevertheless, piecemeal diagnosis obviously could not be attempted because the spatial resolution of the parallel collimator scan and even of the pinhole collimator scan is not sufficiently high to depict specific scan signs. As a result, occult fractures have become one of the important objectives of MR imaging and CT. As mentioned, GCPBS has lately paved a new, economical road to a fine piecemeal diagnosis of occult fractures [1].

The image presentation of individual occult fractures on GCPBS is impressive in that radiographically invisible fractures are clearly depicted, permitting precise detection and reliable identification of different types of the most cryptic fractures. Such distinct and sharp portrayal of occult fractures on GCPBS is the result of selective elimination or washout of low penumbral tracer uptake in edema and congestion that makes bone scan images blurry and nonspecific. Another advantage of the pinhole scan is the cumulative imaging effect of γ -rays emitted from the whole lump of bone. In this connection, it needs to be mentioned that the sectioning of MR image (3–4-mm slices) has the advantage of separating areas of interest, but this is achieved at the expense of significant loss of volume integrity (Fig. 6).

Neck Sprain and Whiplash Injury

Sprain and strain are common in the neck, especially after motor vehicle accidents [12]. Sprain is defined as an articular injury with rupture of the supporting ligamentous fibers

Fig. 5 Use of the original DICOM image is critical for the best possible pictorial resolution of GCPBS. **a** Original DICOM pinhole scan and **b** image size and resolution adjusted pinhole scan were tested

by serially increasing gamma values from 50 to 100. Note that the tiny linear landmark fracture in the upper field (arrow) remains sharply depicted on **a**, but blurred and erased on **b**

Fig. 6 Cumulative gain of pixels in speckled uptake on a pinhole scan that is not sectioned and reduced pixels on sectioned MR image. **a** Anterior pinhole scan of the left knee in a 52-year-old woman shows blurry speckled hot areas in the left patella (circle). **b** Gamma correction scan (gamma=70) shows multiple speckled hot areas (circle). **c** and **d**

Two contiguous 3.5-mm-thick slices of coronal T2-weighted MR images (3,500/18) show several stippled lesions with high signal intensity (arrows). Observe that speckles are more distinct and far more numerous on the gamma correction pinhole scan than on MRI slices

without severance, and strain as resulting from extreme exercise, sports activities, or physical use of a body part. Since such injuries are non-osseous in nature, they cannot be seen on conventional radiographs, but indirectly suggested by spinal straightening and other signs.

GCPBS is able to detect enthesitis and occult fractures that accompany sprain or strain by showing characteristic tracer uptake at the attachments of injured ligaments and tendons, for example, at the odontoid process, and C1 and C2 neural arches in sprains of the upper cervical spine. Figure 7 shows a typical instance of C1 and C2 sprain with associated whiplash injury of the lower cervical spine.

Whiplash is a popular nonspecific term given to the state of sudden acceleration or deceleration trauma to the cervical spine, and whiplash-associated disorder (WAD) refers to the symptoms that develop following a whiplash injury [13]. Whiplash injury caused by motor vehicle accidents is one of the most common traumatic disorders of the neck [14], and the great majority of cases result from a rear-end vehicle collision at speeds of less than 14 mph (or 22.5 kmph) [15]. The injury typically occurs at the junction of the 4th and 5th cervical vertebrae, and usually includes occult fractures at the tips of the spinous processes because of the sudden and forceful flexion pull of the interspinous and supraspinal

Fig. 7 Neck sprain with occult fractures in the odontoid process and C5–7 spinous processes. **a** Posterior pinhole scan of the cervical spine in a 25-year-old woman who sustained multi-collision type neck injury in an overturned car accident shows blurred tracer uptake in the odontoid process (box) and button-like uptake in the C5–7 spinous processes (arrows). **b** Gamma correction pinhole scan (gamma=84) shows discrete speckled uptake in the dense (D) and right neural arch

of the atlas (NA). **c** Lateral radiograph shows straightening of the cervical lordosis. **d** Lateral radiograph shows blurring of the dense (D) and suspicious fractures in the posterior atlantoaxial joint (arrow). **e** Topograph shows cruciate ligaments (CL), alar ligaments (AL), and joint capsule (JC). Adopted from Anatomy. Clements CD, 2nd ed. München: Urban & Schwarzenberg, 1981

ligaments. Conventional radiography can identify with certainty most traumatic injuries in the cervical spine, such as ordinary fractures, subluxation, and dislocation, and MDCT and MR imagings are useful for finding occult injuries. We found that GCPBS is another potent and economical measure that can sensitively and specifically diagnose whiplash injury. On GCPBS, whiplash injuries are featured by prominent button-like tracer uptake at the spinous processes of the lower cervical vertebrae (Figs. 7 and 8). The tracer uptake is characteristically localized to the lower three or four cervical vertebrae with little or no uptake in the remaining upper vertebrae when the injury is not compound. The finding appears to reflect that the sudden concentrated vertical impact of neck anteflexion is dispelled at the lower neck. It needs to be mentioned that whiplash injury of the lower cervical spine can occur in association with C1–2 sprains in multiple collision-type trauma of the cervical spine (Fig. 7).

Bone Marrow Edema

Edema is a pathological state in which abnormal amounts of body fluid accumulate in intercellular spaces or body cavities, being produced by the fluid leaked from capillaries as permeability is increased by hyperemia, congestion, or a mixture of both. It is a common manifestation that accompanies trauma, infection, and tumors [13] and tumorous conditions. The edema tightly enclosed by cortex in the medullary space can conversely or reciprocally injure bone trabeculae.

Until recently, MR imaging was the sole noninvasive diagnostic means for bone edema [16–18] and occult fractures [19]. However, GCPBS is now used as a convenient and economical imaging method that not only can sensitively detect edema and occult fractures, but also can accurately distinguish edema from fracture because ^{99m}Tc -HDP uptake in edema is washable, whereas the uptake in fractures remains unwashed (Fig. 9). As demonstrated in this and many other cases, MR imaging cannot always discriminate edema signal from fracture signal. It appears that the sensitivity and specificity of GCPBS in the diagnosis of edema and occult fractures are higher than or as good as MR imaging.

Microfractures of Bone Trabeculae

GCPBS of trabecular microfractures is considered to be an ideal model of ‘the fine anatomic and metabolic imaging’ in a strict and practical sense in that it can clearly depict pinpoint fractures that measure ± 0.5 mm in size and small rod- or lattice-like trabecular microfractures that measure $\pm 0.5 \times 2.5$ mm. It is of interest that the GCPBS depiction of trabecular microfractures observed in the tibial tuberosity of our case is almost exactly the same as that of the microfractures that occurred in the trabeculae of macerated lumbar spine described by Vernon-Roberts and Pirie in 1973 [9] (Fig. 10). GCPBS can further distinguish the tracer uptake due to edema or congestion from that of fractures.

Fig. 8 Whiplash injury caused by motorcycle-automobile multi-collisions. **a** Posterior pinhole scan of the cervical spine in a 29-year-old male motorcyclist shows characteristic button-like tracer uptake in the spinous process of C5–7 (arrows). **b** Gamma correction pinhole scan (gamma=84) shows sharp depiction of occult injuries of C5–7 spinous

processes (arrows). **c** T1-weighted (430/24.40) MR image shows low signal intensity at the tips of the C6–T1 spinous processes (arrows). Note characteristic involvement of the lower cervical spine as in Fig. 6. Bright signal intensity in the upper portion is positioning artifact

Fig. 9 Washout of edema uptake and persistence of geographic 1 occult fracture uptake. **a** Anterior pinhole scan of the right knee in a 30-year-old woman who had been in a motor vehicle collision shows a geographic hot area at the medial tibial condylar edge (*arrow*) and speckled and comet-

like uptake of edema (*circle*). **b** Gamma correction ($\gamma=86$) scan shows complete washout of edema uptake (*circle*). **c** Coronal T2-weighted (3,500/18) MR image shows geographic occult fracture (*arrow*) and comet-tail edema with bright signal intensity (*circle*)

Evident, Gaping, and Stress Fractures

Evident fracture designates bone breaks that are diagnosable using conventional radiography. Peculiarly, the evident fractures of small bones, such as phalanges and carpal and tarsal bones, and irregular bones, such as the clavicle, coracoid process, and patella, tend to accumulate tracer rather intensely as long as fragments are not devascularized, even if they are

widely separated (Fig. 11). Bone fractures are genetically determined to be completely reconstituted by a reactivating process that takes place physiologically during embryogenesis [20]. The reconstitution can be imaged using bone-seeking radiopharmaceuticals such as ^{99m}Tc -HDP. However, if fragments are widely separated, the gap is filled up with a large hematoma that fabricates a framework of fibrinous mesh from which soft and bony calluses evolve. A gap in the fracture can

Fig. 10 **a, b** Distinct depiction of trabecular microfractures by GCPBS. **a** Lateral pinhole scan of the left knee of a 78-year-old man injured in a bicycle collision shows a large area of increased tracer uptake in the tuberosity (*arrow*). **b** Magnified gamma correction scan of apparently homogenous uptake discloses lattice- and rod-like hot areas (*white arrows*) and pinpoint uptake (*black arrows*) that respectively measure ± 2.5 mm in length and ± 0.5 mm in size. The rod and

lattice are an en face view of the tabeculae, and the pinpoint is the transaxial view. The inset is a part of a macerated lumbar spine showing trabecular microfractures (*arrows*) [9]. Note the closeness of the GCPBS and anatomical presentation of trabecular microfractures, and clean washout of edema uptake and the presumed impact epicenter (*EP*) and dissipation in the periphery

Fig. 11 Ovoid tracer uptake in evident fracture of the coracoid process. **a** Anterior pinhole scan of the right shoulder girdle in a 58-year-old man shows intense tracer uptake in the coracoid process (*arrow*). **b** Gamma correction (gamma=87) scan separates ovoid fragment uptake (*arrow*) from stippled stump uptake (*arrowhead*). Prominent uptake in

the fragment reflects that the blood supply is well maintained. **c** Anteroposterior radiograph with external rotation shows evident fracture of the coracoid tip (*arrow*) separated from the stump (*arrowhead*). Observe separation of the glenohumeral joint (*double-headed arrow*)

become a site of nonunion when it is stuffed with soft tissues (Fig. 12). We noted that GCPBS is useful for assessing callus formation in such a situation. Understandably, the gap should not be too wide in a small or thin bone for a fracture to heal with good callus.

Stress fractures can be defined as bone breaks induced by repeated cyclic physical impact, the strength of which is less than what causes fracture, including fatigue and insufficiency fractures. Conventional bone scan shows simple ‘hot’ areas that may be defined sharply or poorly. GCPBS, however, can

disclose reticular, block-like, and fusiform fractures that typically involve the cortical bones stressed or fatigued by repetitive low-impact activities (Fig. 13). Bone scan is also useful to detect not only the major stress fractures, but also minor cryptic satellite injuries.

Fish Vertebrae

“Fish vertebrae” is the term to describe osteoporotic or malacic vertebrae with concave endplate deformity [21].

Fig. 12 Gaping fractures of the ischiopubic ring. **a** Anterior gamma-correction pinhole scan of the right pelvis in a 24-year-old woman shows gaping fracture in the pecten pubis (*top arrow*) and the inferior ischiopubic junction (*bottom arrow*). Note prominent tracer uptake in the ischial fracture, which is crushed (*arrowhead*). **b** Anteroposterior radiograph shows gaping fractures with the one in the pecten pubis being comminuted and the other one in the inferior ischiopubic

junction widely separated. **c** T2-weighted (6,000/70) coronal MR image shows gaping fracture at the pecten pubis insinuated by soft tissue and bony fragments (*arrow*). Note subtle contusion with microfractures in the superior ramus of the pubis (*circle*), which are not seen in the other two images. This case demonstrates the advantages and disadvantages of each imaging modality

Fig. 13 Fusiform intracortical tracer uptake in a stress fracture. **a** Anterior pinhole scan of the left mid-tibial shaft in a 16-year-old male soccer player shows vertically oriented fusiform tracer uptake in the medial cortex (*large arrows*) and an oblique element with mild tracer uptake (*small arrows*). **b** Gamma correction ($\gamma=86$) scan shows

unwashed uptake in a stress fracture with washed out edema. **c** Coronal CT scan shows diffuse cortical thickening with endosteal thickening (*arrows*) and an oblique element. Note hypertrophy of the gastrocnemius muscle (*GCM*)

Radiographically, the deformity is presented as a biconcave compression of the upper and lower endplates of a vertebra. Fish vertebrae are not uncommon in the elderly population, especially postmenopausal women with severe osteoporosis, and tend to occur in the lower thoracic and whole lumbar spine. Biomechanically, the intervertebral discs, especially the nuclei, should retain sufficient elasticity to pliantly compress and deform porotic vertebrae. Hence, dehydrated discs are unable to produce fish vertebrae. The bone scan finding is characterized by biconcave deformity of the endplates with moderately increased tracer uptake (Fig. 14). It is of interest that such endplate uptake is readily washable by gamma correction, suggesting that the increased uptake in fish

vertebrae is likely due to edema and not actual fractures. If bruised or fractured, however, depressed endplates may come to positively accumulate tracer that is not washed out (Fig. 14b). Thus, a gamma correction scan helps differentiate a simple fish vertebra from a compression fracture.

In summary, it is concluded that GCPBS is a new potent and economical measure to sensitively and specifically diagnose traumatic bone disorders including occult fractures, neck sprain and whiplash neck injury, marrow edema, trabecular microfractures, and evident, gaping and stress fractures, as well as fish vertebrae. The use of GCPBS can be extended further to the study of many bone diseases other than traumatic injuries.

Fig. 14 Washable tracer uptake in fish vertebra. **a** Posterior pinhole scan of the lower lumbar spine shows increased tracer uptake in biconcave deformity of L3 endplates and L4 upper endplate (*arrows*). **b** Gamma correction ($\gamma=89$) scan shows complete washout of tracer in fish

vertebrae (*arrows*) denoting that uptake is due to edema or congestion. **c** Anteroposterior radiograph of the lower lumbar spine in another patient shows typical fish vertebra deformity

References

1. Bahk YW, Jeon HS, Kim JM, Park JM, Chung YA, Kim EE, et al. Novel use of gamma correction for precise (99 m)Tc-HDP pinhole bone scan diagnosis and classification of knee occult fractures. *Skeletal Radiol.* 2010;39:807–13.
2. Bahk YW, Kim SH, Chung YA, Bahk WJ, Park JM, Kang YM, et al. Depiction of nidi and fibrovascular zones of osteoid osteomas using gamma-correction Tc-99m HDP pinhole bone scan and conventional radiograph, and correlation with CT, MRI, and PVC phantom imaging. *Nucl Med Mol Imaging.* 2011;45:21–9.
3. Bahk YW, Kim OH, Chung SK. Pinhole collimator scintigraphy in differential diagnosis of metastasis, fracture, and infections of the spine. *J Nucl Med.* 1987;28:447–51.
4. Bahk YW, Park YH, Chung SK, Kim SH, Shinn KS. Pinhole scintigraphic sign of chondromalacia patellae in older subjects: a prospective assessment with differential diagnosis. *J Nucl Med.* 1994;35:855–62.
5. Yang W, Bahk YW, Chung SK, Choi K, Jo K, Jee MK. Pinhole skeletal scintigraphic manifestations of Tietze's disease. *Eur J Nucl Med.* 1994;21:947–52.
6. Kim SH, Chung SK, Bahk YW, Park YH, Lee SY, Sohn HS. Whole-body and pinhole bone scintigraphic manifestations of Reiter's syndrome: distribution patterns and early and characteristic signs. *Eur J Nucl Med.* 1999;26:163–70.
7. Holst GC (1998) CCD arrays, cameras and displays. In: eds. Bellingham: SPIE Optical Engineering Press, pp 169–171
8. Poynton CA (2003) Digital video and HDTV. In: eds. Algorism and interfaces. Burlington: Morgan Kaufmann pp 260–630
9. Vernon-Roberts B, Pirie CJ. Healing trabecular microfractures in the bodies of lumbar vertebrae. *Ann Rheum Dis.* 1973;32:406–12.
10. Batillas J, Vasilas A, Pizzi WF, Gokcebay T. Bone scanning in the detection of occult fractures. *J Trauma.* 1981;21:564–9.
11. Holder LE. Bone scintigraphy in skeletal trauma. *Radiol Clin North Am.* 1993;31:739–81.
12. Quinlan KP, Annest JL, Myers B, Ryan G, Hill H. Neck strains and sprains among motor vehicle occupants-United States, 2000. *Accid Anal Prev.* 2004;36:21–7.
13. Jensen TS, Kasch H, Bach FW, Bendix T, Kongsted A. Definition, classification and epidemiology of whiplash. *Ugeskr Laeger.* 2010;172:1812–4.
14. Evans RW. Some observations on whiplash injuries. *Neurol Clin.* 1992;10:975–97.
15. Bannister G, Amirfeyz R, Kelley S, Gargan M. Whiplash injury. *J Bone Joint Surg Br.* 2009;91:845–50.
16. Eustace S, Keogh C, Blake M, Ward RJ, Oder PD, Dimasi M. MR imaging of bone oedema: mechanisms and interpretation. *Clin Radiol.* 2001;56:4–12.
17. Karantanas AH. Acute bone marrow edema of the hip: role of MR imaging. *Eur Radiol.* 2007;17:2225–36.
18. Fowkes LA, Toms AP. Bone marrow oedema of the knee. *Knee.* 2010;17:1–6.
19. Deutsch AL, Mink JH, Waxman AD. Occult fractures of the proximal femur: MR imaging. *Radiology.* 1989;170:113–6.
20. Rosenberg AE. Skeletal system and soft tissue tumors. In: Cotran RS, Kumar V, Robbins S, eds. *Pathologic basis of disease.* 5th ed. Philadelphia: WB Saunders; 1994. p. 1213–46.
21. Resnick DL. Fish vertebrae. *Arthritis Rheum.* 1982;25:1073–7.
22. Fazzalari NL. Trabecular microfracture. *Calcif Tissue Int.* 1993;53 Suppl 1:S143–146. discussion S146–147.