Elbow dysplasia is a common developmental anomaly in dogs. The term comprises fragmented medial coronoid process, ununited anconeal process, osteochondrosis dissecans, and joint incongruency. Inherited, developmental, metabolic, and mechanical factors play important roles in the development of these diseases. Osteoarthritis secondary to these factors is a common cause of forelimb lameness in dogs. In osteoarthritic disease, the subchondral bone plate, which is located directly beneath the calcified zone of joint cartilage and varies from 2 to 4 mm in thickness depending on joint size, remodels and appears to thicken prior to degradation of the articular cartilage. Therefore, non-invasive assessment of subchondral bone density patterns might provide a useful method for the early diagnosis of osteoarthritic disease.

A few studies have described systematic investigations of mechanical factors in the elbow joints of dogs. Computed tomography was shown to have several advantages over conventional radiography in the diagnosis of elbow osteoarthritis; it provides precise cross-sectional images of the joint and allows the user to differentiate superimposing structures, distinguish among tissues of various densities, and obtain volumetric data in high resolution. The CT method discloses full anatomic detail of the osseous structures of the elbow joint in dogs and allows accurate diagnosis of fractured medial coronoid processes and elbow joint...
The use of advanced imaging software enables 3-D image rendering to be generated on the basis of transverse CT scans of the elbow, allowing precise estimation of radiolucent joint incongruence. Computed tomographic osteoabsorptiometry is a functional CT technique for visual evaluation and quantification of the relative distribution of maximum subchondral bone density that enables a noninvasive, load-dependent assessment of the subchondral bone plate.

By means of CTOAM, the topographic distribution of mineralization within subchondral bone can be assessed. This mineralization pattern is directly related to joint mechanics. Previous studies have evaluated subchondral bone density patterns in elbow joints of clinically normal and abnormal dogs; these have shown that CTOAM is a noninvasive and repeatable technique for the investigation of bone density distribution in the elbow joints of dogs. The objective of the study reported here was to evaluate the age-dependent, long-term mechanical adaptation of subchondral bone in elbow joints of healthy dogs by means of CTOAM.

Materials and Methods

Sample collection—The left and right elbow joints of 220 clinically normal dogs of various breeds and ages that were euthanized for research unrelated to the present study were evaluated. Dogs were termed clinically normal when no signs of joint pathology were detected macroscopically or via CT evaluation. The limbs were separated transversely at the midshaft of the humerus and antebrachium. The specimens, still covered by skin, were soaked in saline solution, double bagged in sealed plastic freezer bags, and stored at –18°C until CT evaluation. At evaluation, a thorough, macroscopic inspection of the joint surfaces was performed to rule out joint disease. Joints with even the slightest roughening of articular cartilage were discarded. All joints with macroscopically smooth cartilage surfaces were evaluated via CT. Joints with signs of subchondral sclerosis were also excluded from the study. The elbow joints of 29 dogs fulfilled the study criteria; 42 of these elbow joints were used in the study (the contralateral joints of some dogs were subjected to biomechanical testing in an unrelated study).

Body weight, breed, sex, and age of each dog were recorded. The median body weight of the dogs was 28.8 kg (range, 10 to 60 kg). Dogs were of various breeds. Six dogs were females (3 spayed), and 23 were males (17 neutered). The median age was 6 years (range, 2 months to 17 years).

The 29 dogs from which joints were collected were divided into 3 groups according to age: juvenile (< 1 year of age; n = 9 joints of 5 dogs [left and right joints of 4 dogs and the right joint of 1 dog]), adult (1 to 8 years of age; 16 joints of 13 dogs [left and right joints of 3 dogs and the left or right joint of 10 dogs]), and geriatric (> 8 years of age; 17 joints of 11 dogs [left and right joints of 6 dogs and the left or right joint of 5 dogs]).

Joint preparation—Each specimen was thawed to room temperature (21°C) before testing. The skin was removed, and the humerus was disarticulated from the radius and ulna. The antebrachial bones remained connected by the anular radial ligament and partially by the interosseous antebrachial ligament. The humeral and antebrachial shafts were secured in a block of foam with the joint surfaces left exposed.

CT evaluation—A series of 1-mm slices of each elbow joint was obtained by use of a CT scanner with 110-kV, 249-mA settings. A water-hydroxyapatite phantom (water density, 0 HUs; cancellous bone density, 300 HUs) was placed lengthwise beneath the specimens and included in each scan. A sagittal sectional plane was chosen, scanning entire joint surfaces in a lateral to medial direction. Computer software was used to convert the CT data (mean number of slices/joint, 90) from the digital imaging and communications in medicine (ie, DICOM) file format into raw image formats. The density values obtained were calibrated in reference to the phantom.

Computer image analysis—Commercially available computer software was used to correct variations in density within the individual CT images (caused by inherent fluctuations in CT scanner performance and beam-hardening artifacts) on a slice-by-slice basis. The

Figure 1—Images of 3-D models (generated by use of CTOAM) with color densitograms depicting subchondral bone densities at joint surfaces of the distal aspect of the left humerus in dogs. A 15-color Hounsfield scale (left) that ranged from violet (500 HUs, least density) to red (2,100 HUs, maximum density) was selected as the basis for color densitograms of elbow joint surfaces. In panel A, a summation image (coronal view) of the distribution of subchondral bone density was compiled by use of data from 21 elbow joints of 13 clinically normal dogs of various ages and breeds. An area of increased bone density is noticeable in the groove between the lateral and medial aspects of the condyle, extending further in a distal to mediolateral direction. In panels B through D, images of the same joint surface in individual joints of representative juvenile (B), adult (C), and geriatric (D) dogs indicate age-dependent changes in subchondral bone density. The humerus of the juvenile dog has a zone of increased bone density on the cranioproximal aspect of the joint surface. This zone is displaced distally in the adult dog. The humerus of the geriatric dog has maximum density in the sagittal groove extending across the trochlea.
phantom of known density was included in each image as a reference. Custom computer software, modified to suit our needs, was used to select each bone (humerus, radius, and ulna) in each slice of the individual CT images and to subsequently convert these to 3-D surface models. The 3-D surface models were calculated on the basis of individual CT data sets obtained from the CT slices for each bone. The maximum density of the subchondral bone plate was determined at every point on the 3-D joint surface model (from 9,000 to 50,000 points, depending on the type of bone and data sets). A penetration depth of 1.5 mm was chosen perpendicular to the junction of joint cartilage and subchondral bone, and the highest HU value measured at each point was established.

For an optically clearer and more objective depiction of the 4,096 grayscale values (corresponding to various degrees of bone mineralization) in the CT images, the biologically significant range of 500 to 2,100 HU for the depiction of mineralized bone was selected. In a further step, the values were projected onto the surface of a corresponding 3-D CT image. This provided a 3-D model depicting the topographic distribution of subchondral bone density.

A color scale that consisted of 15 colors ranging from red to violet was chosen to depict subchondral bone densities. The red color represented the maximum density (2,100 HUs), and the violet color represented the least density (500 HUs).

Summation image—To allow quantitative comparison of maximum subchondral bone density between the different specimens, a summation image compiled from 21 elbow joints from 13 dogs across all 3 age groups (1 dog < 1 year old, 6 dogs 1 to 8 years old, and 6 dogs > 8 years old) was created by means of computer software. The program, which can register single and multimodal 3-D images accurately without any user interaction via rigid-body or affine transformations, geometrically matched the individual CT data (from individual slices of individual joints) to a target image data set. Each measured point in a CT slice was matched to the same location on the target image data set. The reference joint chosen as the target was of a randomly selected medium-sized dog (weight, 27 kg, closely representing the median body weight [28.8 kg]) in which anatomical conformation of the joint surfaces subjectively corresponded to that of most individual joint surfaces of the other dogs. The matched individual CT image data and 3-D models of the humerus, ulna, and radius of the reference joint were used to project the maximum subchondral bone density as previously described. This process resulted in one 3-D model of each of the 3 bones, with anatomically corresponding CTOAM data of the individual joints depicting mean maximum values for all dogs. Data sets of single left (2 dogs), right (3 dogs), and contralateral (16 joints of 8 dogs) bones were mirrored right to left during the

Figure 2—Distal views of 3-D models depicting subchondral bone densities at joint surfaces of the distal aspect of the right humerus (summation image and the same dogs in Figure 1). In panel A, the groove in the center of the condyle in the summation image gives rise to a narrow region of increased bone density extending medially into a prominent density maximum. Toward the lateral aspect, density decreases but then gives rise to an area of increased density, before decreasing again near the lateral margin of the joint surface. In panels B through D, comparison of the individual joint surfaces of juvenile, adult, and geriatric dogs reveals an age-dependent expansion and increase in density in the groove and at the medial aspect of the joint surface. See Figure 1 for remainder of key.

Figure 3—Caudal views of 3-D models depicting subchondral bone densities at joint surfaces of the distal aspect of the left humerus (summation image and the same dogs in Figure 1). In panel A, a wide zone of increased bone density can be observed in the olecranon fossa in the summation image; this zone decreases lateroproximally and medially toward the joint surface. In panels B through D, comparison of the individual joint surfaces of juvenile, adult, and geriatric dogs reveals an age-dependent increase in bone density in the olecranon fossa. See Figure 1 for remainder of key.
matching process, and summation images were generated. Due to improper image matching and patchy 3-D model rendering in 2 juvenile dogs that were < 5 months old, only 21 joints of 13 dogs could be matched.

Statistical analysis—Topographic distribution of maximal subchondral bone density was evaluated qualitatively. The grayscale values of individual bones were analyzed by use of a statistical analysis program. The assumption of normality for the distribution of variables was not rejected by use of the Anderson-Darling test. A 1-way ANOVA was used to compare mean values of the radius, humerus, and ulna within and among the 3 age groups. The test was performed via comparison of means within the groups, and a subsequent Bonferroni multiple comparison test was performed. The influence of age on bone density was evaluated via univariable linear regression of CT values for the joint surfaces of the 3 individual bones of 21 joints used in the summation image. Values of $P < 0.05$ were accepted as significant.

Results—Qualitative interpretation of subchondral bone density distribution at elbow joint surfaces of the humerus, ulna, and radius—In the cranial view of the summation image of the humerus, an area of increased bone density was noticeable in the groove between the medial and lateral coronoid processes; density increases medial and proximal to this region. In panels B through D, a substantial age-dependent increase in bone density in the medial coronoid process is revealed via comparison of the individual joint surfaces of juvenile, adult, and geriatric dogs. See Figure 1 for remainder of key.
lateral and medial aspects of the condyle, extending further in a distal to mediodistal direction. Lateral and medial to the groove, bone density decreased, apart from a small area on the lateroproximal aspect of the joint surface indicative of increased bone density (Figure 1). A zone of increased bone density was detected on the cranioproximal aspect of the joint surface in individual 3-D models of the humerus in juvenile dogs. This zone was displaced distally in adult dogs. In geriatric dogs, a region of maximum density was evident in the sagittal groove extending over the trochlea.

In the distal view of the summation image of the humerus (Figure 2), a narrow region of increased bone density was detected in the sagittal groove. Medially, a prominent density maximum was noticeable. Toward the lateral aspect, this density decreased but then increased to an area of greater density, before it decreased again near the lateral margin of the joint surface. In individual 3-D models of the humerus in juvenile, adult, and geriatric dogs, an age-dependent increase in bone density was noticeable in the sagittal groove and on the medial condyle.

In the caudal view of the summation image of the humerus, a wide zone of increased bone density was observed in the groove of the olecranon fossa, decreasing lateroproximally and laterally toward the joint margin (Figure 3). Comparison of individual 3-D models of juvenile, adult, and geriatric dogs revealed that this density increased with age. The density distribution revealed in color densitograms was highly similar among the examined joint surfaces of the individual humeri.

In the summation image of the ulna, an area of increased density was detected on the medial coronoid process (Figure 4). This density extended with a slight decrease toward the anconeal process. A zone of decreased density was wedged between the 2 coronoid processes, increasing medially and proximally. A region of apparently decreased density on the thin medial rim of the medial coronoid process was attributed to an articular artifact. The bone density maxima of individual 3-D models of juvenile, adult, and geriatric dogs had similar distribution patterns. Overall, the degree of density increased distinctly with age.

In the summation image of the radius, a bone density maximum was evident in the craniomedial region of the joint surface (Figure 5). This density decreased laterally and caudally toward the ulna. The distribution of bone density maxima in individual 3-D models had a similar pattern, and overall, the degree of density increased distinctly with age.

Quantitative analysis of subchondral bone density distribution at elbow joint surfaces of the humerus, ulna, and radius—Grayscale density values of subchondral bone were evaluated at the joint surfaces of the humerus, ulna, and radius (Figure 6; Table 1). Subchondral bone density of all 3 bones increased significantly (P < 0.001) with age (between juvenile and adult groups as well as between adult and geriatric groups). The slope of subchondral bone density versus time plots was significantly (P < 0.001) for all 3 bones different from 0 for the humerus, radius, and ulna.

A significant (P < 0.01) difference was also detected in paired comparisons of mean subchondral bone density of the radius and ulna among all 3 age groups and within the adult dog (P < 0.01) and geriatric dog (P < 0.006) groups. The radius had significantly (P < 0.01) decreased density, compared with that of the ulna, for these 2 groups. No significant (P = 0.18) difference was detected between juvenile and adult dogs. No significant (P < 0.001) difference was detected between juvenile and geriatric dogs.

Table 1—Mean ± SD grayscale CT values and results of linear regression analysis for subchondral bone density at joint surfaces of the humerus, ulna, and radius in 21 elbow joints of 13 healthy dogs.

<table>
<thead>
<tr>
<th>Joint surface</th>
<th>No. of points*</th>
<th>Juvenilea</th>
<th>Adultb</th>
<th>Geriatricc</th>
<th>Correlation (R²)</th>
<th>Slope</th>
</tr>
</thead>
<tbody>
<tr>
<td>Humerus</td>
<td>52,371</td>
<td>2,203 ± 3546</td>
<td>2,509 ± 7668</td>
<td>2,658 ± 12745a</td>
<td>0.7776</td>
<td>4.08811</td>
</tr>
<tr>
<td>Ulna</td>
<td>26,340</td>
<td>2,305 ± 2946</td>
<td>2,564 ± 4768</td>
<td>2,681 ± 9745b</td>
<td>0.8441</td>
<td>3.53127</td>
</tr>
<tr>
<td>Radius</td>
<td>9,285</td>
<td>2,209 ± 2568</td>
<td>2,427 ± 7645</td>
<td>2,578 ± 12945a</td>
<td>0.8096</td>
<td>4.04811</td>
</tr>
</tbody>
</table>

Bone density relative to a water-hydroxyapatite phantom was assessed by means of CTOAM. Grayscale CT values (range, 0 to 4,096) represent values of subchondral bone density.

*Mean number of points on individual joint surfaces at which subchondral bone density was measured.
†Values are significantly different from 0.
‡Values with different superscript letters are significantly (P < 0.001) different within rows.
detected for paired comparisons within the juvenile dog group. Mean density values of the humerus were not significantly different from those of the ulna or radius (Table 1).

Discussion

Subchondral bone density measurement via CTOAM allows in vivo imaging of mineralization patterns and calcium content of the subchondral bone layer. The method used in the present study permits a 3-D model rendering of bone from CT data and an undistorted representation of joints in their original form. Sagittal CT slices perpendicular to the joint surface with a 1- to 2-mm slice thickness were chosen to include the full thickness of the subchondral bone layer, as described in other studies and to fulfill the basic requirements of Mueller-Gerbl et al. Other studies have described the highly reproducible results obtained by use of this method. To reduce measurement inaccuracy within practical limits, a phantom of known density was included in each series of scans for calibration of individual CT images. The use of a phantom as a standardization method has been reported to improve reproducibility of CT numbers, and results obtained in the present study indicated that the inclusion of a reference phantom enhanced the precision of these values.

Distribution of subchondral bone density at the joint surface is influenced by several factors. The summary of momentary load distributions over time on a joint surface has been described as its loading history. The load within a joint is dependent on the size and position of contact areas as well as on the magnitude and penetration point of resulting joint forces. The CTOAM-determined density of subchondral bone could represent a self-optimizing structural adaptation of the bone under natural and physiologic conditions.

Computation of summation images allowed individual bones from several dogs to be matched onto randomly selected corresponding standard bones. The target elbow joint that was chosen subjectively appeared to represent the anatomical conformation of the majority of 3-D models of joints from dogs in the study. Of 42 elbow joints that were used in the study, 21 were used to produce the summation image; the individual joint surfaces of this image indicated a comparable distribution of the subchondral bone density in relation to the individual color densitograms. Densitograms of individual joints as well as summation images in the present study showed a distribution pattern similar to those described in other veterinary studies.

In the study reported here, linear regression analysis revealed a significant increase in mean subchondral bone densities of the elbow joint surfaces of dogs with increasing age. The subchondral bone density in dogs < 5 months of age had CT grayscale values in the region of 500 to 700 HUs, generating very patchy 3-D constructs and precluding their use in the summation images. However, in the individual juvenile dogs, areas of increased bone density corresponded to those detected in adult and geriatric dogs. The continuous loading of these areas characteristically increases subchondral bone density over extended periods; Mueller-Gerbl et al demonstrated that bone mineralization increases under continuous loading in human athletes as a result of qualitative and quantitative bone adaptation. In contrast, postoperative immobilization leads to decreased bone mineralization. Therefore, the results of CTOAM analysis indicate individual density patterns influenced by loading history in a joint. It would be interesting to study the changes in subchondral bone...

Figure 6—Scatterplots of the relationship between subchondral bone density grayscale values (range, 0 to 4,096) and age in 21 elbow joints of 13 healthy dogs of various ages and breeds. Density values were determined by means of CTOAM measurements obtained at joint surfaces of the humerus (panel A), ulna (B), and radius (C). Each circle represents the mean value of all measurements obtained for an individual joint. Equations for the regression lines were as follows: y (humerus) = 2,233 + (4.0881 X age); y (ulna) = 2,326 + (3.5312 X age); y (radius) = 2,164 + (4.0481 X age).

Figure 7—Distension stresses within the radioulnar joint (double-headed arrow). During weight bearing, distension forces (short arrows) are transmitted between the cranio-medial process of the radius (circle) and the anconeal process of the ulna.
density patterns for individual dogs with and without elbow joint abnormalities throughout their lifetimes. This might provide a better understanding of long-term adaptation within subchondral bone and development of peak load areas and stresses within the elbow joints of such dogs.

A study by other investigators indicated that bone density of concave joint surfaces was greater than that of convex surfaces. In regions where concave surfaces are shallower than convex surfaces, greater load can lead to increased tension in the center of the joint surface and generate unfavorable mechanical conditions. This appears to be a predisposing factor in the development of osteoarthritic changes. In our investigations, we detected areas of increased subchondral bone density at concave joint surfaces. The only exception was an area of increased bone density on the convex-shaped radioulnar joint surface of the medial humeral condyle. This is most likely due to cross-tension and shearing forces that prevail in this region of the humerus. This area corresponds to the location of osteochondrosis dissecans on the humeral condyle.

Subjectively, the density distribution in color densitograms of individual humeral and radioulnar joint surfaces barely differed, assuming a relatively even distribution of bone density between these 2 joint surfaces in all the individual joints. This was apparent within the 3 age groups and also for all dogs. The finding of increased bone density in the medial coronoid process of the ulna, in comparison with that of the craniomedial portion of the radius, suggests that the ulna is subjected to substantial peak loads within the elbow joint. This would contradict previous load models, which suggested that the radius is the predominant transmitter of load onto the distal part of the forelimb within the elbow joint.

Although the distribution of forces over a larger joint-surface area might also explain decreased density on the radial head in comparison with the ulna, results of the present study support those of Samii et al, which indicated that increased bone density is possibly caused by a physiologic incongruency. Increased forces (resulting in increased bone density) in the medial coronoid process might contribute to fractures or osteo- or chondromalacia in this region. We did not directly compare the 2 articulating joint surfaces with each other. It would be of interest to compare the bone density of the medial coronoid process with that of the radius or to compare contacting areas of the humerus with those of the radius or ulna. This would probably allow a more definitive comparison among age groups. However, it would also require that the contact areas within the elbow joint be defined; because the contacting elbow joint surfaces alter with load, it may be difficult to establish the actual contact area without artificially determining a biologically irrelevant surface area.

A partial volume artifact caused the appearance of an area of decreased density on the lateral aspect of the medial coronoid process in color densitograms of the ulna; this resulted from the 1.5-mm penetrating beam adding air measured behind the thin layer of bone into the density calculation. The density in this area was therefore suspected to be much greater than that depicted in the model.

The nearly bicentric density distribution on the ulnar joint surface (maximum density, mediodistal and proximal) could be attributable to the load occurring more frequently in these areas. The effects of extensor and flexor muscle activity during stance increase tension on the mediodistal and proximal areas of the ulnar joint surface. Contact measurements in the elbow joints of dogs suggest that these areas have first contact with the humeral condyle upon weight bearing. Transarticular force maps in another study indicated that the proximal articular surface of the ulna greatly contributes to load transfer through the elbow joint in dogs.

The combined data lead to the conclusion that the elbow joints of dogs as well as those of humans are physiologically incongruent joints. In the study reported here, an area of decreased bone density was detected in between 2 regions of increased density on the ulnar joint surface. Eckstein et al found that contact of the ulnar joint surface with the humeral joint surface was achieved only during high loads through the deformation of cartilage and subchondral bone. The finite-element analysis method could also prove that a primary incongruent joint becomes congruent under load. Decreased bone density in the area of the trochlear notch is necessary to allow for deformation in order to increase congruency of the humeral and ulnar joint surfaces during load bearing. A bicentric load distribution could be assigned to the entire radioulnar joint. A zone of increased bone density was detected on the radius extending from the craniomedial process to the ulna. With its craniomedial process, the radius represents an extension of the concave joint surface of the ulna. An increase in joint loading and the contraction of elbow joint musculature (especially the triceps brachii) causes the humerus to be forced down into the elliptic joint socket formed by the radius and ulna. During increasing loads, the ulna and radius form a functional unit in which distension forces run from the anconeal process to the craniomedial process of the radius (Figure 7). Furthermore, the secure connection formed between the radius and ulna by the annular radial and intersosseous antebrachial ligaments prevents the 2 bones from drifting apart. The short, yet strong, intersosseous antebrachial ligament is likely to play an especially important role in the distribution of forces from the ulna to the radius in the distal part of the antebrachium.

The deep socket of the radioulnar joint and its bicentric load bearing are thought to improve the distribution of load over the joint surfaces and to have beneficial effects on the metabolism, nutrition, and lubrication of joint cartilage. Finite-element model calculations have also revealed a more even load distribution in joints (eg, elbow or hip joint) in which the socket is situated more deeply, relative to the head (head of the humerus or femoral head). With increasing load, the contact areas shift from the joint margin toward the center and the load is more evenly distributed from peripheral regions. Dynamic studies of the elbow joints in various breeds of dogs would be necessary to confirm these findings.
The population of dogs in the present study varied in age, weight, sex, and breed. Further investigations should be performed that are restricted to individual dog breeds. Variations in weight, gait dynamics, and the presence of diseased joints in other limbs are certain to have an influence on the load within a joint. Controlling or accounting for these variables would result in a more complete study.

On the basis of results of the study reported here, we determined that subchondral bone density of the elbow joint surfaces in dogs significantly increased in an age-dependent manner. Areas of increased subchondral bone density were found to correspond to regions that are involved in common elbow joint diseases. The finding of bicentric bone density distribution on the ulnar joint surface supports the concept of physiologic incongruency in the elbow joints of dogs. Improved understanding of the biomechanical properties of the elbow joint may aid in the early recognition of joint disease in dogs and in the development of screening tests for affected breeds; this knowledge may possibly help to advance novel treatment modalities. The variations detected in subchondral bone density may provide characteristic patterns for osteoarthritis in elbow joints. The patterns of subchondral bone density may also provide an indication of the degree of cartilage degeneration.

References


