Calcified cartilage zone and its dimensional relationship to the articular cartilage in the human temporomandibular joint of elderly individuals

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The aim was to describe the appearance of the calcified cartilage zone (CCZ) and to determine its dimensional relationship to the articular cartilage thickness in the normal human temporomandibular joint. An autopsy material comprising 21 joints from 12 elderly individuals was examined microscopically. The appearance of the CCZ was examined, and the thickness of the CCZ and of the total articular cartilage was measured in 18 different positions in each joint. The CCZ was outlined by a flat or gently undulating tidemark and an irregular osteochondral junction. The cellularity of the CCZ varied extensively. The cells were numerous in the CCZ when the overlying articular cartilage displayed high cellularity. Statistical analysis of the measurements demonstrated a relationship ($p < 0.001$) between the thickness of the CCZ and of the articular cartilage. Our findings, both qualitative and quantitative, indicate a close relationship between the physiology of the CCZ and of the overlying articular cartilage. □ *Autopsy; cartilage, articular; microscopy; temporomandibular joint*

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Several studies have been reported on the articular cartilage of the temporomandibular joint (TMJ). Little attention has, however, been paid to the interface between bone and soft tissue—that is, the calcified cartilage zone. The calcified cartilage zone (CCZ) is defined as the calcified tissue between the articular soft tissue and the subchondral bone in synovial joints (1). The function of the CCZ is not clearly understood. Benninghof, in 1925 (2), suggested that it may make up an anchorage for the collagen fibers of the articular cartilage to the bone. Recent findings from human hip joints suggest that the dimension of the CCZ reflects the mechanical load supported (1). For the human TMJ the dimensions of the CCZ have not been studied. Only the thickness of the total articular soft tissue layers has been reported (3). It was claimed that in areas with thin layers of articular soft tissue the functional load is small. This suggestion has, however, not been confirmed. An analysis of the distribution of the CCZ might indirectly shed more light on the loading pattern in the human TMJ.

According to Johnson (4) and Radin et al. (5), degenerative changes in synovial joints might start at the bony interface—that is, the osteochondral junction and its surrounding tissues. The finding from magnetic resonance imaging of the knee joint (6) that trabecular lesion can occur as an isolated finding further supports this concept. The embryogenic origin of the human TMJ is, however, different from other synovial joints (7). According to Wright & Moffett (8), the osteogenesis of the temporal component in the area of articular contact with the condyle is quite special and resembles the metaplastic conversion of matrix to bone seen in the mineralization of tendons and sutural ligaments. They further stated that the condylar calcified cartilage is replenished by the proliferative layer during the first two decades of life, when the TMJ is growing. Thereafter, the calcified cartilage

is replaced by enchondral ossification and disappears gradually as internal remodeling occurs. Findings from the CCZ of other joints may therefore not be directly applicable to the TMJ.

In a previous study on human TMJs (9) erosive changes of the CCZ and the osteochondral junction were found beneath an apparently intact soft tissue layer in some joints similar to the findings of the hip joint (5). These findings indicate that degenerative changes might start at the bony interface below an intact covering soft tissue also in the TMJ and that the CCZ might play a significant role in the initial changes of the joint. We therefore considered an investigation of the CCZ in normal TMJs worthwhile, to elucidate the appearance of this tissue layer and its relationship to the articular cartilage.

Materials and methods

Material

Records of the medical history of the patients showed that two individuals had rheumatoid arthritis. Joints from these individuals were excluded from the material before examination. Further data on medical history and cause of death were limited. The examined material consisted of the right and left TMJ from 19 individuals who before death had donated their bodies to research. The specimens, removed as blocks, were examined macroscopically. Then the TMJ specimens were fixed in a 10% neutralized buffered formaldehyde solution. The specimens were demineralized in 0.5 M ethylenediaminetetraacetate (Na_2H_2-EDTA) for 16–20 weeks and then embedded in paraffin. Sagittal microtome sections, with the microtome set at 6 μm, were taken at every millimeter from the most lateral aspect of the joint to the most medial one. The histologic sections were stained with Mayer's hemalun–eosin solution (10).

Of the original 38 joints, 21 joints were selected on the basis of the macroscopic and microscopic examination. The inclusion criteria were that the joint should be normal and that the tissue preparation should be of high quality, making the tracing of the tissue layers possible. A joint was defined as normal in accordance with the following definitions, which are a modification of the criteria set by Byers et al. (11, 12).

Macroscopic appearance: A smooth outline of the articular cartilage, with no or mild changes such as localized superficial fraying or mild fibrillation.

Microscopic appearance: No changes or occasional superficial fraying. Clearly defined cartilage layers. No bony changes (Fig. 1A).

The 21 joints consisted of the bilateral joints of 9 individuals, 8 men (mean age, 70 years; range, 60–86) and 1 woman (age, 71 years) and of 3 unilateral joints from 2 men (ages, 80 and 86 years) and 1 woman (age, 88 years). From these joints the best sagittal section, based on technical quality, was selected from the lateral, central, and medial thirds of each joint.

The CCZ and the articular cartilage

The appearance of the CCZ and surrounding tissues—that is, the fibrocartilage and the subchondral bone—was studied with the aid of a light microscope (Nikon, Optiphot) at magnifications between ×4 and ×100. The division of the articular cartilage and the nomenclature of the different zones, which follows that used by de Bont et al. (13), are presented in Figs. 1A and 1B. Special attention was paid to the demarcation line between the CCZ and the fibrocartilaginous zone, *the tidemark*, and to the interface between the CCZ and the subchondral bone, *the osteochondral junction.* The distribution of cells, the presence of vessels, and duplicate tidemarks were noted.

Measurements of the dimensions of the CCZ and the articular cartilage

Each section was photographed in six selected areas, as shown in Fig. 1C (Nikon, Optiphot, Ektachrome film, 50 ASA, filter NCB 10) at ×25 magnification. By means of a video camera (Tomron, Fotovix) and an IBM-compatible computer with a frame grabber (Commodore PC-40, equipped with

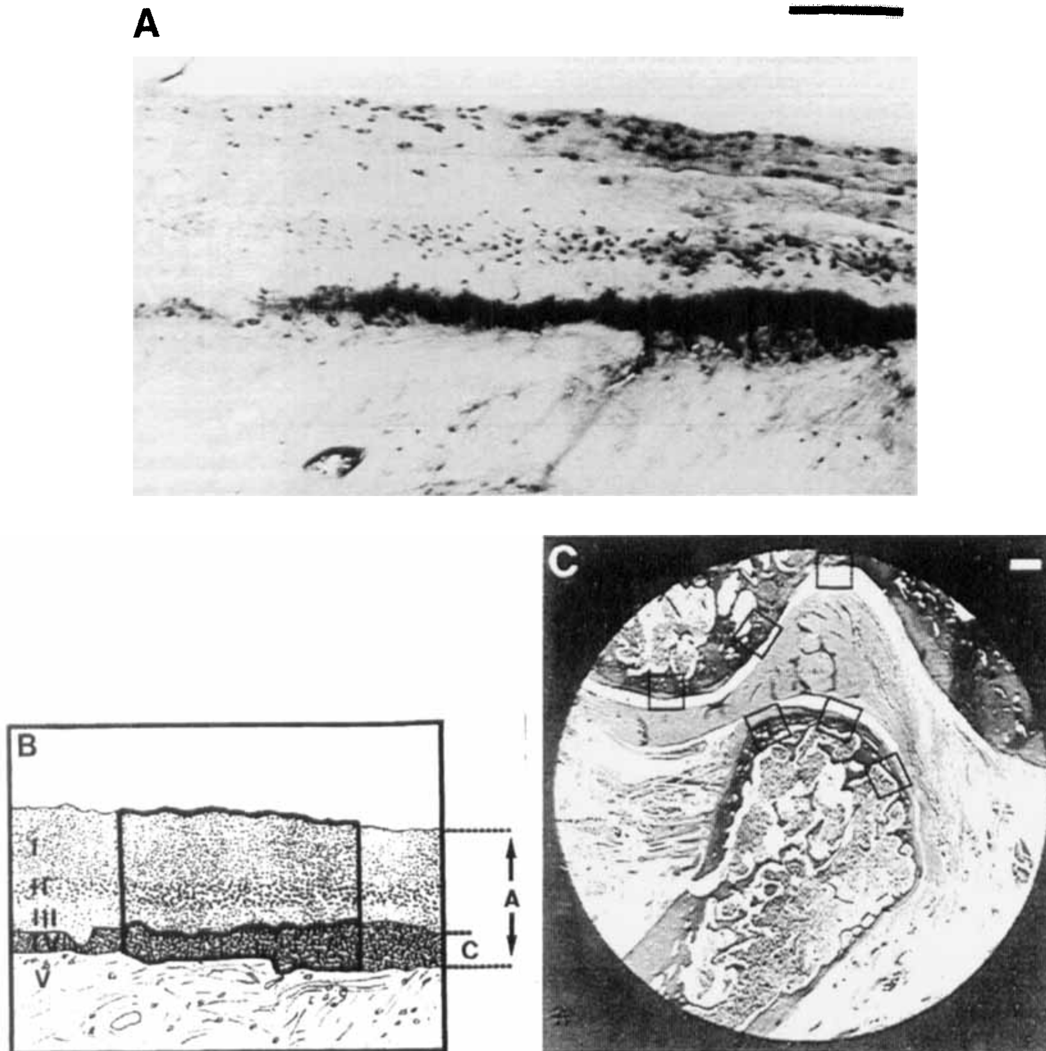

Fig. 1A. Photomicrograph of the articular cartilage and the subchondral bone tissue of a human normal mandibular condyle. Bar = 0.5 mm. 1B. Schematic representation of Fig. 1A, depicting the areas of the calcified cartilage zone (CCZ) and the total articular cartilage in a single section. The different zones are I = articular zone; II = proliferation zone; III = fibrocartilaginous zone; IV = CCZ; V = subchondral bone. The demarcation lines between the CCZ and the fibrocartilaginous zone (the tidemark) and between the CCZ and the subchondral bone (the osteochondral junction) are indicated. A = articular cartilage, and C = calcified cartilage. 1C. Photomicrograph of a human temporomandibular joint presenting the six areas used for the measurement of the CCZ and of the articular cartilage. Bar = 1 mm.

the Sigma-scan program, Jandel scientifics), the image of the color slide was digitized and presented on a computer screen. In each image the areas of the CCZ and of the articular cartilage were traced with a cursor and the anteroposterior dimension was recorded using a mouse and a graphic tablet (Fig. 1B). The tidemark closest to the articular surface was traced when duplicate tidemarks were present. From these tracings and measure-

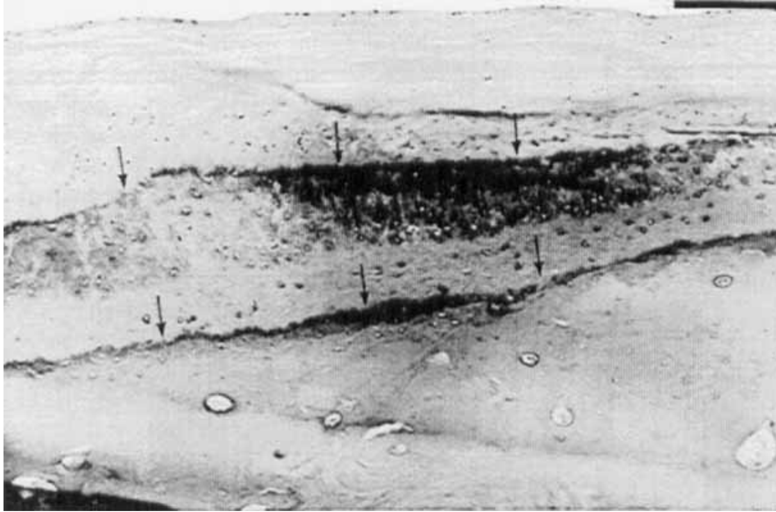

Fig. 2. Photomicrograph of the articular cartilage and the subchondral bone in a human mandibular condyle showing duplicate tidemarks (arrows). The adjacent subchondral bone displays small marrow spaces. Bar = 0.5 mm.

ments, the mean thickness of the two tissue layers was derived mathematically. The computations were made to the nearest 0.001 mm with the aid of the computer.

Analysis

The error of the measurement method was estimated from duplicate tracings of 2 areas in each of 18 sections, made with 1 months' interval. The 18 sections were randomly chosen from 3 joints. The estimate was computed by means of the formula

$$\sigma = \sqrt{(\Sigma d^2/(2n))}$$

where σ denotes the error, d the difference between the first and second measurements, and n the number of differences (duplicate observations). The error of the measurement method was 0.009 mm for the measurement of the CCZ—that is, 12% of the mean thickness of the CCZ—and 0.021 mm for the

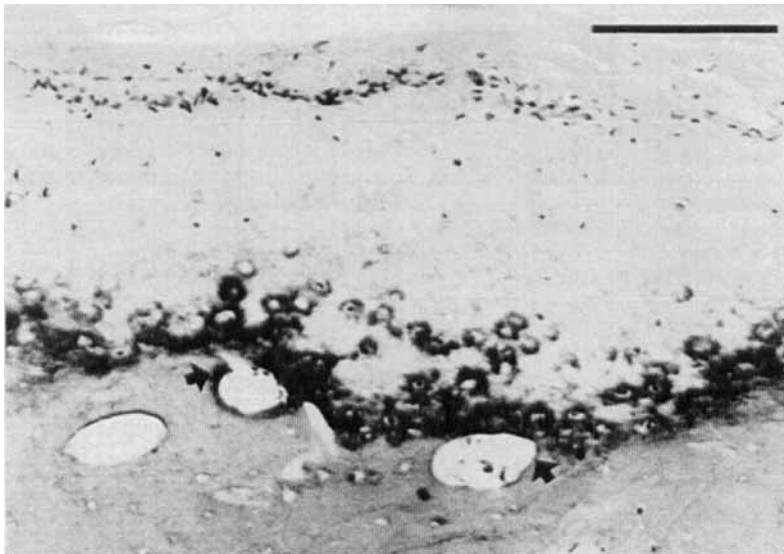

Fig. 3. Photomicrograph of the articular cartilage and the subchondral bone in a human normal mandibular condyle showing chondrocytes in the fibrocartilaginous zone surrounded by a heavily stained matrix. Small chondrocytes not filling the surrounding cavities are numerous. Empty lacunae can be seen in the subchondral bone. Two medullary cavities are in contact with the calcified cartilage zone (arrow). Bar = 0.5 mm.

measurement of the articular cartilage—that is, 5% of the mean thickness of the articular cartilage.

For each of the two tissue layers, CCZ and articular cartilage, the difference between left and right joints was tested by first forming, for each joint, the mean of the layer thickness in the 18 positions, and then comparing left versus right by means of a two-tailed sign test. Intraclass correlation coefficients were used for analyzing, for each position separately, whether the thickness of one of the layers was more similar in the left and right joints of the same person than in joints from different persons. To calculate a correlation coefficient between the thickness of the CCZ and that of the articular cartilage, not for one particular position but for all positions at the same time, and not for one particular joint but for all joints, we fitted, for each tissue layer separately, an additive two-factor model (factors: joint, position) to the data after taking logarithms of all thickness values. Then we computed the correlation coefficient between the residual CCZ log-thickness value and the residual articular cartilage log-thickness value. This can be thought of as a technique for computing a correlation coefficient in the whole data set, compensating both for variations between joints and for variations between positions. These computations were performed for those 16 joints that had the fewest missing values. The 7% missing values of these 16 joints were subjected to imputation in accordance with Healy & Westmacott (14).

Results

Appearance of the CCZ and the articular cartilage

The CCZ was clearly seen as a basophilic zone (Fig. 1A). This zone was generally outlined towards the cartilage by a marked basophilic line, the tidemark (Figs. 1A, B), which was flat or gently undulating. In 11 sections of 7 joints duplicated tidemarks (Fig. 2), and in 1 section triple tidemarks, were seen. The osteochondral junction (Figs. 1A, B) was irregular, with bone trabeculae extending into the CCZ. Minor horizontal splitting at the osteochondral junction was observed in 10 sections of 6 joints and at the tidemark in 3 sections of 3 joints.

Small chondrocytes lying in cavities of considerably larger size than the cells were common in the CCZ and in the fibrocartilaginous zone (Fig. 3). In some of the specimens empty lacunae were seen in the CCZ and in the surrounding tissue (Fig. 3). Thus, both in the fibrocartilaginous zone and in the superficial layers of the subchondral bone, even in areas with an otherwise normal appearance, empty lacunae were present. Sometimes chondrocytes were seen in cavities surrounded by a heavily stained calcified matrix in the deep layer of the fibrocartilaginous zone (Fig. 3). The cellularity of the CCZ varied extensively both between different joints and between different areas within the same joint. The cells were numerous in the CCZ when the overlying articular cartilage displayed high cellularity. No vessels could be observed in the CCZ. In a few specimens direct contact between medullary cavities and the CCZ could be seen (Fig. 3).

Dimensions of the CCZ and the articular cartilage

The mean thickness of the CCZ was 0.08 mm, with a range from 0.004 to 0.44 mm. There was no difference between the mean thickness of the CCZ of the right TMJs and that of the left TMJs. Table 1 presents the thickness of the CCZ in different areas of the lateral, central, and medial thirds of the joint. The CCZ was thickest in the inferior area and thinnest in the fossa in the lateral part of the temporal component. In the condyle, the thickest CCZ was found in the superior area in the central third, and the thinnest CCZ was found in the posterior area in the medial third of the TMJ.

The mean thickness of the articular cartilage was 0.40 mm, with a range from 0.04 to 1.02 mm. The mean thickness of the articular cartilage of the right TMJs did not differ from that of the left TMJs. As can be derived from Table 1, the thickest cartilage was

Table 1. Thickness of the calcified cartilage zone (CCZ) and of the articular cartilage in different parts of the condyle and the temporal component of normal human temporomandibular joints: number of sites measured (n) and mean ($\bar{x}$) and standard deviation (SD), expressed in millimeters

	Condyle									Temporal component								
	Anterior			Superior			Posterior			Inferior			Slope			Fossa		
	n	$\bar{x}$	SD	n	$\bar{x}$	SD	n	$\bar{x}$	SD	n	$\bar{x}$	SD	n	$\bar{x}$	SD	n	$\bar{x}$	SD
CCZ																		
Lateral	18	0.08	0.05	18	0.11	0.04	16	0.07	0.03	18	0.15	0.11	19	0.05	0.03	15	0.03	0.02
Central	18	0.10	0.06	20	0.10	0.07	19	0.06	0.02	20	0.12	0.07	20	0.05	0.02	19	0.03	0.03
Medial	13	0.07	0.03	10	0.09	0.02	13	0.05	0.01	15	0.11	0.08	14	0.06	0.03	13	0.04	0.02
Articular cartilage																		
Lateral	18	0.44	0.15	18	0.55	0.13	16	0.32	0.11	18	0.71	0.20	19	0.43	0.19	15	0.20	0.10
Central	18	0.40	0.12	20	0.46	0.12	19	0.25	0.06	20	0.65	0.19	20	0.38	0.14	18	0.14	0.10
Medial	13	0.33	0.10	10	0.34	0.09	13	0.23	0.09	15	0.60	0.14	14	0.36	0.16	13	0.17	0.08
Ratio articular cartilage/CCZ																		
Lateral		5.05			5.14			4.57			4.64			8.08			5.55	
Central		4.12			4.67			4.38			5.47			7.06			4.35	
Medial		5.11			3.54			4.90			5.36			5.56			3.90	

found in the same area as the thickest CCZ—that is, in the inferior area of the tubercle in the lateral third of the joint. The cartilage was also thick in the superior area in the lateral third of the condyle. The thinnest cartilage was found in the fossa in the central third and in the posterior area of the condyle in the medial third of the joint.

Table 1 presents the ratio between the thickness of the articular cartilage and the CCZ in different areas. The overall correlation coefficient between the CCZ thickness and the articular cartilage thickness, adjusted both for variations between joints and for variations between positions, was 0.52 ($p < 0.001$). In one area, the lateral third of the eminence, the correlation between the left and right joint within the same individual was significant for both the CCZ and the articular cartilage ($p < 0.005$). In two other areas there was a significant correlation between the left and right side for the CCZ only ($p < 0.05$) and in two other areas for the articular cartilage only ($p < 0.05$).

Discussion

It is difficult to establish a uniform definition of a normal joint. As we had limited information on previous medical history and status, it was not possible to exclude the possibility of clinical signs and symptoms from the TMJ. Thus, our definition of a normal joint does not include any clinical findings but is based on the macroscopic and the microscopic appearance of the joint. We consider this procedure to be appropriate for the aim of this study. It appeared also to be a selective procedure, as half of the original material was excluded. Although some changes, such as progressive remodeling, could be regarded as a physiologic process and constitute a common finding in joints free from pain or loss of function, we used the term normal in a sense that excluded joints exhibiting general remodeling from the material.

As undecalcified sections of the TMJ are difficult to prepare, decalcification of the specimens was preferred. The comparison of findings of the CCZ with those of other studies on the CCZ (15–21) was also facilitated, as a common method of choice of previous studies was decalcification together with hematoxylin–eosin staining.

The irregularity of the osteochondral junction resulted in the thickness of the CCZ showing considerable local variation. To

avoid the influence of this local variation, we preferred to use a measurement method by means of which the mean thickness was derived from an area rather than from a linear distance. The error of the measurement method was small and should not influence the results. The reason the error was small was probably that tissue sections of high quality were measured and that normal joints were studied. If the measurements of the tissue layers, the thin CCZ in particular, were to be made in joints with changes, the measurement error might be higher.

The theory that the function of the CCZ is to anchor the collagen fibrils in the cartilage to the subchondral bone (2) has been accepted for a long time. Such a mechanical concept cannot be based solely on the morphologic appearance, as collagen fibrils are anchored directly into the bone tissue in the periodontal membrane around the tooth. Thus, this tissue interface has a different morphology from the TMJ, as it lacks the CCZ. The embryogenic origin and the different function of the two tissue compartments may well explain their different structural appearances.

According to Wright et al. (8), the CCZ and the deep layers of the fibrocartilaginous zone in the human TMJ are inactive after the first 3 decades of life. In our opinion the CCZ might better be considered a biologically active zone, even in the adult TMJ, which responds to different stimuli with remodeling or degenerative changes. Previous findings reported in the literature also support such a concept (9, 22–24). On the basis of a regression analysis, Müller-Gerbl et al. (1) reported a strong correlation between the thickness of the CCZ and the articular cartilage in human hip joints. They suggested that the thickness of the CCZ is a function of the mechanical load. Our findings were based on a more detailed statistical analysis. We were able to demonstrate not only a correlation but also a physiologic relationship between the thickness of the CCZ and of the articular cartilage. Thus, when there was a positive deviation in thickness from what could be expected in the articular cartilage, in any area of any TMJ, the same applied to the CCZ of the same area, and vice versa. Moreover, our findings, both in the condyle and in the temporal component, indicated activity in the CCZ as part of a process also including the other structures of the joint. For instance, the cellularity of the CCZ reflected the cellularity of the overlying tissue layers. Thus, when the articular cartilage displayed high cellularity, this was also the case for the CCZ. The appearance of the chondrocytes, surrounded by a calcified matrix occasionally seen in the deep portion of the fibrocartilaginous zone, also gave the impression that the calcification of the CCZ originates from these cells as an ongoing process, in agreement with findings of Bullough & Jagannath (20). Furthermore, duplicate tidemarks were seen in areas with progressive remodeling of the bone tissue.

Minor horizontal splitting was found predominantly at the osteochondral junction and less frequently at the interface between the fibrocartilage and the CCZ, the tidemark. This finding may indicate that the area at the tidemark has a greater ability to withstand shearing stresses than the osteochondral junction. This is in agreement with the theories presented by Redler et al. (25). They suggested that the tidemark provides a tethering mechanism for the collagen fibrils of the deepest portion of the non-calcified articular cartilage and prevents the fibrils from being sheared at their point of anchorage to the calcified zone.

The presence of empty lacunae in the cortical bone and small chondrocytes with a shrunken appearance sometimes is regarded as a finding associated with degenerative joint disease (26). In our material these findings were present in joints without other pathologic signs, and it is reasonable to believe that this phenomenon mainly is due to excessive shrinkage of the chondrocytes and osteocytes during tissue preparation—that is, an artefact. In ultrastructural examination of fresh cartilage specimens this finding is non-existent (27).

Another finding of our study is that the thickness of the tissue layers was strongly correlated to that of the contralateral joint in only one area, the lateral part of the eminence. The tissue layers were also

thickest in this area. One explanation for the bilateral correlation might be that the thickness of the tissues in this area remains constant throughout life. The appearance of the tissue layers in this area did, however, indicate a high biologic activity as compared with the other areas. The thick tissue layers also indicated high loads, which would promote remodeling. The pattern of joint movements has to be further investigated before a conclusive explanation can be presented. In four other areas there were significant but weak correlations between the left and right side for either the CCZ or the articular cartilage. These areas seemed randomly distributed.

Direct contact between medullary cavities and the CCZ was found in only a few specimens. This is in contrast to the observations from studies on normal knee joints, where canal-like contacts up through the CCZ with contact between bone–medullary cavity and the hyaline cartilage were frequent (17). Nor was ingrowth of blood vessels into the CCZ found. Blood vessels growing close to the CCZ were, however, present in areas with erosion of the CCZ and subchondral bone examined in our previous study (9). Therefore, it might be suspected that the presence of blood vessels in the CCZ of human TMJ is a marker of an ongoing process such as in degenerative joint disease or remodeling. Such a theory has also been proposed by Moffett et al. (22) and more recently by Luder & Schroeder (28), who in an ultrastructural study on TMJs from *Macaca* monkeys found that vascular canals penetrating the osteochondral junction were related to chondroclast resorption and articular remodeling.

Further experimental studies of the TMJ including ultrastructural examinations of the CCZ and surrounding tissues might shed more light on the function of the CCZ in normal TMJs and in TMJs affected by joint diseases.

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