Original Article

Radiomorphological Manifestations of Femoral and Tibial Cortical Bones at Different Stages of Limb Lengthening

Abstract

Background: There has been a lot of research done on Ilizarov's limb lengthening; however, very few publications focus on the quantitative assessment of the distractional bone regeneration in tibial and femur lengthening. Data regarding quality of the bone after lengthening are needed to consider the time of frame removal and develop a rehabilitation program. **Materials and Methods:** Computed tomography (CT) assessment of a parent bone was performed on 136 patients with limb length discrepancy and bone deformity of various etiologies before and after lengthening. Transosseous osteosynthesis technique with the Ilizarov's external fixation was used for limb lengthening and deformity correction in all the cases. A 64-slice scanner was used for CT assessments. Specific Roentgen-negative units of the Ilizarov apparatus and techniques for interpreting CT findings were employed for artifact-free densitometric assessment. **Results:** Cortical density of the femur and tibia in patients with limb length discrepancy and bone deformity of various etiologies was shown to have differences as compared to the contralateral limb. The lengthening process was accompanied by decreased cortical density of the segment being lengthened, and the decrease in the density was greater in the areas adjacent to the distractional bone regeneration. The cortical structure underwent characteristic changes. Osteonal density of the cortical bone was higher in the norm and at long term followup as compared to the density of external and internal plates. **Conclusion:** Cortical bone of the femur and tibia in patients with limb length discrepancy and bone deformity of various etiologies showed various preoperative local densities of external, internal, and osteon layers. The cortical bone demonstrated heterogenic structures with resorption areas of various magnitude and density, with minimal values at the boundary with regenerate bone during distraction and fixation with frame on and at short-term followup. Complete organotypical restructuring of the bone was shown to occur at a 1-to-3-year followup depending on the etiology of the disease and amount of lengthening performed.

Keywords: *Corticotomy, femur, Ilizarov, limb lengthening, radiologic assessment, regenerate, tibia*

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Introduction

The distraction osteogenesis (DO) principle propounded by G. A. Ilizarov has many applications in limb lengthening and reconstruction procedures. This technique has been extensively used in limb lengthening in achondroplasia patients, treatment of infections in bone, and limb deformity correction. External fixation, especially ring fixation, is the most commonly used device for DO and has stood the test of time. Complications occurring during treatment are directly related to external fixation time. Hence, methods to decrease external fixation time are being invented. Quality of regenerate at corticomy site significantly influences the external fixation period. Assessment of the quality of regenerate at corticotomy site is advised to avoid complications such as refracture. Over the years, classical radiography was the only method for *in vivo* assessment of the parent bone and distractional bone regeneration and is the fundamental basis for screening and diagnostic examination.[1-3] Computed tomography (CT) has long been used to diagnose bone diseases and injuries; nevertheless, quantitative CT assessment of reparative processes in fracture repair and limb lengthening has a short history.[4,5] Application of CT, magnetic resonance imaging (MRI), and ultrasonography allowed for gaining new findings of bone structure in various pathologies and the reparation course.[6-9] Previous studies reported intense remodeling processes at the site of newly formed bone and the adjacent

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parts of the parent bone, with the density being changed at various stages of distractional bone regeneration during limb lengthening.[10,11] However, bone restructuring is not limited by changed bone density and manifested by a diversity of Roentgenmorphological changes detected by the current imaging modalities.[12,13] The present retrospective study aimed to evaluate Roentgenmorphological manifestations of the cortical bone of the femur and tibia in dynamics at various stages of limb lengthening and long term followup using CT.

Materials and Methods

The present retrospective study was conducted at Russian Ilizarov Scientific Centre for Restorative Traumatology and Orthopaedics, Kurgan, Russia. This center is an advanced tertiary-level hospital and attracts a large number of patients from all over the world for limb lengthening and reconstruction procedures. Inclusion criteria of the study were as follows: (a) patients undergoing DO at corticotomy site; (b) patients undergoing CT scan preoperatively, at the time of fixator removal or at subsequent followups; and (c) minimum followup of 1 year after frame removal. Exclusion criteria of the study were as follows: (a) pathological fractures; (b) presence of hormonal disorders or mental retardation; and (c) presence of any medical or skeletal illness affecting bone healing except for patients with Vitamin D-resistant rickets. All patients gave informed consent for inclusion into the study. A total of 136 patients (50 males and 86 females) met the inclusion criteria during the study period of 2006–2017. There were 39 achondroplasia cases, 24 patients with sequelae of hematogenous osteomyelitis, 28 with congenital limb shortening, 21 with posttraumatic limb shortening, 14 with Vitamin D-resistant rickets, and 10 with subjectively low height. The mean age in the groups of patients with achondroplasia, phosphate diabetes, and sequelae of hematogenous osteomyelitis was 11.3 ± 3.4 years and 25.7 ± 9.6 years in the remaining groups. Transosseous osteosynthesis technique with the Ilizarov external fixation was used for limb lengthening and deformity correction in all the cases. Polypositional radiographs were produced for all the patients preoperatively and at the stages of treatment [Figure 1]. A Light-Speed VCT-64 scanner (GE Healthcare, Chalfont St. Giles, UK) was used for CT assessments preoperatively, at the time of fixator removal or at subsequent followups of 6 or 12 months according to indications. The distribution of patients according to the nature of the pathology and the observation period during which CT was performed is shown in Table 1. Preoperative indications to CT included the necessity to determine bone density prior to the next limb lengthening stage with doubtful radiological findings, evidence of decrease/increase in local density at the site of preplanned osteotomy, in particular, or expressed impairment of architechtonics. Radiation exposure dose was recorded in every case of conventional radiology and CT. Specific Roentgen-negative rods were developed for the Ilizarov apparatus, and techniques for interpreting CT findings were employed for artifact-free densitometric assessment. The introduction of CT with high resolution into clinical practice facilitated the technique to be used for distractional bone regeneration assessment. Technical regulations for producing a topogram (plain digital radiograph) included the usage of Hip, Knee, Foot computer programs with a voltage of 120 kV, current strength of 50 mA, and length of 350 mm to be provided for the majority of studies.

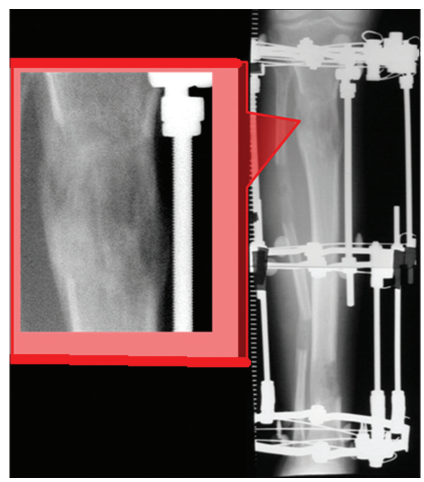

Figure 1: Anteroposterior radiograph shows tibial bones of a patient with subjectively low height after Ilizarov limb lengthening of 9 cm. Proximal regenerate bone appears increased

Table 1: Distribution of patients according to the nature of the pathology and the observation period during which computed tomography was performed

Study period	The number of patients examined					
	Achondroplasia	Subjectively low height	Posttraumatic limb shortening	Congenital limb shortening	Sequelae of hematogenous osteomyelitis	Vitamin D-resistant rickets
Preoperative	39	10	21	28	24	14
Distraction and consolidation period	4	4	-	5	-	5
At the time of fixator removal	9	4	10	12	13	14
6-7 months after fixator removal	15	-	4	5	6	2
1-2 years of followup	29	7	7	7	5	10
2-15 years of followup (long term followup)	10	-	-	4	-	4

Technical regulations for spiral CT scanning included the usage of Hip, Knee, Foot software with a voltage of 135 kV, current strength of 100–250 mA, slice collimation of 3.0–5.0 mm, pitch of 3.0–5.0, algorithm of bone standard, and high resolution. A plain digital radiograph (topogram) was the first step of the examination. Density of the femur and tibial cortices and the parent bone at the site of future osteotomy was measured using axial cuts and multiplanar reconstructions (MPRs) [Figure 2]. Total bone density and local cortical density were measured at the end of distraction (lengthening phase), during fixation with frame on, and after frame removal at subsequent followups. The standard procedures and protocols were followed during operation and postoperative period of treatment. The present study focuses on CT findings only. The research was approved by the hospital's ethics committee and was performed with informed consent from the patients to ensure patients' anonymity. The authors certify that the procedures followed were in accordance with the ethical standards of the responsible committee on human experimentation (institutional or regional) and with the Helsinki declaration of 1975, as revised in 2000.

Statistical data analysis

Statistical data analysis was performed using a personal computer and *AtteStat* computer program (I. P. Gaidyshev, 2001) in Microsoft Excel. The level of statistical significance quoted was $P < 0.05$ with P being an estimate of the probability. All the results were presented in the form of M ± σ, where M is sample mean and σ is standard deviation.[14]

Level of evidence

Level III study.

Results

Preoperative density of the cortical bone in the femoral and tibial shaft of achondroplasia patients at various age groups showed approximately equal values and measured 1267 ± 74.8 HU (M ± σ) [Figure 3]. Minimal cortical density in the involved limb of patients with sequelae of hematogenous osteomyelitis measured 923 ± 27.9 HU with statistically significant (P <0.05) differences in density values compared to those of intact limb. Maximal cortical density in the involved limb measured 1478 ± 163.5 HU in patients with posttraumatic limb shortening and deformity and 1288 ± 198.6 HU (M ± σ) in patients with congenital bone deformity. Cortical density of the parent bone was shown to decrease at an average of 340 ± 87 HU (according to MPR) at the end of distraction that can be explained by resorption. Axial CT cuts showed a distinctive heterogeneous pattern of cortical density with rarefaction areas of different shape and size [Figure 3].

Round rarefaction areas of 0.5 mm in diameter and density of 400–600 HU were observed at the center of the tibial tubercle. Patchy rarefaction measured 1 mm close to the external cortical contour. Rarefaction areas at the inner cortical contour were seen as a chain of rectangles measuring 2.5 mm × 1.0 mm. Bone density ranged from 1100 to 1150 HU outside the sites. The bone had heterogeneous structure at the site of regeneration and adjacent areas immediately following external fixator removal.

The findings showed the lowest cortical density immediately following external fixator removal in

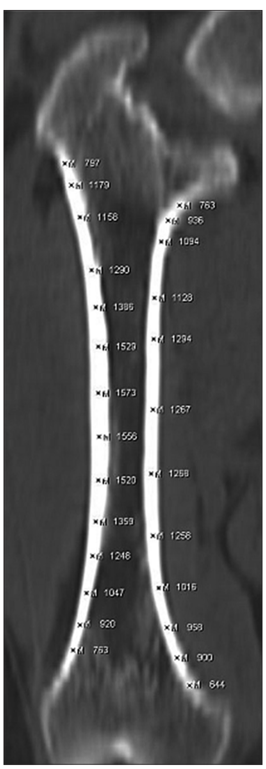

Figure 2: Preoperative computed tomography scan of the left femur in a 16-year-old achondroplasia patient. Multiplanar reconstructions, cortical density measurement

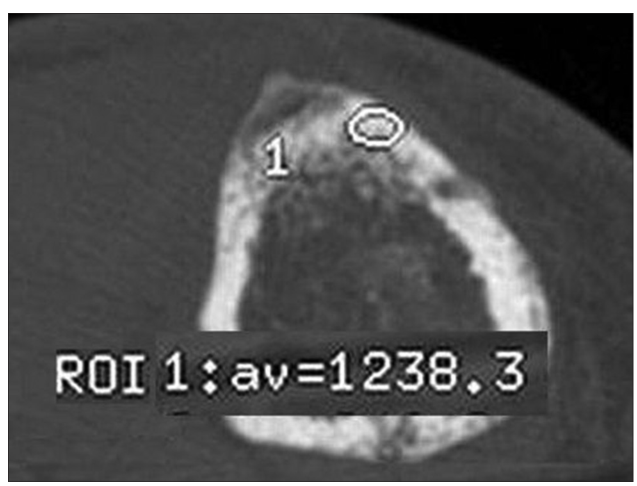

Figure 3: Computed tomography scan axial cut of tibiae in a 51-year-old patient with subjectively low height after tibial lengthening of 7 cm. Cortical bone density measurement

achondroplasia patients, patients with Vitamin D-resistant rickets, and those with congenital bone shortening and deformity that measured 798 ± 78, 802 ± 92, and 828 ± 30 HU, correspondingly. A low density level could be described to mineral resorption over the course of continuous treatment because an amount of lengthening in patients with achondroplasia and congenital bone shortening and deformity ranged from 5.89 ± 3.98 to 9.64 ± 1.43 cm (M ± σ) that required at least 7–9 months of treatment [Figure 4].

The density was shown to increase to 770–850 HU in 6–7 months of frame removal and up to 1100–1370 HU in a year [Figure 4]. Significant changes appeared to occur in the cortical bone distally and proximally of the distractional bone regeneration. Cortical density was shown to decrease to 527 ± 29 HU at the osteonal level (central part of the cortical bone) and to 345 ± 98 HU at the external cortical bone.

Increase in the cortical density at a long term followup was relatively proportional in different groups of patients with statistical significance in achondroplasia cases and posttraumatic limb shortening. No changes in the cortical density were detected in a group of patients with sequelae of hematogenous osteomyelitis.

Intramedullary canal was shown to completely remodel at 1-year followup in achondroplasia patients, with normal density regained in the cortical bone [Figure 5].

In addition to the measurements of overall cortical density, we measured a local density of the cortical bone using a bone window. The technique included density measurements on the HU scale using axial cuts and MPR with hardware-enhanced filter at three points located in the external, inner, and central parts of the cortical bone to allow assessments of the local density corresponding to the external, overall, and inner cortical bone and osteonal layer between them [Figure 6].

Measurements of the local cortical density at a long term followup of bone lengthening showed maximal values for the medium osteonal layer, whereas cortical density of external and inner parts was reduced by 300 to 500 HU [Figure 7].

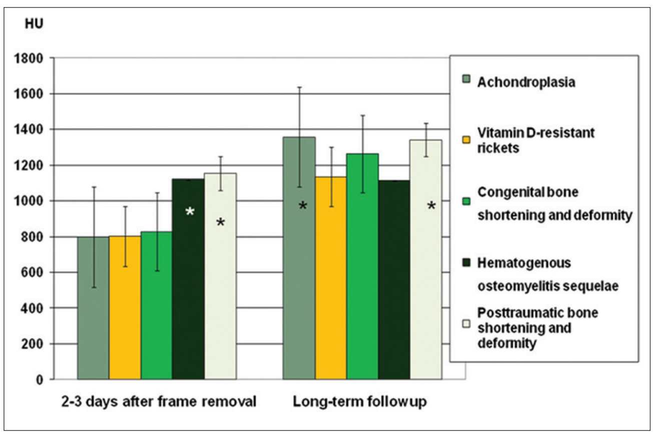

Figure 4: Tibial cortical bone density 2–3 days of external frame removal and at a 1-year followup of limb lengthening in patients with different pathologies

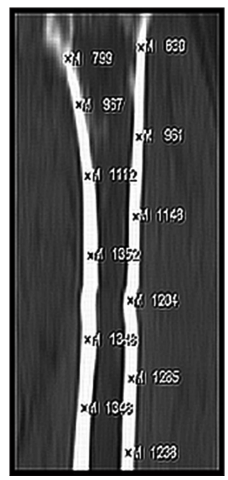

Figure 5: Computed tomography and multiplanar reconstruction of the distractional bone regeneration and adjacent portions of the parent bone at the upper- and middle-third of the femur 12 months after frame removal in a 13-year-old patient with achondroplasia. Complete organotypical restructuring occurred, with cortical bone density being similar to preoperative values

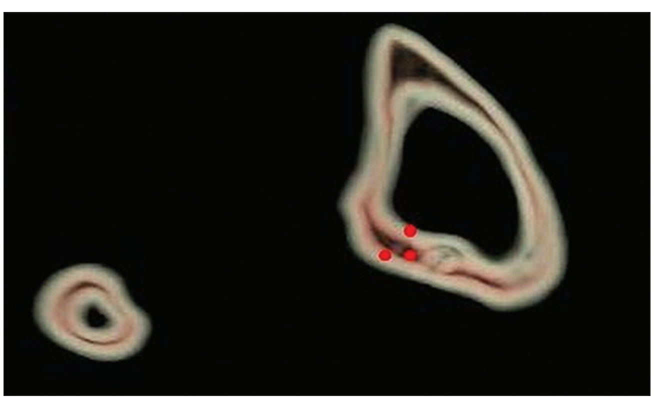

Figure 6: Computed tomography scan of tibia in a 15-year-old patient with achondroplasia at 18-month followup. Axial cut made at the boundary of the upper- and middle-third of the left tibia, three-dimensional reconstruction, employing workstation hardware-enhanced filter, scheme for measuring local cortical bone density

Figure 7: Computed tomography scan of tibiae in a 16-year-old patient at 18-month followup; axial cut of the right tibia and cortical bone fragment in bone window. Cortical bone density in the point located at the central zone (osteonal layer) (measurement № 66) measured 1548 HU

A specific workstation filter was employed for better visualization of the cortical bone zones, and a zone for measuring local density could be clearly seen [Figure 8]. Cortical density at the point located at the inner surface measured 1720 HU (Point 1), and cortical density at the point located at the external surface measured 1492 HU (Point 2). Similar measurements were obtained with MPR.

Measurements of the local cortical density in achondroplasia cases at a long term followup of bone lengthening showed osteonal increase of 324 ± 12 HU as compared to the external cortical bone and osteonal increase of 419 ± 87 HU as compared to the inner cortical bone [Figure 9].

Measurements of the tibial cortical bone density in the intact, completely supporting limb in patients with different unilateral conditions (straightforward fracture, injury to ligaments or knee meniscus, and Grade I deforming arthritis – control group) also revealed differences of 234 ± 42 HU in the local cortical density; however, the differences were less evident than those in patients with bone shortening and deformity [Figure 10].

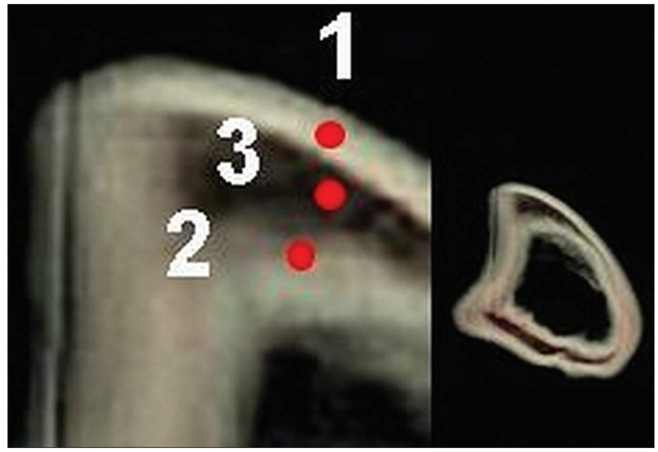

Figure 8: Computed tomography scan of tibiae in a 16-year-old patient at 18-month followup; axial cut of the right tibia and cortical bone fragment after the usage of hardware-enhanced filter. Points are marked to measure osteonal density (Point 3), inner cortical bone – system of inner bone plates (Point 2), external layer – system of external cortical bone (Point 1). HU = Hounsfield units

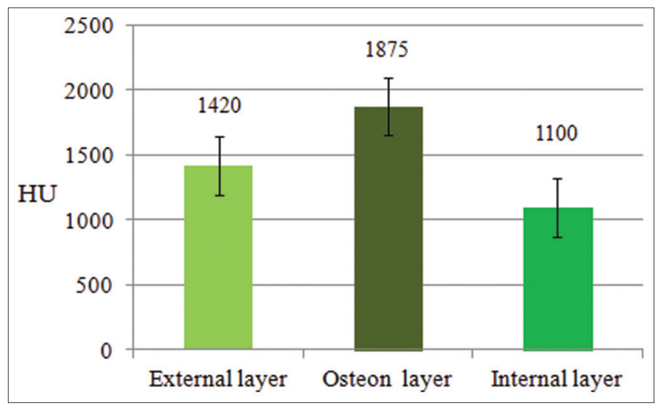

Figure 9: Density of external, osteonal, and inner layers of the tibial cortical bone in achondroplasia patients at a long term followup. HU=Hounsfield units

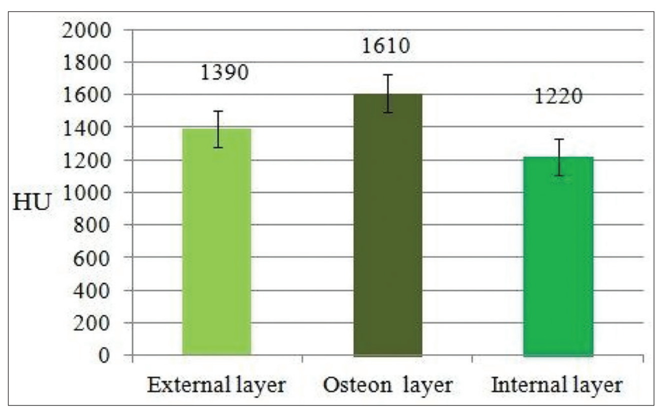

Figure 10: Density of external, osteonal, and inner layers of the tibial cortical bone of intact limb in patients with unilateral pathology bone fracture, HU = Hounsfield units

Discussion

DO is a commonly used technique for limb lengthening and other limb reconstruction procedures. The quality of regenerate directly affects the timing of removal of the fixation device. Premature removal of the fixator after a lengthening procedure can result in gradual bending or acute fracture of the regenerate.[15] Attempts are being made constantly to establish objective guidelines for early and safe removal of a fixator using a sensitive and quantitative measurement technique.[16] The present study reports CT scan findings in patients undergoing limb lengthening.

Several methods have been used to assess the regenerate's strength in DO including plain radiography, digital radiography, ultrasound, quantitative CT, dual-energy X-ray absorptiometry, and three-dimensional quantitative CT (3D-QCT). Plain radiographs are most commonly used to evaluate the degree of bone healing after an osteotomy. However, Anand *et al*. assessed intraobserver and interobserver reliability of plain radiography and reported its lower reliability across surgeons.[17] They concluded that the determination of the extent of bone healing by plain radiography was subjective.[17] Several authors have assessed the quality of regenerate using pixel value ratio (PVR) (ratio of pixel value of regenerate versus the mean pixel value of adjacent bone) on digital radiographs. Song *et al*. reported no fracture or wire breakage in patients who began fixator removal and full weight-bearing when the PVR was 1 in the three callus segments at the regenerate.[18] In a study by Zhao *et al*., partial weight-bearing with crutches was permitted when the PVR was 1 in two cortices and full weight-bearing without crutches was permitted when the PVR was 1 in three cortices.[19] The authors reported no subsequent fracture following the above criteria.[19] Hazra *et al*. compared the bone mineral density (BMD) ratio and PVR and observed a good correlation between BMD ratio and PVR, with a Pearson's coefficient of correlation of 0.79.[20] The authors reported PVR as a good method for assessing callus stiffness to judge the timing of fixator removal.[20] Song *et al*. reported that BMD measurement can provide an objective and noninvasive method for assessing the rate of new bone formation during DO.[16] BMD measurement can be an effective adjunct to measure callus stiffness, along with PVR, using digital radiographs, especially in cases where callus maturation and stiffness is doubtful.[16] In a study by Saran and Hamady, fixators were removed once the BMD had plateaued to a <10% increase and plain radiographs showed no obvious defects precluding fixator removal.[15] The authors reported a low rate (3.6%) of fractures using serial Dual-Energy X-ray Absorptiometry (DEXA) scans during the consolidation phase of lengthening while maintaining an acceptable bone healing index without excessively increasing the fixation time.[15] Fedorov *et al*. reported that CT helps followup all the periods of bone regenerate formation and maturation and permits the detection of deviations in this process, if any.[21] CT assessment permits analysis of the bone regenerate ossification time course that is important for the assessment of the distraction rate and of the time of removing the external fixation apparatus.[22] Swennen *et al*. compared 3D-QCT with the conventional QCT and reported that 3D-QCT-based bone densitometry could be valid for future DO research.[22]

Assessments of tibial and femur cortical density in patients with limb shortening and deformity of various etiologies showed different values compared to that of contralateral limb in the present study. It could be related to limited functional loading on the involved limb and Roentgenmorphological-specific bone structure in patients with sequelae of hematogenous osteomyelitis and posttraumatic and congenital limb shortening.[23,24] Limb lengthening was accompanied by decreased cortical density in the segment being lengthened, and greater decrease in the cortical density was observed at the site adjacent to the distractional bone regeneration. The decrease in cortical density by 250–300 HU should suggest preventive measures for fractures that are reported to occur at the site as a complication. The density of nonrestructured central portion of the regenerate bone was normally higher at the end of fixation and at a short-term of frame removal due to the presence of cancellous bone and the absence of intramedullary canal at the site.[6,10]

Our findings showed that cortical density measurements at the site of the whole cortical bone thickness were shown to be different from those at the median zone (osteonal layer), external parts (layer of external bone plates), and inner parts (system of inner general plates). Osteonal cortical density in the norm and at a long term followup showed increased measurement of 350 ± 80 HU as compared to the density of the external and inner cortical bones. Measuring cortical density at one point or at a smaller area might yield false-low or false-high results that would be followed by inconsistent recommendations on the timing of frame removal and functional loading. For this reason, we found it necessary to measure both general and local cortical bone density to get complete information on the quality of the cortical bone. Assessment of the bone quality should be made using advanced imaging modalities.[25]

CT may be useful for radiological deviations from reference values in case of delayed regeneration, areas of low density in the regenerate bone, disturbed formation of the cortical bone observed during treatment to allow correction of the distraction rate, and regenerate stimulation. Structure and the density of the cortical bone and of the whole regenerate bone could be identified better with CT in order to develop rehabilitation program (weight-bearing on the limb, exercise therapy) in case of doubtful radiological findings and the need to assess new bone layer after layer.

The present study is a retrospective analysis of CT scan in patients undergoing limb reconstruction with DO during the period of 2006–2017. The study focused on CT findings only and we were unable to comment on whether CT scan assessment influenced the time of fixator removal or not. However, our study reports characteristic changes at the distraction site over a period of time, and we believe that this study will be helpful for further research in this direction.

Conclusion

The findings showed that changes in the cortical bone density of different portions of the femur and tibia at various periods of treatment were dependent on the etiology of the disease and length of treatment. Cortical bone of the femur and tibia in patients with limb shortening and bone deformity of different etiologies was shown to have different local density of external, osteonal, and inner cortical layers. All groups of patients showed heterogeneous cortical bone structure with resorption areas of various size, shape, and density that was minimal at the boundary with regenerate bone during bone distraction and fixation with frame on and at a short term following removal of the Ilizarov apparatus. Cortical bone density showed differences across the width and at the extension. Minimal density measurements after frame removal were observed at the border to the regenerate bone, in the external and inner parts of the cortical bone.

Organotypical restructuring of the bone was complete within 1 year to 3 years. The algorithm of quality bone assessment should include improved CT and MRI techniques, with general and local density being incorporated into cortical bone density measurements. The usage of CT modalities for measuring local cortical bone density can further be rationalized by studying the mechanisms of bone resorption during bone lengthening and other conditions, preventing complications that can occur due to fractures and deformities of the bone adjacent to the regenerate.

Declaration of patient consent

The authors certify that they have obtained all appropriate patient consent forms. In the form, the patients have given their consent for their images and other clinical information to be reported in the journal. The patients understand that their names and initials will not be published and due efforts will be made to conceal their identity, but anonymity cannot be guaranteed.

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Nil.

Conflicts of interest

There are no conflicts of interest.

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