Radiosonographic Substantiation of Algorithms for Examination of Patients During Operative Lengthening of the Tibia

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Abstract
The muscles of 70 patients with lower limb shortening due to various etiologies were studied using three radiographic diagnostic methods: contrast radiography (CR), ultrasonography (US), and computed tomography (CT). The studies were performed before surgery, during lengthening using the Ilizarov external fixator, during the fixation period following distraction, and after apparatus removal. The data compiled using these modalities described alterations in the muscles during lengthening which enabled us to develop algorithms for patient examination during the process of lower extremity lengthening with the aim of solving tactical tasks.

Despite our 30-years of experience with limb lengthening we cannot yet say that we have all the answers in this complex and important orthopaedic issue. Several areas of ongoing research include the amount of one-stage bone lengthening, problems of soft tissues lengthening, as well as reserve abilities of joints, growth centers, and other limb parts.

The study of soft tissues in the limb began almost simultaneously with our research of bone tissue regeneration during lengthening. However, even today there are many unanswered questions regarding the state of muscles, vessels, and nerves during the process of lengthening, alongside the control of the dynamics of their morphological and functional parameters. Moreover, the problem of creating the most optimal conditions for soft tissue regeneration cannot be considered solved yet.1-6

In addition, the study of the muscles that play an important part in providing function during various periods of lengthening should be continued. Despite the fact that in the recent 10 years there have been many experimental and clinical studies on soft tissue conditions during lengthening, one cannot say that every component of the complex soft tissue systems has been completely investigated.7-14 Moreover, it is important to define the methods that can be used for evaluating anatomical and functional features of the muscles before treatment and during its treatment stages.15,16

In this study, we have attempted to use the diagnostic methods of contrast radiography (CR), ultrasonography (US), and computed tomography (CT) to describe features of the tibial musculature during lengthening in order to develop algorithms for the examination and determination of the reserve abilities of the muscles during and after treatment.

Materials and Methods
The muscles of the lower leg were studied before, during, and after leg lengthening in 38 patients with achondroplasia and in 32 patients with congenital leg length discrepancy. Modern methods of CT, US, and CR were used in the study to provide visualization of the subcutaneous fat, muscular, and para-articular tissues. Computed tomography scanning was performed using CT Somatom AR.HP (Siemens, Germany) with the commercially available “Extremity” program.

Muscular tissue density was measured in Hounsfield units. The area of the scans of the tibia in the upper, middle, and lower thirds, and the area of the musculus tibialis anterior in the middle third of the lower leg were measured by means of a cursor and a special CT program.

Ultrasoundography was done with Sonoline SL-450 (Siemens, Germany) and the echo chamber Aloka SSD-630 (CTD, Japan). The thickness of the muscles was measured by means of an available program.

A special angle-meter was used to define a deflection...
angle of muscular fascicles relative to the anatomical axis of the limb. Echodensity was evaluated in histograms. The histogram displays the number of pixels at each level of gray in the area traced with a trackball and displays the results on the scanner’s monitor. The histogram reflects the intensity of the echo area in the ultrasound tomographic image. All calculations are automatic.

Contrast radiography of the soft tissues was performed according to the technique developed at the Russian Ilizarov Scientific Centre for Restorative Traumatology and Orthopaedics: injection into a muscle or the subcutaneous fat of the water-soluble non-ionic contrast substance Omnipaque (Nicomed) or Ultravist (Scherering). The length and thickness of the muscle belly was measured in radiographs in 1 mm divisions. The data were placed into the table and statistically analyzed with the Student’s mathematical statistics criteria.

Results

Our comparative study showed that the muscles of the shortened lower leg have both age-dependent and etiologic peculiarities related to the amount of shortening, disease duration, and number and character of previous surgical procedures.

Congenital or Acquired Shortening

In the patients with congenital or acquired shortening of the tibia, atrophy of the muscle belly was noted and revealed as a reduction of its thickness (CR, US) and length (CR). Unclear differentiation into muscular fascicles and inter-fascicle spaces (US, CR) was also noted but was more greatly expressed in the patients having a shortened tibia accompanied by fibular aplasia. Ultrasound and CR revealed the alteration in the orientation angle of the muscular fascicles to the longitudinal axis of muscle (and bone). The reduction of the angle to 2° to 3° is associated with atrophy of the muscular fascicles, the thickness decrease of muscular fascicles, and their reorientation (Fig. 1).

In the uninvolved limb, the reduction of the angle of inclination and increase in echodensity also took place but to a lesser degree. An unclear image (CR, US) and hyper-echogenicity (US) were characteristic of the muscles of the shortened lower leg. An important feature that has significance for evaluation of the functional properties of muscle is its contractile ability; this can be determined with the aid of CR and US. However, the latter gives a more visualized and dynamic presentation and allows defining reorganization of the muscular structure by minimal preservation of its contractile ability. When compared, CR gives a complete presentation of the slipping function of the muscle belly and contractile reaction when the range of motion in the joint is not less than 45°. Both US and CR revealed disorders in the continuity of the muscular fascicles and their deformity in the patients with posttraumatic shortening. Ultrasound demonstrated areas of increased echodensity that were seen in the radiographs as clear areas that proved the thickening of connective tissue spaces and fibrosis (Fig. 2).

This fact was confirmed by previous experimental contrast radiographic and histologic studies. Tibial lengthening was accompanied by alterations in morphological and topographic parameters of the muscles in all patients; however, the grade of these changes was different and depended upon the amount of lengthening, initial status of the muscles (conditioned both by limb weight bearing or functional ability), as well as by the character and number of previous surgeries.

Ultrasound examination revealed more expressed changes in the extensor digitorum longus during lengthening of the congenitally shortened tibia, which was evident by a greater reduction in its thickness and increased echodensity (p < 0.05).

Both CR and US studies showed reduction in the thickness of the muscular fascicles, and their almost parallel positioning relative to the longitudinal axis of the tibia.

In the patients with fibular aplasia, the alterations during distraction were more evident and were characterized by considerable echodensity and atrophy. In the fixation period, the reduced thickness of the muscle belly and thinned muscular fascicles positioned longitudinally were preserved. Prolonged distraction resulted in the appearance of “opaque glass” in sonograms which by CR study appeared as enhanced contrast, so the muscle was presented as a continuous dark stripe (Fig. 3).

Anatomical features of the muscles seen by CR recovered faster after the removal of the apparatus, whereas structural alterations of the anterior group of the muscles visualized in US scans were maintained for a long time. Moreover, if the initial condition was severe they did not disappear even

Figure 1 Sonogram of the anterior group of the lower leg muscles of a 16-year-old patient P., congenital shortening of the right lower limb: Left, intact limb; Right, shortened limb.
Achondroplasia

Contrast radiography and US studies of the patients with achondroplasia showed age-dependent and typological peculiarities in the muscle structure of the lower leg. Children and adults had a characteristic increase in the thickness of the muscle belly of the musculus tibialis anterior and of the extensor digitorum longus, which had a statistically significant difference in the age groups of 8 to 10 and 15 to 17-year-old children (p < 0.01) (Table 1). The muscles had a heterogeneous structure with oblique and longitudinal lines of orientation. The angle of inclination of the muscular fascicles in the musculus tibialis anterior to the longitudinal axis of the tibia ranged from 10° to 15° to 25° in the distal areas that considerably exceeded the normal value. In children the angle value was less and measured 4° to 6°.

Contractile features of the muscles are markedly expressed; by static tensioning, the belly thickness increased more and was accompanied by a decrease in echodensity. The sonograms of 8- to 10-year-old children demonstrated thickening of the myoseptum and muscular fascicles. In adult patients the well-differentiated muscular fascicles notably change their direction under tension and also demonstrated thickening (Fig. 4).

Along with peculiar features in the structure of the tibial muscles in the patients with achondroplasia revealed by US examination, there were considerable anatomical differences that were well visualized with contrast radiography, as it was possible to determine the length of the muscle belly, its thickness, and some structural features. We found that the length of the muscle belly of the musculus tibialis muscle and extensor digitorum longus in adults was 75% to 89% of the length of the tibia whereas the normal length should not exceed 55% to 60%. In children, the relative size of the muscle belly was less and measured 50% to 60%. When the longitudinal growth of the bone stops but the muscles continue to grow, this percentage relationship changes to reflect the muscle belly increase.

The use of CT scanning of the soft tissues resulted in new findings in the anatomical and topographic features of the muscles and subcutaneous fat layer. Considerable age-dependent manifestations were found reflecting the findings of US and CR. The ability of the muscles to increase their length while the bone growth retards and then stops demonstrates that there is some advantage in performing limb lengthening in achondroplastic children.

The transverse scans of the lower leg in children had a smaller area than in adults and also demonstrated a smaller thickness of the subcutaneous fat. Both children and adults

Figure 2 Sonogram of the anterior group of the lower leg muscles in a 37-year-old patient P before treatment. Posttraumatic shortening of the right lower limb. A, intact limb; B, shortened limb; in each sonogram the left side is at rest and the right is under stress.

Figure 3 Sonogram of the anterior group of the lower leg muscles. Congenital consolidated pseudoarthrosis of the right tibia and a 20-cm shortening in a 26-year-old patient S: on the left is structure of the musculus tibialis anterior and the extensor digitorum longus after 3 month of distraction; the right shows the intact lower leg.
showed a more asymmetrical positioning of the muscles of the posterior group, especially at the expense of the muscleus gastrocnemius, than is evident in normal subjects, (Fig. 5).

The areas of the scans in the upper, middle, and lower portions differed considerably, as well as did the thickness of the subcutaneous fat and the area of the muscleus gastrocnemius and muscleus tibialis anterior (Fig. 6).

The muscles of achondroplastic patients were swollen at the beginning of distraction, lost their clear contours, and the muscle fibers did not have a marked orientation. All these alterations were well visualized during US examination. After 4 to 5 weeks of distraction, the contrast radiographs showed enhanced contrast (fibrosis), the muscular fascicles were positioned longitudinally, and the muscle belly was atrophic. Ultrasound study revealed parallel positioning of the muscular fascicles relative to the longitudinal muscle axis, an unclear image of the myoseptum, absence of contractile reaction, a 20% to 30% echodensity enhancement from the initial value, and decrease in the muscle thickness (p < 0.05).

In the patients of an older age group, similar changes took place. Once the fixator was removed, the structure of the anterior group of muscles recovered more slowly than in the femur. This finding is associated with the anatomical features of the muscles as well as with a relatively larger amount of tibial lengthening.

Findings on CT showed that once lengthening was completed, the thickness of the subcutaneous fat decreased considerably, the scan area and transverse section surface of the muscles reduced, and connective tissue formations in the subcutaneous fat could be visualized more clearly.

Certain alterations occur in the intact segment, but they are considerably less significant than in the lengthened portion. Even if only tibias are undergo lengthening, there is a reduction of the scan area in the femur and a considerable decrease in the thickness of the subcutaneous fat.

When all the segments of the lower limbs are lengthened, the changes are maintained for a long period of time. Even at a long-term follow up (7 to 10 years) the geometrical sizes of scans, muscle area, and thickness of the subcutaneous fat, do not return to the initial values. However, the mentioned parameters approximate the normal values that are characteristic in healthy subjects.

**Discussion**

The alterations in the muscles during lengthening studied by us with US and CR correlate well with the theory of double staged neuromyogenesis under the conditions of distraction osteosynthesis that was proposed by Shein.17

The swelling, reorientation of the muscular fibers, atrophy, and thickening of the connective tissue spaces that appear during distraction, clearly demonstrated with US examination during the first 2 to 4 weeks of distraction, lead to the disorders of the contractile reaction and

**Table 1** Thickness (cm) of the Anterior Group of the Tibial Muscles in Patients with Achondroplasia Before Treatment, Ultrasound Findings

<table>
<thead>
<tr>
<th>Examined muscle</th>
<th>Age (years)</th>
<th>6-7</th>
<th>8-10</th>
<th>11-15</th>
<th>16-18</th>
</tr>
</thead>
<tbody>
<tr>
<td>m. tibialis anterior</td>
<td></td>
<td>0.69</td>
<td>0.76</td>
<td>0.78</td>
<td>0.81</td>
</tr>
<tr>
<td>m. digitorum longus</td>
<td></td>
<td>0.79</td>
<td>0.88</td>
<td>0.99</td>
<td>1.07</td>
</tr>
</tbody>
</table>

**Figure 4** Sonogram of the anterior group of the lower leg muscles in a 10-year-old patient A., with achondroplasia. Before treatment: left, at rest; right, under tension.

**Figure 5** CT scan of the left un-lengthened lower leg in its upper third in a 17-year-old patient M. Achondroplasia: two years after lengthening of the left femur and right tibia.
alteration of the features of the muscles (alteration stage). The enumerated anatomical changes are well visualized with CR at 4 to 6 weeks of distraction and after its completion. After removal of the fixator, the structure, anatomy, and function of the muscles return slowly, but the rate of these processes differs and depends upon the initial state of the muscle, amount of shortening, and lengthening performed.

Nevertheless, there is a correlation with the theory of the “adaptation” stage during which the reserve is formed for gaining muscular length and elasticity providing restoration of the required range of motion in the adjacent joints. Prevalence of the reparative process which is expressed in normalization of muscle structure, decrease of atrophy, and partial or complete recovery of contractile features can be visualized in sonograms, contrast radiographs, and computed tomography.

All these studies enabled us to determine basic algorithms for muscle examination in the patients with various pathologies and during different periods of treatment (Table 2).

## Table 2  Algorithms for Muscle Examination in the Patients with Shortened Tibia During Different Lengthening Periods Treated with the Ilizarov Techniques

<table>
<thead>
<tr>
<th>Method of Study</th>
<th>Before surgery</th>
<th>Distraction period</th>
<th>Fixation period</th>
<th>After removal of the fixator</th>
</tr>
</thead>
<tbody>
<tr>
<td>US</td>
<td>All patients</td>
<td>3–4 procedures depending on the amount of lengthening</td>
<td>2–3 procedures</td>
<td>2-3 procedures depending upon the range of motion in the joints and muscle condition</td>
</tr>
<tr>
<td>CR</td>
<td>Expressed atrophy, scars and adhesions in achondroplastic patients with deformities, when CT is not possible</td>
<td>In the second half of the distraction period if pain persists or contractures in the knee and ankle joints develop</td>
<td>When indicated (slow recovery of the function, considerable muscle atrophy)</td>
<td>As above, plus if the second stage of treatment is required</td>
</tr>
<tr>
<td>CT</td>
<td>Considerable atrophy, topographic alterations, deformities, gross volume of soft tissues</td>
<td></td>
<td></td>
<td>If the second treatment stage is required, deformities, atrophy</td>
</tr>
</tbody>
</table>

### Conclusion

This research demonstrates that diagnostic methods (US, CR and CT) used for the examination of muscle status enable orthopaedic surgeons to obtain accurate and objective assessments of the anatomical and functional features of the muscles. This evaluation can provide an accurate assessment of the reserve potential of the soft tissues in order to aid in making alterations in the treatment plan for limb lengthening.

### References

3. Ilizarov GA, Shchurov VA: Effect of stretching tension on the


