THE FIRST EXPERIENCE OF USING CUSTOMIZED FIXATORS IN THE SURGICAL TREATMENT OF ABDUCTO-PLANO-VALGUS FOOT DEFORMITY IN CHILDREN

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Background. Abducto-plano-valgus foot deformity is one of the most common diseases affecting children and teens. Recently, various methods of surgical treatment have been proposed for the same. However, despite the availability of various operational methods, there are several contradictions in the feasibility and success of a particular operation.

Aim. To improve the technique of Evans Calcaneal osteotomy through the use of customized heel bone fixators.

Materials and methods. A total of 30 patients (42 feet) aged 9–15 years with abducto-plano-valgus foot deformity were included. We undertook clinical examination, X-ray, computed tomography, and experimental researches. The surgical treatment consisted of Evans Calcaneal osteotomy, with the use of the standard method of fixation in group 1 (n = 33 feet) and the use of a customized fixator in group 2 (n = 9 feet).

Results. The improved technique of Evans Calcaneal osteotomy using a special customized fixator allowed making the necessary correction in 100% of cases. The period of restoration of the heel bone integrity was reduced by an average of 30% (p < 0.05). The period of restoration of the support became faster by almost 45% (p < 0.05).

Conclusion. The use of a special customized fixator for Evans Calcaneal osteotomy could significantly improve the outcomes and shorten the treatment time for children with abducto-plano-valgus foot deformity.

Keywords: flatfoot deformity; abducto-plano-valgus foot deformity; Evans Calcaneal osteotomy; bone grafts; osteosynthesis; fixation.
Материалы и методы. Представлено лечение 30 пациентов (42 стопы) в возрасте от 9 до 15 лет с абдукто-плано-вальгусной деформацией стоп. В работе использованы клинический, рентгенологический, компьютернотомографический, экспериментальный методы исследования. Хирургическое лечение заключалось в проведении остеотомии пяточной кости по Эвансу. В одной группе (n = 33) остеосинтез выполняли стандартным способом, в другой (n = 9) — с помощью кастомизированного фиксатора.

Результаты. Благодаря усовершенствованной методике остеотомии пяточной кости по Эвансу с применением специального кастомизированного фиксатора удалось осуществить необходимую коррекцию в 100 % случаев. Срок восстановления целостности пяточной кости сократился в среднем на 30 % (p < 0,05). Период восстановления опоры уменьшился практически на 45 % (p < 0,05).

Заключение. Использование специального кастомизированного фиксатора при выполнении остеотомии пяточной кости по Эвансу позволяет улучшить результаты и сократить сроки лечения детей с абдукто-плано-вальгусной деформацией стоп.

Ключевые слова: стопа; плоскостопие; абдукто-плано-вальгусная деформация; остеотомия пяточной кости по Эвансу; костные трансплантаты; остеосинтез; фиксация.

Abducto-planovalgus foot deformity is a very common orthopedic pathology among pediatric patients. Several surgical interventions for this pathology have seen notable improvements in the recent decades [1–3]. Although several surgical approaches exist, indications for those and their success rates are inconsistent [4–6].

One of the recognized surgical methods for the treatment of this foot deformity is the Evans procedure. This intervention enables eliminating the displacement of the talus and lengthening the lateral edge of the foot to correct the external deviation of the forefoot.

Evans had first performed a modification of the calcaneus osteotomy procedure in a patient with poliomyelitis with abducto-planovalgus foot deformity in 1961 and later published the details of his technique in 1975 [7]. The focus of this surgery was to lengthen the lateral column of the foot. To achieve this, the author had performed an osteotomy of the anterior end of the calcaneus in a plane parallel to the calcaneocubital joint and 1.5 cm behind it. In the osteotomy area, after the separation of the calcaneal bone fragments, several autografts from the fibular bone were placed as spacers. However, the author noted several overcorrections postoperatively.

Subsequently, the Evans procedure was modified by several authors [8–11]. The modifications concerned both the direction of the osteotomy plane and the use of auto- or allografts (shape and quantity) [12–14].

The Mosk modification [15] of the Evans procedure is often used in modern surgical practice for correcting mobile equino-planovalgus foot deformity in pediatric patients with cerebral palsy. This modification replaces the originally perpendicular plane of the calcaneus osteotomy, passing 1.5 cm from the line of the calcaneocubital joint, with an oblique plane (from the proximal-lateral to the distal-medial direction), and uses a wedging trapezoidal autograft instead of a mixture of several bone autografts, with the autograft in the osteotomy area fixed with several Kirschner wires.

Although several modifications exist to the Evans procedure, the procedure outlined below is typical to such surgery.

A layer-by-layer approach to the calcaneus body along the outer surface of the foot is used. The peroneus brevis tendon is lengthened in a Z-shaped manner. A transverse osteotomy of the calcaneus between the medial and anterior articular facets of the calcaneus, parallel to the calcaneocubital joint and retreating from it posteriorly by 1.5 cm, is performed using an oscillatory saw. An expander is installed in the osteotomy area, using which the fragments of the calcaneus are moved apart to form a wedge-shaped diastasis, with the base outward. The bone defect is filled with a graft, and the bone fragments are fixed (usually with wires or screws). The wound is then sutured in layers.

Of note, fixation of bone fragments in the above-described manner is unreliable. The bone fragments may be displaced, which may cause loss of correction; furthermore, prolonged use of a plaster cast (at least 3 months) and avoiding load-bearing on the leg are necessitated. Moreover, the use of autologous bone to fill in the bone defect can cause noticeable additional injury in pediatric patients, which limits the volume of bone that can be collected. As such, selecting the precise autograft size is challenging; an insufficiently sized autograft...
can lead to insufficient correction of the calcaneus valgus, whereas an oversized autograft can lead to overtensioning of the plantar aponeurosis and overcorrection of calcaneal valgus. Furthermore, the donor bone can cause allergic reactions and can be rejected, which would increase the risk of pyoinflammatory complications. In addition, complications such as graft fracture often develop intraoperatively and postoperatively, and consolidation is often impaired (alloplasty with wedges requires a long time to reconstruct, and chips do not have sufficient mechanical strength). These challenges prolong the recovery period and complicate the treatment process.

This study aimed to improve the Evans calcaneal osteotomy procedure with the use of customized heel bone fixators.

Materials and methods

We included 30 patients (42 feet; aged 9–15 years) with abducto-plano-valgus foot deformity who underwent surgical correction between 2017 and 2019 at the Center for Pediatric Orthopedics of the Priorov National Medical Research Center of Traumatology and Orthopedics. The patient population included 6 girls (20%) and 24 boys (80%). The patients were followed up from 6 months to 3 years postoperatively. The average age at the time of surgery was 12.75 ± 0.47 years. Surgical treatment consisted of a lateral lengthening osteotomy of the heel bone. In 33 cases, surgery was based on the Evans procedure, with wire fixation, and in 9 cases, a customized structure for osteosynthesis of the heel bone was used.

Inclusion criteria. We included patients aged >8 years, with grade II abducto-plano-valgus foot deformity with the following radiometric parameters: a longitudinal arch angle of 135°–160°, >5° increase in the talo-metatarsal angle (distortion of the Shade line), <15° decrease in the angle of inclination of the calcaneus, a talocalcaneal divergence angle of 40°–50° on the lateral view and >40° on the frontal view, calcaneus valgus of >10° with abduction, abduction of the anterior segment (the angle between the lateral process of the calcaneus and the metatarsal bone V <5°, and history of surgery.

Patient evaluation included clinical examination (assessment of complaints, obtaining medical history), X-ray examination, computed tomography, and experimental studies (mechanical and strength).

Clinical examination

All patients complained of gait abnormality, rapid fatigability, and pain during prolonged physical exertion. Examination revealed a decrease in or absence of the longitudinal arch with a convexity of the plantar surface in the middle section, retraction along the external-dorsal surface of the foot, heel valgus (>10°), transverse hypermobility in the middle section of the foot, and abduction of the anterior section (the “spying toes” symptom).

X-ray examination

X-ray examination was performed for all patients before treatment, immediately after surgery (day 1), and at 3, 4, 6, 9, 12, 18, 24, and 36 months after surgery. The feet were radiographed, with the patient standing (feet under load), in frontal, lateral, and Saltzman views. The angle of the longitudinal arch, the calcaneal inclination angle, the talocalcaneal divergence angle in the frontal view, the talo-metatarsal angle (Shade line deformity), the angle between the calcaneal lateral process and the metatarsal bone V, and the angle of the heel bone valgus were the most significant parameters in assessing anatomic changes in the foot.

Computed tomography

Computed tomography was performed for every patient for a detailed assessment of pathologic changes and deformities in the bones of the foot and the ankle joint, the relationship between joint structures in several planes, the detection of dislocation of the talus bone, and ruling out tarsal coalitions [16, 17].

In addition, in 9 pediatric patients, correction was planned preoperatively, with the size of the individual fixator determined using multilayer spiral computed tomography. First, we evaluated the bones of the foot and the various angles characterizing the deformity. Then, we simulated the restoration of the correct proportions in the joints of the foot by eliminating the deformity, and the required angle of correction was calculated. The angle of correction
was used to determine the diastasis between the heel bone fragments, and the customized fixator was prepared to the exact dimensions. The customized heel bone fixator is an H-shaped reconstructive titanium plate (VT-6 alloy) developed by us, with the design patented in Russia [18]. After simulation and preparation of patient-specific designs, the fixator was 3D-printed. Using a customized fixator during surgery ensured necessary correction.

Experimental research

Three series of mechanical and strength tests of the reliability of osteosynthesis of the native calcaneal bone using an H-shaped customized plate were performed on a universal testing machine LFM-50kN (Fig. 1).

We studied the reliability of fixation in the plate-bone system during compression and cantilevered bending, which is of high importance for stable osteosynthesis and retention of correction. Under compression, the fixed fragments remained stable under an average load of 0.619 ± 0.384 kN (F<sub>max</sub> = 0.738 kN). An average force of 0.188 ± 0.162 kN was needed to induce transverse shear. The data obtained indicate that osteosynthesis of the heel bone with an H-shaped reconstructive plate can withstand a load of approximately 60–70 kg, which is a remarkable result in pediatric practice. Further addition of external immobilization would completely avoid postoperative deformities and loss of correction.

Statistical analyses were performed using Microsoft Excel 2019. The continuous variables were presented as means and standard deviations. The paired Student t test was used to assess significance. The results were considered statistically significant at p < 0.05.

Indications for surgical treatment

Indications for Evans calcaneus osteotomy were grade II static abducto-plano-valgus foot deformity in children aged >8 years with the following radiometric parameters: the angle of the longitudinal arch of 135°–160°, a >5° increase in the talo-metatarsal angle (distortion of the Shade line), a decrease in the calcaneus inclination angle of <15°, a talocalcaneal divergence angle of 40°–50° in the lateral view and >40° in the frontal view, calcaneus valgus of >10° in combination with abduction, abduction of the anterior section (>5° angle between the lateral process of the calcaneus and the metatarsal bone V).

In 33 cases, surgery was performed according to the conventional Evans procedure, using wedge-shaped cortical-spongious allografts and fixation with wires. In 9 cases, a customized structure was used for calcaneal bone osteosynthesis, and the defect was filled with bone chips.

Surgical technique

A layer-by-layer approach to the heel bone body along the outer surface of the foot was used, per the Evans method. The peroneus brevis tendon was lengthened in a Z-shaped manner. A transverse osteotomy of the calcaneus between the medial and anterior articular facets of the heel bone was

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**Fig. 1.** Mechanical and strength tests of the H-shaped reconstructive plate. 
*a*, Native calcaneal bone after wedging osteotomy and fixator installation; 
*b*, the testing machine, LFM-50kN; 
*c*, registration of the test schedule.
performed using an oscillatory saw parallel to the calcaneocubital joint and retreating from it posteriorly by 1.5 cm. An expander was installed in the osteotomy area, using which the fragments of the heel bone were moved apart to form a calculated, outward wedge-shaped diastasis, with a base width $S$ and an angle $A$ between the surfaces of the separated bone fragments (Fig. 2).

A customized H-shaped fixation element (reconstructive plate) was inserted into the formed bone defect. The reconstruction plate is designed in the form of 2 pairs of tabs located centrally and protruding from the lower surface of the plate in the transverse direction from the opposite sides of the plate along the lines of their conjugation with the bridge. They are supported by the calcaneus cortical plate. The pairs of tabs are at an angle and opposite to each other, with the angle between the opposite pairs equal to the angle $A$, between the sides of the wedge-shaped diastasis formed. The distance between the bone fragments contacting the surfaces and the surfaces of the opposite tabs of the fixing element along the lines of their intersection with the lower surfaces of the opposite sides of the plate is equal to the width $S$ of the base of the wedge-shaped diastasis formed.

Subsequently, the calcaneal bone fragments were fixed relative to each other with 4 screws through 2 pairs of holes on opposite sides of the plate.

The bone defect resulting from the correction was tightly filled with bone chips (Fig. 3). The H-shape of the fixator enabled freely
immersing the grafts in the diastasis zone and controlling their adjacency. The wound was then sutured in layers, and a plaster cast was applied from the metacarpophalangeal joints to the upper third of the lower leg for 8 weeks.

Results

Surgical treatment results

The treatment results of the 2 groups were compared 6 months after the surgery. The early-postoperative-period parameters compared included postoperative wound healing time, the presence of an inflammatory reaction, and other complications; the late postoperative period parameters included the time to graft restructuring and consolidation of the osteotomy zone, on which the resolution of the load on the limb depended, the load-bearing capacity of the foot after the start of ambulation, the position of the calcaneal bone, and the height of the longitudinal arch, radiographic parameters of foot dynamics. The functional results of treatment were assessed using the AOFAS Clinical Rating Systems.

Postoperative wound healing mostly occurred within was 12–14 days). In group 2, no complications were reported. In group 1, 5 patients (15%) had a prolonged wound healing time (up to 3 weeks) because of aseptic inflammation in reaction to the allograft (average wound healing time, 15 days). In addition, in group 1, the time to graft restructuring and bone defect replacement was significantly longer, by approximately 30%, and load-bearing was allowed no earlier than 4.5 ± 0.11 months after removal of the fixation wires (patients with wires were not allowed to walk owing to the possible wire migration and the risk of wire fracture). In group 2, the bone structure restored much faster, and full load was resumed after 3.1 ± 0.12 months, even before the metal fixator was removed, using rational shoes with an instep raiser. The plate was removed after the patient resumed normal ambulation. No patient in this study experienced dislocation and/or destruction of the structure; the screws and the plate showed no displacement and no loss of calcaneus correction or subsidence of the graft rearrangement zone was seen.

In all patients, the load-bearing capacity of the foot improved through deformity reduction. Clinically, all feet showed functional improvement,
the heel was located in the midline, the longitudinal arch was well visualized, and the gait improved.

Radiographic measurements before and after treatment revealed significant improvement in both groups with regard to the angle of the calcaneus inclination, the longitudinal arch angle, the talocalcaneal divergence angle in the frontal view, the talar-metatarsal angle (deformity of the Shade line), and the angle between the lateral process of the calcaneal bone and metatarsal bone V (Table 1).

As shown in Table 1, all parameters showed significant improvement in both groups immediately after surgery. However, after 6 months, some loss of the correction was seen in group 1 (the angle of the longitudinal arch, the angle between the lateral process of the calcaneus and the metatarsal bone V). This could be attributed to both allograft subsidence and the spongious structure of the heel bone. This was not seen in group 2.

The mean AOFAS score after treatment was 92.14 ± 4.58 points in group 1 and 93.56 ± 5.15 points in group 2. These increased significantly compared to the preoperative values in both groups (Table 2).

**Clinical case**

Patient K., aged 15 years, received the diagnosis of abducto-plano-valgus deformity of the right foot and was admitted with the complaints of gait disturbance, feet deformity (more pronounced on the right), and pain on prolonged walking. Clinically, she had abducto-plano-valgus deformity of the right foot, heel valgus at an angle of 15°, tarsal valgus up to 35°, and abduction of the anterior section of 20°; the longitudinal arch was significantly lowered, with a convexity of the plantar surface in the middle section, retraction along the external-dorsal surface of the foot, and hallux valgus. Right foot radiography showed the angle of the talocalcaneal divergence of 40° on the frontal view, the angle between the lateral segment of the calcaneus and the metatarsal bone V of 17°, the angle of the longitudinal arch of 145°, the talocalcaneal angle of 53° on the lateral view, and the talar-metatarsal angle of 13°. The mean AOFAS score was 64 before treatment (Fig. 4).

To eliminate the deformity of the right foot, Evans lateral calcaneal osteotomy was performed using a customized H-shaped reconstructive plate. The defect was filled with bone chips. Additional immobilization with a plaster cast was applied for 8 weeks. Load-bearing on the foot was allowed 3 months after the surgery. The plate was removed after 4 months. One year after the surgery, the patient had no complaints. Clinically, the foot was in the middle position, the heel was along the midline, the longitudinal arch was formed well, and support was on the entire plantar surface of the foot. According to the radiography results, the bone-articular relationships in the foot improved; namely the angle of the talocalcaneal divergence on the frontal view was 25°, the angle between the lateral process of the calcaneus and the metatarsal bone V was 0°, the angle of the longitudinal arch was 126°, the talocalcaneal angle on the lateral view was 48°, and the talar-metatarsal angle was 0°. The AOFAS score had increased by 29 points to 93.

**Discussion**

This study has some limitations. Specifically, the follow-up period after surgical treatment was relatively short (complete information can only be obtained by monitoring the child until the end of growth) and the sample size was small. Further study including a larger sample of patients is required for definitive conclusions.

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<tr>
<th>Group</th>
<th>Average score</th>
<th>Increase in average score</th>
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<tr>
<td></td>
<td>Before the treatment</td>
<td>6 months after the treatment</td>
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<tr>
<td>1</td>
<td>62.22 ± 12.59</td>
<td>92.14 ± 4.58</td>
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<tr>
<td>2</td>
<td>62.42 ± 12.19</td>
<td>93.56 ± 5.15</td>
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| Table 2 | Clinical and functional results of treatment according to the AOFAS scale |
When performing lateral lengthening osteotomy of the heel bone according to the generally accepted Evans technique, we encountered several complications. First, the bone wedges corresponding the size of the defect, to avoid both hypo- and overcorrection, were prepared intraoperatively, which increased the surgery time. Second, the lack of a stable fixation precluded the possibility of early loading. We could not find fixators for pediatric patients meeting our needs in Russia. Third, selecting the suitable material to fill the bone defect is challenging given that it must be mechanically strong, biocompatible, and quickly reconstructable. In several cases, wedge-shaped cortical-spongious grafts caused allergic reactions, causing aseptic inflammation. Therefore, complete filling of the defect is not possible using such materials. Hematoma in the cavities occurs frequently, which increases the risk of infection. We could manage these complications, however, at the expense of increased hospital stay. The use of autografts (from the wing of the ilium or fibula) to fill the bone defect causes a significant additional trauma, which limits the collection of graft material in pediatric patients.

In addition, wedge-shaped cortical-spongious bone grafts require longer time to rebuild than bone chips (chips are small, soft, and fill the entire space). In some cases, a fragment of the cortical-spongious graft can be displaced into the subtalar sinus or the plantar side, because during the passage of the wire for fixing the graft and bone fragments, the graft usually fractures at the sharp part of the wedge. Graft segments may split and fall into the diastasis, which is difficult to notice or control. Subsequently, an unfixed fragment of a cortical-spongious graft with sharp angles is displaced into the sinus or to the plantar side.

To overcome the aforementioned challenges, we developed a technique for Evans lateral lengthening osteotomy...
calcaneal osteotomy using a customized H-shaped reconstructive plate. This technique is based on multispiral computed tomography data and leverages modern rapid prototyping technologies. This technique yielded high precision, as neither overcorrection nor hypocorrection was registered. The size of the H-shaped plate is calculated based on the exact size of the wedge, which in turn is calculated based on the anatomic dimensions of the calcaneus and the required correction angle. The design characteristics of the plate ensure reliability, low-trauma rate with the intervention, the possibility of early axial loading, and the use of small-fraction grafts for dense filling of the bone defect. Moreover, the H-shaped plate is manufactured in Russia. The positive results from the first use of the customized H-shaped reconstructive plate in treatment of abducto-planovarus deformity in children and adolescents with Evans lateral calcaneal osteotomy are evidence of the superiority and benefits of this technique. Per this study, this novel fixation method has significant advantages. Further improvement of the surgical technique is planned. In addition, we are conducting further study into the efficacy of this technique based on biomechanical parameters of walking.

Conclusion

The Evans procedure is proven to yield good outcomes in the correction of reducible planovalgus deformity of the foot with abduction of the forefoot and transverse overmobility in the midfoot. Calcaneus osteotomy enables correcting all 3 deformities at once, namely, eliminating the abduction of the forefoot, raising the arch, and centering the calcaneal axis. Because the correction is performed in several planes at once, an accurate mathematical calculation is very important for complete correction of all deformity elements.

During preoperative planning, using the capabilities of multislice computed tomography, the magnitude of the correction angle, the size of the wedge-shaped defect, and the volume of the replacement material required can be calculated.

The use of a customized fixator for osteosynthesis of the heel bone during Evans osteotomy ensures accurate correction and reliable fixation of the calcaneus fragments and prevents their displacement in all planes, which significantly reduces the risk of correction loss.

The design characteristics of the H-shaped reconstructive plate developed by us significantly simplify its installation during the surgery, improve visual control of the osteotomy area and access to this area, and enable the use small-fraction grafts (bone granulate, chips, homogenate of the patient’s own spongious bone) for dense filling of the bone defect, which may not have significant mechanical strength. Furthermore, graft restructuring and replacement of the calcaneus defect were significantly faster with the customized fixator than with other grafts.

The first clinical experience of using the customized fixator for calcaneus osteosynthesis during Evans osteotomy yielded no complications, accurate and stable correction, reduced surgery time and intraoperative injury, and accelerated healing of the calcaneus and the possibility of early loading.

Additional information

Source of funding. The work was conducted within the framework of the State assignment.

Conflict of interests. The authors declare no conflict of interest.

Ethical statement. The study complied with the tenets of the Declaration of Helsinki of the World Medical Association, as amended by the Ministry of Health of Russia, within article 38, part 5, of the Federal Law number 323-FZ on 11/21/2011 (“On the Fundamentals of Public Health Protection in the Russian Federation”) and was approved by the ethical committee of the Priorov National Medical Research Center of Traumatology and Orthopedics (protocol number 4, dated 09/08/2019). The authors had obtained written voluntary consent from patients (or their legal representatives) toward participation in the study, manufacture of customized implants, surgical intervention (including the installation of this product), and publication of anonymized personal data.

Author contributions

O.V. Kozhevnikov created the concept and design of the study, conducted surgical treatment of patients, performed staged and final editing of the manuscript.

I.V. Gribova created the concept and design of the study, collected and processed the mate-
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