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C. Iacobellis
A. Bulzacchi
A. Rioda

CT evaluation of regenerated osseous segments following bone transport

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C. Iacobellis (✉) • A. Rioda
Orthopaedic Traumatology Clinic
Department of Medical Surgical Specialities
University of Padua
Via Giustiniani 3, I-35121 Padua, Italy
E-mail: claudio.iacobellis@unipd.it

A. Bulzacchi
Radiology Service 1
Padua Hospital, Italy

Abstract A morphological analysis using radiography and computed tomography was performed in a total of 17 bone segments following single or double bone transport in 11 and 3 patients, respectively. All bone transports involved the tibia, with the exception of 2 single bone transports, which were femoral. The following parameters were measured: cortical wall thickness, sectional area of the medullary canal, and density of the cortical bone and medullary canal in Hounsfield units (HU). The regenerated segments showed a cortical thickness and density that were less than the contralateral portion, with an enlargement of the medullary canal and an increase in density due to the presence of cancellous bone in the medullary area. Successive controls showed an increase in thickness and density of the cortical bone and a small reduction in the diameter of the medullary canal and its cancellous bone. The variations in the cortical and the medullary canal appeared to be independent of the length of the regenerated segment. In the 3 tibia treated by double bone transport, the anatomical variations in the distal regenerated portion varied less from normal values than the proximal portion of the same segment. In the 2 femurs examined, enlargement of the regenerated section was smaller with respect to cases involving regeneration of the proximal tibia. These differences are presumably dependent on the fact that in the latter case, a more vascularized segment is produced after osteotomy in spongy bone, with respect to those involving the distal tibia or femur. Double transport is preferable due to the reduced treatment times.

Key words Bone regeneration • Bone transport • Distraction osteogenesis

Introduction

Newly formed bone with distractional osteogenesis after bone transport presents morphological characteristics that are different from the contralateral bone segment. These differences are visible upon radiographic examination, which can show increased diameter of the newly formed bone. The information given by radiography (anteroposterior and lateral view) is not however sufficient for precise definition of the morphological characteristics of the regenerated segment and, consequently, is inadequate for assessment of mechanical quality. With reference to several earlier morphological and quantitative studies of regenerated bone after lengthening [1–3], we chose to examine similar properties (thickness of the cortical wall, sectional area of the newly formed medullary canal, density of the regenerated bone fragment in the cortical and medullary components) of corticalized, regenerated bone in order to assess any possible relationships to clinical utility.

Materials and methods

A total of 14 patients (10 male, 4 female) were studied with an average age of 44.2 years (range, 25–75 years) at the first computed tomography (CT) exam and an average age of 45.5 years at the second CT exam. The patients were treated by bone transport in 12 tibia and 2 femurs. The tibial pathologies were: 6 bone losses for open fractures, 6 bone resections for chronic osteomyelitis (2 cases), atrophic nonunion (2 cases), infected nonunion (1 case), malignant neoplasm (1 case). The femoral pathologies were 2 artrophic nonunions. In 9 tibia and in 2 femurs, the transport was single and in the proximal-distal direction. In 3 tibia, double bone transport was employed. In 2 of these cases, the transport was proximal-distal and distal-proximal with successive union of the stumps. In the last case, the transport was "twin" with both stumps transported in the proximal-distal direction [4]. Thus, considering that double transport was employed in 3 cases, a total of 17 regenerated segments were examined. The transports were preceded by osteotomy with a Gigli saw positioned under the periosteum, after incision and appropriate disbonding. Following transport, all patients were subjected to a second intervention in order to remove the agglomerate of soft tissue, which was always present between the transported and distal (or proximal) stumps. In our experience, this procedure provides a greater probability of successful union of the 2 stumps.

The time at which transport was complete was considered as time 0. After an average of 13 months following the completion of transport (range, 7–23 months), an initial CT exam was performed in all the patients. In 11 patients, a second control was performed at variable times following the completion of transport. In 2 patients a third control (after 303 and 315 days) was performed. The following instrumentation was used: General Electric Pro Speed (work station, Advantage Windows General Electric), Siemens Emotion (work station, Magic View Siemens), Siemens Volume Zoom (work station, Virtuoso Siemens and Magic View Siemens).

Four parameters were measured: (1) thickness of the cortical wall; (2) sectional area of the medullary canal; (3) density of the cortical wall and medullary canal; and (4) length of the regenerated bone.

1. *Thickness of the cortical wall.* This parameter was measured at 3 equidistant levels: proximal extremity, midpoint, and distal segment of regenerated bone. The thickness of the cortical wall surrounding the sectional area of the medullary canal of the regenerated osseous segment was measured in millimeters at 4 symmetrical points (anterior, posterior, medial, lateral). The average thickness of the cortical wall of the regenerated osseous segment was calculated at each of the 4 points. The arithmetic mean of these 4 measurements was then determined. Analogous measurements at the same levels of the normal contralateral bone were also made. The percent variation (d) of the thickness of the cortical wall of the regenerated bone (R) with respect to that of the contralateral segment (N) was calculated as (R-N)/N = d/100. Therefore, d = (R-N) x 100/N.
2. *Sectional area of the medullary canal.* This parameter was measured at 3 equidistant levels: proximal extremity, midpoint, and distal segment of regenerated bone. At each level, the sectional areas of the medullary canal of the regenerated bone and of the equivalent contralateral segment were calculated in square millimeters. As the sectional area is nearly circular, the average lengths of the 2 perpendicular diameters were calculated. From the average of the 3 sectional areas of the regenerated and contralateral segments, the percent variation (D) of the regenerated segment (Ar) with respect to the contralateral portion (An) was calculated using the formula (Ar-An)/An = D/100. Therefore, D = (Ar-An) x 100/An.
3. *Density of the cortical and medullary canal.* This was measured by CT performed in 11 patients in this series and was done by quantitative densitometry using Hounsfield units (HU) [1]. The Hounsfield scale includes different values considering the tissue under examination. The density values were calculated considering water as 0 and air as -1000. For compact bone, the Hounsfield values are greater than 250 HU, while for spongy bone these values are 130±100 HU. In the present cases, the average densitometric value was calculated from 3 levels of regenerated bone: proximal extremity, midpoint, and distal segment of regenerated bone, with respect to the contralateral segment.
4. *Length of the regenerated bone and morphological variations.* We considered only 12 cases with transport of the proximal tibia in order to form a homogeneous group of patients relative to the same skeletal segment. Two subgroups were taken into consideration in relation to the length of the regenerated segment. Group A had a length between 25 and 55 mm and group B had a length between 75 and 150 mm. Comparative statistical analysis of the percentage reduction of the thickness of the cortical wall and of sectional area of the medullary canal was performed in the two groups of patients. Density of the cortical wall and medullary canal were not taken into account due to the limited number of measurements available.

Results

We examined the characteristics of regenerated bone, on the basis of radiographic and computed tomographic findings, in 14 patients who underwent bone transport in the femur or tibia.

1. *Thickness of the cortical wall* (Tables 1a, 2a, 3). In the 9 single tibial transports (all in the proximal-distal direction), the cortical wall thickness was reduced by an average of 32.8% at the first control and 24.8% at the final assessment. In the 3 cases in which double tibial transport was employed, the regenerated segments in the proximal portion showed cortical thickness values similar to those seen in the single transport group, namely -40.1% at the first control and -21.0% in the only case examined at a second follow-up. It is noteworthy that in the double transport cases, the dis-

Table 1a Single tibial transport

Patient	Age, years	Location	Length of regenerated bone, mm	Follow-up, days	Cortical thickness			Sectional area of medullary canal		
					Regenerated bone, mm	Contralateral bone, mm	Percent difference	Regenerated bone, mm^2	Contralateral bone, mm^2	Percent difference
1	31	R	140	515	6.2	7.5	-17.3	783.8	510.4	+53.6
				648	7.1	7.5	-5.3	706.5	510.4	+38.4
2	40	R	55	248	3.6	8.9	-59.5	512.7	195.9	+161.7
				605	6.4	8.9	-28.0	437.2	195.9	+123.2
3	54	L	150	447	8.0	11.5	-30.4	924.0	767.2	+20.4
				1668	8.5	11.5	-26.1	875.0	767.2	+14.1
4	75	L	75	347	11.0	15.3	-28.1	715.8	635.8	+12.6
				1242	11.9	15.3	-22.2	710.7	635.8	+11.8
5	25	R	100	448	3.9	6.6	-40.9	961.6	333.1	+188.7
				624	4.3	6.6	-34.8	870.4	333.1	+161.3
6	36	R	50	221	4.0	4.9	-18.7	1271.4	745.6	+70.5
				625	4.1	4.9	-16.3	1203.8	745.6	+61.4
7	52	R	80	447	6.6	12.5	-47.2	306.6	192.8	+59.0
				570	7.5	12.5	-40.0	292.4	192.8	+51.6
8	26	L	80	372	5.9	8.0	-26.2	1203.8	340.2	+253.8
				688	6.1	8.0	-23.8	1133.5	340.2	+233.2
9	54	R	45	259	6.2	8.5	-27.0	322.5	205.6	+56.8

R, right; *L*, left

Table 1b Single tibial transport (densitometry)

Patient	Follow-up, days	Cortical density, HU		Medullary density, HU	
		Regenerated bone	Contralateral bone	Regenerated bone	Contralateral bone
1	515	689.6	1548.9	349.2	-226.0
	648	735.5	1548.9	349.2	-226.0
2	1668	1067.5	1612.6	127.5	-118.0
3	347	640.0	911.0	21.2	-69.9
4	448	635.0	1600.0	-27.8	-37.8
	624	1040.0	1600.0	-73.1	-37.8
5	570	787.9	1560.83	-58.1	-13.4
6	688	626.7	1272.44	-41.7	-64.8
7	259	238.0	483.8	-12.7	-65.4

Table 2a Double tibial transport

Patient	Age, years	Location	Length of regenerated bone, mm	Follow-up, days	Cortical thickness			Sectional area of medullary canal		
					Regenerated bone, mm	Contralateral bone, mm	Percent difference	Regenerated bone, mm^2	Contralateral bone, mm^2	Percent difference
1[a]	27	Right PT	45	430	5.1	9.0	-43.3	490.0	346.0	+41.6
		Right DT	25	430	9.9	10.3	-3.9	176.6	78.5	+12.5
2[b]	58	Right PT	25	376	4.3	7.5	-42.7	481.3	254.3	+89.3
		Right DT	25	376	5.0	4.9	+2.0	299.8	384.6	-22.0
3[b]	50	Left PT	50	359	5.0	7.6	-34.2	667.5	452.0	+47.7
		Left DT	50	359	6.1	7.0	-12.8	402.0	387.0	+3.9
		Left PT	50	769	5.3	7.6	-30.3	578.6	452.0	+28.0
		Left DT	50	769	6.4	7.0	-8.6	398.0	387.0	+2.8
		Left PT	50	1072	6.0	7.6	-21.0	532.5	452.0	+17.8
		Left DT	50	1072	6.4	7.0	-8.6	395.0	387.0	+2.0

[a] Twin transport; [b] Double transport with successive stump union

PT, proximal tibia; *DT*, distal tibia tally regenerated cortical segment did not undergo significant variation (average, -4.9%). In the 2 femurs examined, the regenerated segment showed a cortical thickness that was reduced by 31.8% at the first control and 23% at the second.

2. *Sectional area of the medullary canal* (Tables 1a, 2a, 3). In the 9 cases of single tibial transport, the regenerated proximal segments showed an average increase of 97.4% at the first control and 86.9% at the final control. In the 3 cases in which double transport was used, the regenerated proximal segments showed an average increase of 59.5% at the first control and 17.8% in the one case observed for a second control. The regenerated distal segments did not undergo significant variation (in 2 cases, +12.5% and 3.9% and in one case -22%). In the 2 femurs examined, the regenerated bone showed increases of 43.7% and 31.6% at the first and second controls, respectively.
3. *Measurement of the density of the cortical wall and medullary canal* (Tables 1b, 2b, 3). The average values of this parameter were not calculated due to the limited number of measurements. However, it is apparent that all cases showed a reduction in cortical density of the regenerated bone and an increase in the density of the medullary canal due to increasing spongiosis. These characteristics were less evident in the regenerated distal segments in the 3 tibial bone transports (Table 2b).
4. *Length of the regenerated bone and morphological variations* (Table 4).
   - *Thickness of the cortical wall*. Group A (25–55 mm): average reduction of 37.5% (-24.86% in successive control visits). Group B (75–150 mm): average reduction of 31.68% (-25.31% in successive control visits).
   - *Sectional area of the medullary canal*. Group A: average increase of 77.93% (+70.86 % in successive control visits). Group B: average increase 98.01% (+85.06% in successive control visits).
   - *Follow-up (average)*: Group A 318 days, Group B 399 days.

From the above data, it appears that in group B the cortical thickness was reduced to a greater degree with respect to group A and, likewise, that the sectional area of the medullary canal was greater. However, it can be seen that regenerated segments of comparable length in both groups have parameters that are quite different from one another (cases 7 and 8 Table 1a; case 6 in Table 1a and case 3 in Table 2a; case 9 in Table 1a and case 1 in Table 2a). It is thus believed that variations in the cortical and medullary canal are independent of the length of the regenerated segment. The different follow-up times (318 and 399 days) do not explain these differences.

Table 2b Double tibial transport (densitometry)

Patient	Location	Follow-up, days	Cortical density, HU		Medullary density, HU	
			Regenerated bone	Contralateral bone	Regenerated bone	Contralateral bone
1	Right PT	430	763.0	1569.7	266.1	-10.2
	Right DT	430	931.5	1606.8	203.1	-86.1
2	Right PT	376	1141.4	1582.0	538.3	-58.0
	Right DT	376	1055.0	1530.0	317.0	-37.0
3	Left PT	1072	1094.0	1664.0	163.0	-53.1
	Left DT	1072	1037.0	1042.0	-32.0	-57.0

PT, proximal tibia; *DT*, distal tibia

Table 3 Single femoral transport

Patient	Age, years	Location	Length of regenerated bone, mm	Follow-up, days	Cortical thickness			Medullary canal sectional area			Cortical density, HU		Medullary density, HU	
					Regen. bone, mm	Contralat. bone, mm	Percent difference	Regen. bone, mm^2	Contralat. bone, mm^2	Percent difference	Regen. bone	Contralat. bone	Regen. bone	Contralat. bone
1	42	Right	80	424	7.6	9.3	-18.3	213.7	138.3	+54.5				
				1636	8.2	9.3	-11.8	199.8	138.3	+44.5	787	793	12:1	-242.8
2	45	Right	70	700	6.0	11	-45.4	213.7	160.7	+33.0				
				882	7.0	11	-36.4	200.0	160.7	+24.4				
				1197	7.2	11	-34.5	191.0	160.7	+18.8				

Table 4 Analysis of two groups of patients (A and B) defined by two different ranges of regenerated segment length

Patient	Length of regenerated bone, mm	Cortical thickness (percent difference from contralateral bone)	Sectional of area medullary canal (percent difference from contralateral bone)	Follow-up, days
Group A: 25–55 mm				
1	55	-59.5	+161.7	248
2	50	-18.7	+70.5	221
3	45	-27.0	+56.8	259
4	45	-43.3	+41.6	448
5	25	-42.2	+89.3	376
6	50	-34.2	+47.7	359
Mean	45	-37.5	+77.9	318
Group B: 75–150 mm				
1	140	-17.3	+53.6	515
2	150	-30.4	+20.4	266
3	75	-28.1	+12.6	347
4	100	-40.9	+188.7	448
5	80	-47.2	+59.0	447
6	80	-26.2	+253.8	372
Mean	104	-31.7	+99.0	399

Discussion

From the follow-up examinations, it is clearly apparent that, even if case-to-case morphological variations are observed, the regenerated bone shows comparable characteristics in all patients. Moreover, these characteristics appear to be long-standing, in contrast to lengthening in which the newly formed bone tends to assume characteristics similar to that of the contralateral bone [1–3]. In particular, in bone transport the regenerated osseous segments consistently presented a cortical thickness and density that were less than that of the contralateral segment, with an enlargement of the medullary canal (Figs. 1–6). This was accompanied by an increase in the density of the canal due to the presence of cancellous bone of the medullary area. This latter finding was also seen during surgery, when a second intervention was required to remove the interpositions of the soft parts where the transported stumps meet. In successive CT scans, an increased thickness and density of the cortical wall was present along with a reduction of the

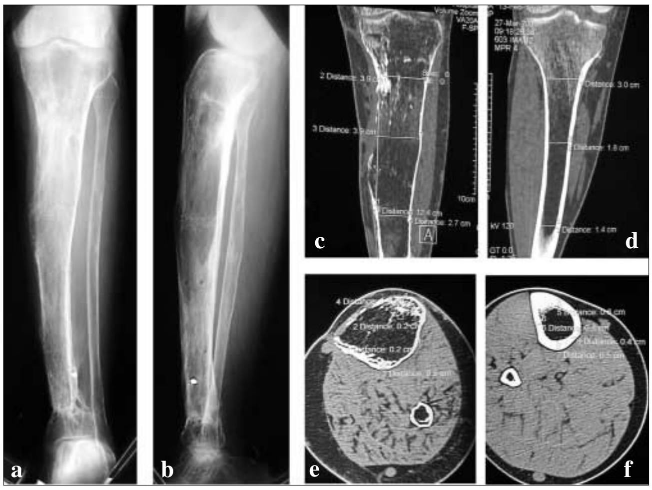

Fig. 1a-f *Proximal regeneration of the tibia after proximal-distal bone transport in a 25-year-old man. Control 448 days after the completion of trasport.* **a, b** Radiographic analysis. **c-f** Comparative CT: the regenerated segment shows a reduced cortical thickness and enlargement as well as cancellous bone of the medullary canal

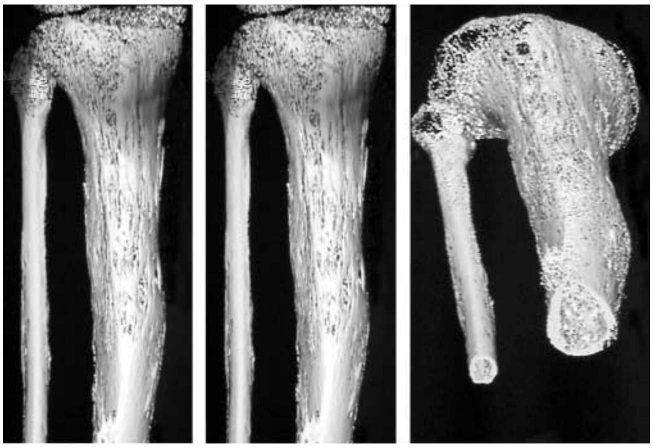

Fig. 2 Same case as in Fig. 1. Three-dimensional CT images 624 days after the completion of transport. Cancellous bone of the medullary canal of the regenerated segment is evident

Fig. 3a-d *Proximal regeneration of the tibia in a 26-year-old male. Control 688 days after the copletion of transport.* **a** Radiographic analysis. **b-d** Comparative CT scans at the proximal (**b**), intermediate (**c**), and distal (**d**) levels

Fig. 4a-c *Proximal regeneration of the femur in a 42-year-old woman. Control 1636 days after the completion of transport.* **a, b** Radiographic analysis. **c** Comparative CT. The regenerated segment shows morphological characteristics similar to the contralateral femur

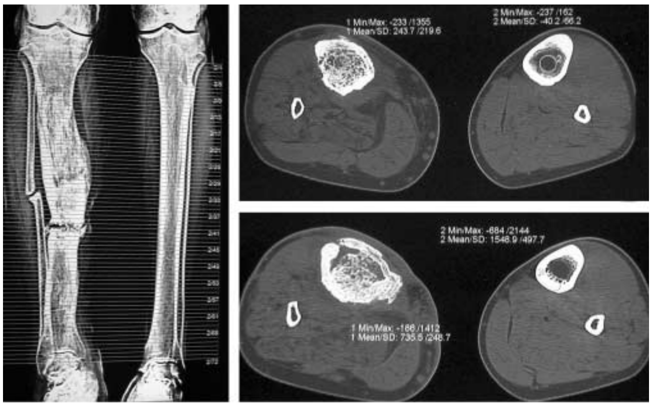

Fig. 5 Proximal regeneration of the tibia in a 31-year-old man 628 days after the completion of transport. The comparative CT scans clearly indicate the spongiosis of the regenerated medullary canal

Fig. 6a-e *Double regenerated segment of the tibia after twin double bone transport. Control 430 days after the completion of transport.* **a, b** Radiographic analysis. **c-e** Comparative CT images of regenerated proximal (**d**) and distal (**e**) segments. The regenerated segment shows morphological characteristics not dissimilar to the contralateral tibia sectional area and cancellous bone of the medullary canal.

The structural changes in the newly formed segments following double transport were more evident in the regenerated bone segments from proximal with respect to distal tibia, where the measurements varied little from those of the contralateral tibia (Fig. 6). With respect to the femur, the enlargement of the section area in the regenerated portion was less than that observed in the proximal tibia (Fig. 4). These differences are presumably dependent on the fact that the proximal tibial segment is produced after osteotomy in spongy, highly vascularized bone, while that of the distal tibia and femur is produced after osteotomy in cortical bone. We demonstrated that the variations of the cortical bone and the medullary canal are independent of the length of the regenerated segment. The mechanical strength of the newly formed bone does not seem to be compromised by the overall enlargement of the perimeter and cancellous bone of the medullary canal, which permit a weight distribution on a greater section that compensates for the reduced capacity of the cortical wall. The anatomical characteristics we observed in the regenerated distal segments in cases treated by double bone transport were close to those in normal osseous segments. This indicates that double transport is preferable to single transport since it drastically reduces treatment times. Lastly, concerning the structural differences of the tibia after single or double transport, the number of cases examined in the present study is too limited to make any definitive conclusions.

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