Remodeling of the tibial plateau after knee replacement

CT bone densitometry

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We measured the changes of bone density by computed tomography of the proximal tibia after total knee replacement in 18 patients, 9 with arthrosis and 9 with rheumatoid arthritis. All the patients had good results after 1 and 2 years. There were no significant radiolucencies at the cement-bone interface. At the early postoperative measurements, we found abnormal mediolateral distributions of density, closely related to the preoperative tibiofemoral angle ($r = -0.67$). This distribution was within normal limits after 3 months in knees with preoperative valgus and after 2 years in knees with preoperative varus. The mean tibial density did not differ between patients with arthrosis and rheumatoid arthritis at the early postoperative examination, but the density in rheumatoid patients decreased by one third during the 2-year period. Although the overall change after knee replacement was loss of density, the preoperatively less loaded condyles had a slight tendency towards increasing density with time, a response that was considerable in some cases.

Compressive failure of trabecular support is probably the most common mode of tibial component loosening (Bargren et al. 1983, Cameron and Hunter 1982, Ducheyne et al. 1978, Rand and Coventry 1980, Walker et al. 1984). Comparison of the compressive strength of the tibial plateau in relation to estimated unit loads during walking suggested that static strength was sufficient in almost all the knees presenting for arthroplasty. However, disregarding the possible beneficial effect of postoperative bone remodeling, nearly 40 percent were thought to be at risk of sustaining a local fatigue fracture (Hvid 1988).

Quantitative computed tomography relates closely to the compressive strength of tibial trabecular bone (Bentzen et al. 1987, Hvid et al. 1987). We have employed this method to study tibial condylar densities during a 2-year period after total knee arthroplasty in patients with arthrosis and rheumatoid arthritis.

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Patients and methods

Twenty patients with arthrosis or rheumatoid arthritis scheduled for total knee arthroplasty were randomly selected for the investigation. The patients were operated on during the period September 1983 to February 1984. The total number of patients operated on in this period was 55. Two patients were excluded later, one because of a large, cement-filled cyst interfering with tomography, the other because of wound complications related to a total ankle replacement performed shortly after the knee operation. Of the remaining 18 patients, 9 were operated on for arthrosis (8 women, 1 man, mean age 72 (63–81) years, and 9 for rheumatoid arthritis (7 women, 2 men, mean age 61 (35–73) years).

At operation, malalignment was corrected by excision of marginal osteophytes and release of tight collateral structures (Insall et al. 1985). The Insall-Burstein® total condylar knee with a non-metal-backed tibial component was used with

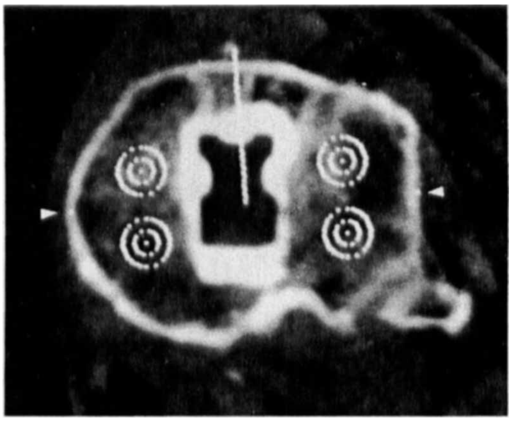

Figure 1. A CT scan from the proximal 3-mm level of a tibia is shown with the region of interest matrix template superimposed (the smaller circles were used in this study). The template with marginal points coinciding with the medial and lateral margins of the condyles (arrow heads) is chosen for a specific tibia, and this template is used for definition of regions of interest in all other scans of that tibia. Reproducibility of template position in relation to the intramedullary post of the tibial component is ensured by recording diagonal postimage coordinates and adjusting subsequent scans to the same relative template position.

bone cuts and realignment performed according to Insall et al. (1985). Standard polymethylmethacrylate bone cement was impacted manually into the jet lavage-prepared trabecular surfaces. The patients were allowed weight bearing from the fourth postoperative day. No major complications were recorded. The mean knee score (Hospital for Special Surgery Knee Rating Scale; Insall et al. 1976) improved from 55 (34–71) to 85 (74–96) at the 2-year follow-up.

Bone density was measured by quantitative computed tomography just before operation and repeated at 1, 3, and 6 weeks, 3 and 6 months, and 2 years postoperatively. Because the method used to secure reproducibility of regions of interest relied on coordinates (Figure 1), which did not exist preoperatively, the examination after 1 week was used as a baseline. Only a few patients were able to return for the examination after 3 weeks, which is therefore not included in this report. All the patients were examined at 1 week and at 2 years, 13 patients at 6 weeks, 15 patients at 3 months, and 14 patients at 6 months.

The scannings were conducted on an EMI 7070 scanner. The knees were centered in the gantry, with a saline-filled plastic bag placed centrally on top of the knees to approximate a circular geometry. Anteroposterior scanograms, in essence digitized radiographs, were obtained, and the lower limbs realigned to place the condylar cement-bone interface of the tibial component parallel to the scan plane. The scanograms were repeated to confirm correct positioning. A lateral scanogram was then obtained, and the gantry tilted to parallel the cement-bone interface in the sagittal view. Consecutive scans with 2-mm-slice thickness were conducted at 1-mm increments distally to define a proximal tibial epiphyseal transverse plane just beneath the cementbone interface. Three consecutive 3-mm scans were then obtained, the proximal limit of the proximal scan coinciding with the proximal transverse plane.

For evaluation of the scans, CT images were transferred to a General Electric RT/PLAN dose-planning system. Four regions of interest were defined for each scan (Figure 1), two at the medial and two at the lateral condyle. The regions were approximately 5 mm in diameter (20 mm^2). A computer program defined a series of electronic templates that could be superimposed on the CT image, rotated and translated to place the regions anteriorly and posteriorly at each condyle. The templates were congruent, differing only in absolute size. The template that matched the mediolateral width of the proximal scan from the first postoperative examination of a particular knee was chosen to define regions of interest on all the scans obtained from that knee. During evaluation of the first postoperative proximal scan, the image coordinates of two diagonal corners of the intramedullary fixation post of the tibial component were recorded. Through measurement of the coordinates of the same two corners on the subsequent examinations, the translation and rotation of the knee relative to the first examination were determined, and the position of the regions automatically corrected. Density is reported in Hounsfield units as the mean value of the pixels contained in a region of interest.

The results of quantitative computed tomography were related to clinical and radiographic variables obtained preoperatively and after 2 years. An activity index ranging from zero (patient unable to stand or walk) to sixty (unlimited walking distance without use of walking aids) was calculated based on information on walking distance and walking aids from the knee rating scale.

A weight index, corrected for sex, was calculated according to Lindberg et al. (1956). The tibiofemoral angle was measured on short (approximately 15 cm of distal femur and 15 cm of proximal tibia) standing anteroposterior radiographs; this angle is related to the mechanical hip-knee-ankle axis by $+ 7 \pm 2°$ (Jokio et al. 1984). Also, the tilt of the tibial component in the frontal plane and a tibial radiolucency index were measured on these radiographs (Hvid and Nielsen 1984). A radiolucency index of 200 (2-mm zone affecting 100 percent of the interface) or more at the condyles or the intercondylar post was considered significant. The stage of arthrosis was determined according to Ahlbäck (1968), also in rheumatoid knees.

The influence of time, diagnosis, and scan level of the bone density was analyzed by three-way analysis of variance (3-way ANOVA; Hald 1952). The influence of single variables was evaluated by the Student's *t*-test. Correlation between clinical and radiographic data and bone density was studied by a nonparametric method with correction for tied observations (Spearman rank correlation; Siegel 1956).

Results

Bone density averaged for the four regions of interest at each scan level was influenced by diagnosis ($P < 0.05$), scan level ($P < 0.001$) and time ($P < 0.03$). At the examination after 1 week, there was no difference between bone density in knees with arthritis and arthrosis at any scan level, whereas at the 2-year examination, bone density was lower in arthritis than in arthrosis at scan level 3 (Table 1). There was a mean 15 percent decrease of bone density with depth between levels 1 and 2 except for patients with arthrosis after 2 years,

Table 1. Mean values of density (Hounsfield units) averaged for the four regions of interest of each level, stratified for diagnosis, scan level and time

	Level	Arthritis		Arthrosis
1 week	1	199	a	248
		b		c
	2	164	a	211
		a		a
	3	160	a	212
		b		a
2 years	1	136	a	214
		d		a
	2	112	a	194
		a		a
	3	108	b	190

Significance levels refer to Student's *t*-test for paired or unpaired data as appropriate: a Not significant, b $P < 0.05$, c $P < 0.025$, d $P < 0.01$.

Table 2. Raw data collection: clinical variables

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S
1	1	62	O	82	171	2	−1	8	0	36	60	60	0	0	75	90	90	123.4
2	1	70	O	67	148	3	−7	3	0	20	30	30	0	0	64	92	90	127.9
3	1	58	R	53	160	3	6	7	−1	3	36	36	0	0	42	87	87	89.7
4	1	67	R	61	152	3	8	8	−2	20	20	20	0	100	46	81	78	113.5
5	1	83	O	74	155	3	24	11	0	20	40	60	0	50	34	64	91	132.7
6	1	63	R	67	167	4	−11	5	0	36	36	36	0	50	66	91	92	105.0
7	1	73	R	55	152	3	10	5	0	24	36	36	0	0	57	85	85	102.3
8	1	82	O	77	153	3	19	10	0	12	36	36	0	0	43	83	80	141.5
9	2	71	O	93	173	2	−8	6	−3	24	60	60	50	150	60	96	96	122.3
10	1	35	R	45	168	3	10	8	1	12	36	36	0	0	50	83	82	69.8
11	2	59	R	69	172	3	−6	7	−3	36	36	24	0	75	62	75	81	91.6
12	1	61	O	75	157	2	−7	8	−4	20	24	36	100	100	53	76	92	131.4
13	1	68	R	54	159	4	18	7	0	12	60	24	0	0	44	87	82	92.4
14	1	77	O	79	158	3	16	9	0	8	16	20	0	50	47	79	74	136.8
15	1	71	O	80	160	3	−9	2	0	20	60	60	0	0	63	91	94	135.4
16	1	75	O	90	162	3	0	5	−2	10	60	24	0	75	71	85	74	148.9
17	2	68	R	70	170	3	1	10	0	24	36	24	0	0	65	75	81	94.7
18	1	54	R	64	159	2	13	9	0	24	60	60	0	0	40	84	84	109.5

A patient code; B sex (1 female, 2 male); C Age; D diagnosis (R rheumatoid arthritis, O arthrosis); E Bodyweight (kg); F Height (cm); G Stage of arthrosis; H Preoperative alignment (degrees, varus angles negative); I Postoperative alignment; J Tibial component tilt (degrees, AP view, varus tilt negative; K Preoperative activity score; L 1-year activity score; M 2-year activity score; N Radiolucency index at 3 months; O Radiolucency index at 2 years; P Preoperative HSS score; Q 1-year HSS score; R 2-year HSS score; S Weight index.

Table 3. Raw data collection: CT data (Hounsfield units)

Level 1.

	1 week				3 weeks				6 weeks				3 months				6 months				2 years			
A	PM	AM	PL	AL	PM	AM	PL	AL	PM	AM	PL	AL	PM	AM	PL	AL	PM	AM	PL	AL	PM	AM	PL	AL
1	258	267	263	191	*	*	*	*	*	*	*	*	232	217	249	234	215	144	185	205	243	160	168	170
2	444	270	204	192	*	*	*	*	378	240	146	105	326	217	184	104	202	234	196	127	202	247	212	97
3	288	259	230	178	*	*	*	*	281	227	208	167	159	112	131	109	209	153	106	79	109	43	126	84
4	265	205	88	151	*	*	*	*	386	264	146	161	*	*	*	*	330	206	107	37	189	181	96	55
5	128	130	574	570	155	146	437	447	282	183	328	324	397	154	95	94	364	243	237	70	267	158	385	46
6	212	122	99	123	*	*	*	*	184	91	108	98	206	134	252	187	190	120	218	187	211	83	233	347
7	187	260	225	195	*	*	*	*	152	140	198	174	160	91	205	111	69	70	135	73	66	55	202	20
8	55	227	114	23	76	188	88	51	28	142	83	27	48	157	54	51	*	*	*	*	52	95	78	50
9	154	272	160	192	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	106	162	111	276
10	148	124	223	131	143	115	199	134	140	110	133	111	155	96	71	123	134	101	59	51	131	105	128	78
11	498	442	98	101	481	541	64	162	530	571	86	103	576	664	59	25	457	756	69	70	333	172	66	29
12	388	484	286	251	*	*	*	*	434	475	409	420	486	522	402	492	562	590	499	656	430	583	516	608
13	46	37	269	179	98	33	282	138	99	43	241	93	70	43	177	109	100	22	154	89	90	10	133	149
14	137	192	302	256	*	*	*	*	*	*	*	*	217	172	233	197	198	203	199	183	269	152	96	102
15	217	232	202	124	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	208	248	137	76
16	368	279	262	255	332	275	247	226	*	*	*	*	316	305	244	190	309	396	212	159	335	306	227	126
17	466	372	263	227	493	394	274	270	535	424	239	207	604	394	243	185	563	284	223	133	305	190	211	95
18	107	39	98	216	*	*	*	*	106	111	135	209	193	301	140	177	*	*	*	*	234	174	71	75

Level 2.

	1 week				3 weeks				6 weeks				3 months				6 months				2 years			
A	PM	AM	PL	AL	PM	AM	PL	AL	PM	AM	PL	AL	PM	AM	PL	AL	PM	AM	PL	AL	PM	AM	PL	AL
1	207	176	221	155	*	*	*	*	*	*	*	*	220	170	232	225	*	*	*	*	212	127	170	208
2	412	242	216	140	*	*	*	*	345	205	166	86	300	192	195	87	281	176	221	101	205	207	201	85
3	186	196	198	142	*	*	*	*	157	161	171	145	109	104	123	94	136	118	129	94	56	52	96	65
4	220	141	101	131	*	*	*	*	313	137	104	140	*	*	*	*	291	120	107	14	177	127	84	14
5	160	143	415	406	138	130	413	342	261	204	159	271	244	166	113	98	275	174	222	79	212	136	241	38
6	180	220	124	120	*	*	*	*	188	63	91	81	218	129	191	146	186	106	175	115	173	67	212	181
7	191	199	209	142	*	*	*	*	135	136	191	127	*	*	*	*	96	50	201	82	79	40	150	13
8	59	203	124	36	77	156	96	50	21	106	77	35	*	*	*	*	*	*	*	*	58	105	62	47
9	172	193	178	254	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	139	120	141	248
10	130	102	126	156	128	96	131	145	117	90	111	126	129	93	52	92	129	89	82	46	126	86	113	65
11	216	315	80	41	383	453	105	106	417	408	68	68	535	509	53	27	516	581	58	16	228	155	53	37
12	328	361	251	151	*	*	*	*	457	433	356	349	499	533	350	399	558	631	416	569	427	538	389	479
13	29	28	262	158	108	22	240	118	118	41	230	64	63	34	178	105	*	*	*	*	87	23	129	123
14	117	177	185	164	*	*	*	*	*	*	*	*	165	162	119	149	198	203	199	183	189	165	74	77
15	220	200	220	170	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	170	273	167	86
16	280	255	268	185	276	213	279	218	*	*	*	*	349	306	260	156	285	271	193	133	298	274	224	174
17	434	328	214	178	441	312	226	208	503	343	164	161	519	397	181	141	457	263	117	93	291	140	150	107
18	122	32	84	192	*	*	*	*	108	75	80	151	196	229	110	144	*	*	*	*	195	173	90	80

Level 3.

	1 week				3 weeks				6 weeks				3 months				6 months				2 years			
A	PM	AM	PL	AL	PM	AM	PL	AL	PM	AM	PL	AL	PM	AM	PL	AL	PM	AM	PL	AL	PM	AM	PL	AL
1	271	149	241	160	*	*	*	*	*	*	*	*	266	206	235	230	207	128	215	225	176	131	184	155
2	377	264	226	124	*	*	*	*	296	192	180	74	*	*	*	*	*	*	*	*	221	207	214	51
3	132	160	165	143	*	*	*	*	*	*	*	*	158	81	114	88	160	126	140	∞7	95	65	95	61
4	214	139	142	84	*	*	*	*	256	123	127	133	*	*	*	*	249	133	110	2	165	109	95	17
5	159	127	330	353	182	154	319	300	194	153	280	246	197	109	181	96	234	200	243	106	237	161	200	38
6	123	410	78	97	*	*	*	*	190	86	110	92	203	167	167	135	182	107	188	116	103	44	204	129
7	178	161	249	123	*	*	*	*	136	224	241	95	*	*	*	*	76	102	273	64	70	111	156	18
8	68	157	170	36	77	129	138	54	2	83	124	40	81	144	128	13	*	*	*	*	60	90	145	42
9	201	252	234	199	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	163	226	116	184
10	136	112	121	128	137	91	112	87	120	64	95	64	113	89	60	117	112	64	52	33	131	71	77	40
11	289	399	49	54	312	413	56	75	267	223	61	46	377	485	5	32	409	453	31	25	238	116	42	23
12	359	324	257	234	*	*	*	*	450	475	337	318	530	554	323	292	*	*	*	*	425	530	350	320
13	74	20	251	122	111	38	193	112	144	67	243	11	91	17	177	87	95	16	149	66	118	71	156	87
14	145	166	174	135	*	*		*	*	*	*	*	164	144	145	126	122	146	120	80	170	113	71	73
15	224	144	248	120	*	*		*	*	*	*	*	*	*	*	*	*	*	*	*	135	301	199	96
16	273	280	262	199	188	135	140	109	*	*	*	*	272	264	234	196	*	*	*	*	333	350	212	146
17	430	354	159	178	435	351	164	159	509	388	153	129	475	331	102	75	401	233	84	30	276	139	141	76
18	82	19	36	156	*	*	*	*	112	61	52	114	200	225	108	133	*	*	*	*	223	175	85	76

A patient code; PM posteromedial; AM anteromedial; PL posterolateral. AL anterolateral.

* Data not obtained.

but no further decrease between levels 2 and 3 (Table 1). In rheumatoid arthritis, there was a mean decrease of density of 32 percent with time at all scan levels. In patients with arthrosis, the mean decrease of density with time was only 11 percent and not significant at any scan level (Table 1).

Preoperatively, the tibiofemoral angle ranged from 11° of varus to 24° of valgus. There was a clear-cut relation between this angle and the distribution of density (Figure 2). Postoperatively, the tibiofemoral angle was corrected to 2–11° of valgus, and the tilt of the tibial component in the frontal plane was within ± 4° relative to the long axis of the tibia. All the knees had a normal distribution of density with higher means medially than laterally after 2 years, but this change was apparent earlier in the valgus knees, where lateral bone density decreased ($P < 0.05$; Figure 3). The decrease of medial density in knees with preoperative varus was not significant; but when varus and valgus knees were taken together, there was a decrease of density with time of the preoperatively more loaded condyle ($P < 0.005$). The mean density at the preoperatively less loaded condyles did not change. Valgus deformity occurred in 4/7 arthritic knees and varus in 6/9 arthrotic knees (NS). There was no difference in overall mean density between varus and valgus knees.

The individual change in condylar density from 1 week to 2 years related to the change in alignment induced by the operation (Figure 4). There was no correlation between the change in medial density and correction of alignment; but for the change in lateral density, this correlation was significant ($P < 0.005$).

There was no influence of age, activity index, or stage of arthrosis on bone density. The weight index correlated with bone density after 2 years (r_s =0.47, $P < 0.05$). The median radiolucency index was 0, ranging from 0 to 150, i.e., no radiolucency exceeded 1.5 mm in width. The bone density at 1 week and 2 years and the radiolucency index at 2 years were not correlated.

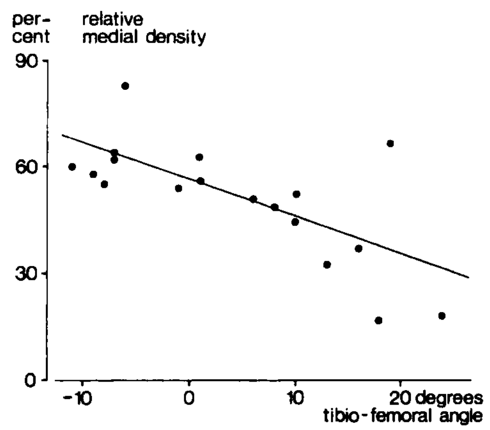

Figure 2. Relation between the tibiofemoral angle (TFA; varus angles negative) and mediolateral density distribution at level 1 at 1 week postoperatively. Relative medial density (RMD) was computed from the sum of quantitative CT results from the two medial regions of interest in percent of the sum of quantitative CT results from all four regions. Linear regression analysis revealed the equation: RMD = −1 TFA + 56, $r = -0.67$, $P = 0.002$.

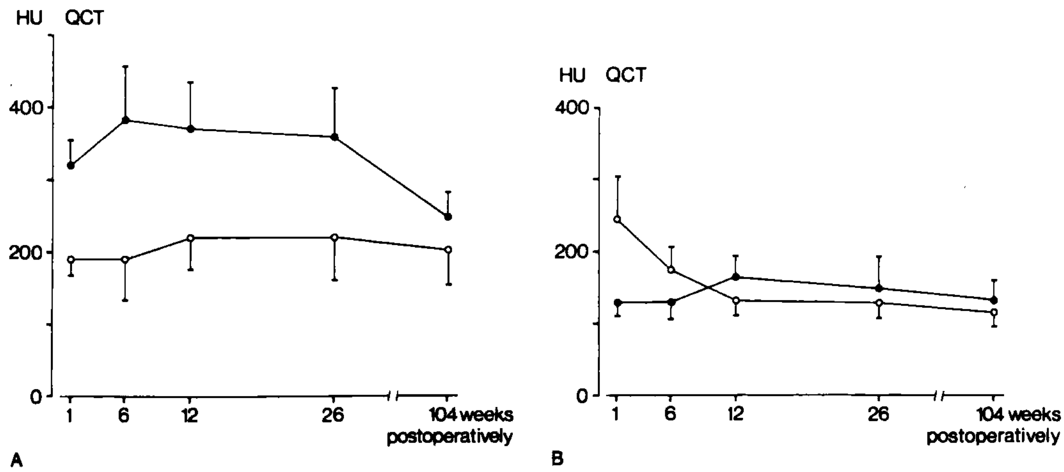

Figure 3. Medial and lateral mean density as a function of time. Bars correspond to 1 SEM ● medial density, ○ lateral density. A. Varus knees (preoperative tibiofemoral angle ≤ 2°). B. Valgus knees (preoperative tibiofemoral angle ≥ 10°).

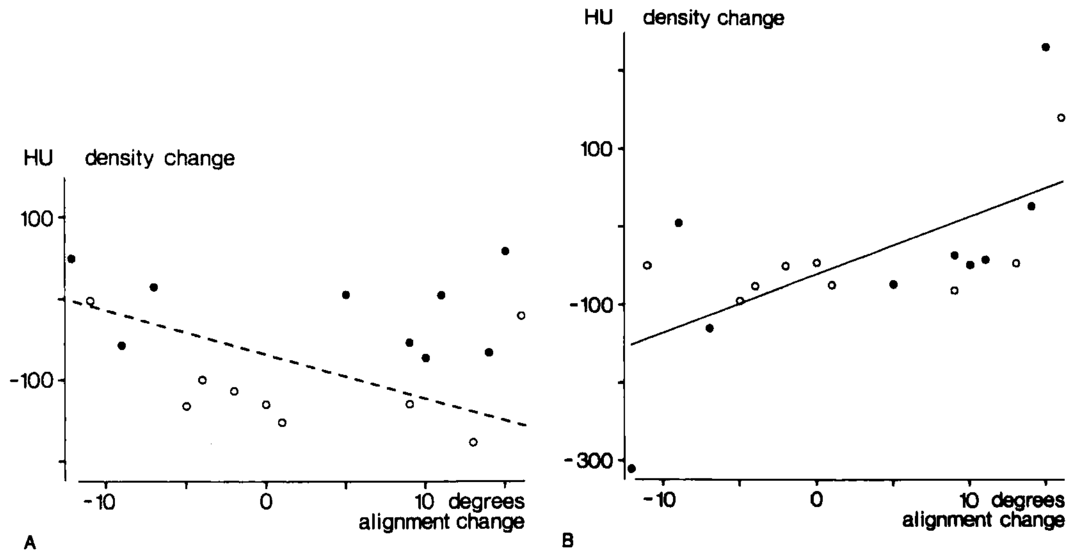

Figure 4. Influence of alignment correction on condylar density change (level 1) after total knee arthroplasty. The abscissa shows alignment postoperatively minus alignment preoperatively (ALC), e.g., −10 designates an alignment change of 10° in the varus direction. The ordinates show the density change (DC; density at 104 weeks minus density at 1 week) averaged for the two condylar regions of interest ○ rheumatoid arthritis, ● arthrosis.
A. Medial condyles. The regression line is indicated dashed (the correlation is not significant).
B. Lateral condyles. The regression line is shown (DC = 7.5 ALC −62.0, r=0.65, $P < 0.005$).

Discussion

The difference in strength of proximal tibial trabecular bone in rheumatoid arthritis and arthrosis is small at the time of total knee replacement (Wixon et al. 1987, Hvid 1988). The same was found for noninvasive bone-density measurement in our present study. The influence of varus and valgus deformity on the distribution of tibial density at the time of operation confirms previous studies (Behrens et al. 1974, Hvid and Hansen 1986, Hvid 1988). The remodeling that takes place with time is characterized by loss of bone at the denser condyle, medial or lateral, according to preoperative deformity. Bohr and Lund (1987) reported on density changes measured by dual-photon absorptiometry after total knee replacement using an uncemented prosthesis. They found a slight initial increase in density from 3 to 6 months after the operation and then apparently a slow decrease for 2 years. The study included 9 patients with no details given on the type of knee pathology or preoperative deformity, and analysis of variance was not performed to exclude the possibility of mass significance.

The overall response of the less dense condyles to the operation was unchanged density throughout the 2-year period. However, the postoperative density actually increased or decreased considerably in some patients (Figure 4), which may be considered significant on an individual basis (changes larger than 99 percent confidence limits of precision on repeated examination; Bentzen et al. 1987, Hvid et al. 1986). The mean 1-week, level-1 density of medial condyles of valgus knees was 130 HU, and of the lateral condyles of varus knees 194 HU. At 120 kVp scanning energy, these figures correspond to 5 and 8 MPa compressive strength (Bentzen et al. 1987, Hvid et al. 1987), when allowance is made for the steep loss of density (Bentzen et al. 1987) and strength (Hvid and Hansen 1985, 1986) with the distance from the joint. A rough approximation of the unit loads after total knee arthroplasty at the lateral and medial condyles during walking suggests average figures of 1.5 MPa for the lateral and 2.3 for the medial condyle (Hvid 1988). Thus, static failure of these condylar structures would not be expected. Avoidance of fatigue failure requires considerably higher static strength, e.g., 4.5 MPa laterally and 7.0 MPa medially have been estimated (Hvid 1988). On this basis, remodeling leading to higher density would not be expected.

Ryd (1986) suggested that fatigue failure of the trabecular support of the tibial component may occur, leading to migration of the component in the order of magnitude of 1 mm during the first postoperative year. However, this does not necessarily imply insufficient compressive strength of the supporting trabecular structure, because the average amount of distal migration was minimal.

The data of Bentzen et al. (1987) suggest that with a direct relation of quantitative CT obtained in 3-mm slices at the tibial epiphyses to penetration strength values obtained during intraoperative measurement in 20 patients including those reported in this study, the strength values are equal to those quoted above. One uncertainty in empirical extrapolation of strength data from density measurements is that density strength relations may change in remodeling bone. However, the density data obtained after 2 years may be confidently transformed to strength data, because a new steady state regarding remodeling must have been reached at that time.

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