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Tensile properties of the knee-joint capsule at an elevated intraarticular pressure

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In order to evaluate the capsular reaction to high intraarticular pressure (IAP) in the knee during arthroscopy, we examined 13 patients admitted for elective surgery with joint infusion to 30, 70, 120 and 170 mmHg IAP (4, 9.3, 16 and 22.7 kPa). The infusion was repeated once, at all IAP levels except 30 mmHg, after 2 min and was recorded for another 2 min. A pressure-time curve was recorded as a combined effect of viscoelastic properties of the capsule and extraarticular fluid absorption. 3 more knee joints were infused directly to 170 mmHg and a pressure-time curve was recorded for 15 min, after which time the joint was reinfused to 170 mmHg in order to estimate the change in joint volume due to absorption or relaxation.

In 10 knees, the curves were uniform. At infusion, the pressure curve was almost linear above 70 mmHg. There were no signs of plastic deformation of the joint capsule at pressures below 120 mmHg, while at 170 mmHg there were signs of capsular deformation. At each pressure level, the curve revealed a rapid fall in initial pressure that gradually decreased because of capsular relaxation or fluid absorption. Repeated infusion delayed the fall in pressure, due to increased capsular stiffness.

In 3 knees infused directly to 170 mmHg IAP, the slope for the first 2 min of the pressure-time curve did not differ from that found at maximal IAP in knees examined with stepwise increasing pressures. Discontinuity of the capsule, even of puncture size, influenced the pressure/volume correlation considerably.

We conclude that at IAP levels of 170 mmHg, there are signs of plastic deformation of the joint capsule. In order to avoid capsular damage, knee arthroscopy should be done at intraarticular pressure levels below 120 mmHg.

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An infusion pump is used at arthroscopy to optimize the intraarticular view, stop bleeding and remove debris. With the pump, however, high inadvertent intraarticular pressures (IAP) might be produced with a risk of tissue damage, capsular rupture and compartment syndrome (Noyes and Spievack 1982, Peek and Haynes 1984, Burgaard et al. 1988). Most authors seem to agree that the IAP should be kept as low as possible during arthroscopy, e.g., Ewing et al. (1986) and Bauer and Jackson (1986) recommended an IAP between 70 and 120 mmHg while Bergstrom and Gillquist (1986) suggested that an IAP level of 20–30 mmHg below the systolic blood pressure was ideal for good visualization.

The degree of joint distension is correlated with the IAP, while the IAP depends on joint position and the rate of position changes. Fast movements of a distended joint create pressure peaks of considerable height (Ewing et al. 1986, Takeshita et al. 1991, Sperber and Wredmark 1993). The tolerance of the joint capsule to high continuous pressure has not been investigated and the pressure limits within which an arthroscopy can be done safely are still not known. We evaluated the joint capsule reaction to various IAPs up to 170 mmHg, to provide guidelines for clinical application in arthroscopy.

Patients and methods

16 consecutive arthroscopy patients (10 men) were examined. Their median age was 26 (13–52) years (Table 1). None of the patients had a joint effusion. All were examined under general anesthesia in the supine position, with the leg supported by a leg holder, without a tourniquet. The knee was at 10° of flexion, with the heel supported by the operating table. Specially designed conical metal cannulae (Figure 1) were used to prevent fluid leakage at the perforation site. The cannulae were introduced after skin incision only and the joint capsule was perforated by the needle-sharp trocar of the cannula. One cannula was in-

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Table 1. Descriptive data on the patients undergoing a pressure-time test of the knee joint

Pat	Sex	Age	Pathology [a]	Height cm	Volume [b] mL	Reinfused [c] mL
1	M	21	LM	173	120	
2	F	23	ACL	164	128	
3	F	25	0	160	115	
4	M	26	ACL	176	123	
5	M	26	ACL	190	175	
6	F	32	0	163	101	
7	F	36	OA	171	98	
8	M	30	MM	184	149	
9	M	38	LM	176	155	
10	M	52	LM	180	126	
11	F	13	0	163	115	9
12	M	15	LB	170	176	12
13	F	24	ACL	160	104	8
14 [d]	M	26	0	179	146	
15 [d]	M	53	OA	177	150	
16 [d]	M	40	MCL	185	188	

[a] ACL anterior cruciate ligament, LB loose body, LM lateral meniscus, MCL medial collateral ligament, MM medial meniscus, OA arthrosis.

[b] The total infusion volume used for a complete series of tests in each knee.

[c] In patients 11–13, the volumes infused after 15 min of continuous relaxation to restore the IAP to 170 mmHg (reinfusion).

[d] A complete test could not be performed in patients 14–16 because of a suspected capsular rupture during infusion with inability to distend the joints to the desired pressure level. Patients 14–15 had had preoperative joint punctures and patient 16 had a MCL injury 6 weeks before the test.

serted into the anterolateral compartment for inflow and the other cannula was inserted into the suprapatellar pouch and connected to a pressure-monitoring device (Triplus, PVB Medizintechnik GmbH, Kirchseen, Germany) and a pressure monitor (KONE Patient Data Monitor 565A, Espoo, Finland). All recordings were stored in a computer with 10-sec interval readings of the mean intraarticular pressure.

In 13 patients, a fluid infusion (I) was performed manually, using a 50 mL glass syringe, to IAP levels of 30, 70, 120 and 170 mmHg. After recording the pressure for 2 min, the infusion was repeated once

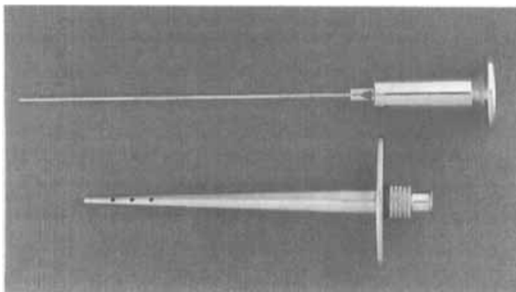

Figure 1. Conical cannula used for intraarticular measurement.

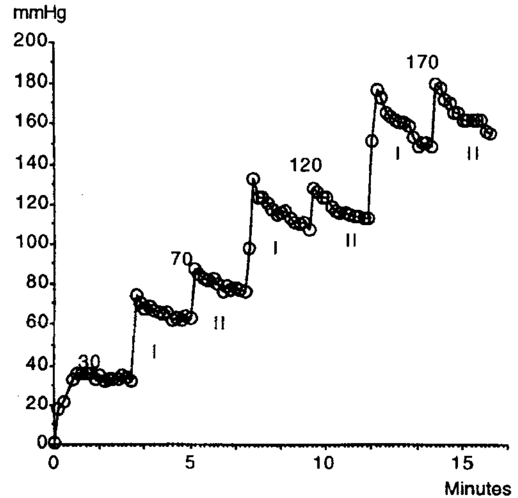

Figure 2. Pressure-time curves of a knee joint repeatedly infused with saline to 30, 70, 70, 120, 120, 170, 170 mmHg IAP. I and II = first and second infusion at each pressure level.

(II), at all IAP levels but 30 mmHg, to the same IAP level (Figure 2). In 3 patients, the joint was distended under an IAP of 170 mmHg directly and the IAP was recorded for 15 min before the joint was redistended under 170 mmHg IAP again. The total volume of injected fluid was calculated for all patients (Table 1). After the examination, the joint was emptied and an arthroscopy was performed.

At infusion, the rate of pressure increase was calculated as the derivative of the pressure-time curve at each pressure step (= the slope). The curve was non-linear at 0–70 mmHg and approximately linear above 70 mm Hg. In the comparisons, the 0–70 mmHg interval approximated a linear pressure change.

In a non-linear pressure-time curve, the rate of pressure fall is a function of the instant pressure but also of the pressure history—for example, the time elapsed from the last pressure level. To describe the configuration of the curve more accurately, the experimentally recorded data were fitted to an exponentially decreasing function $p1 = A + Be^{-t/T}$. The rate of decrease in pressure could then be expressed as the time derivative of the function at any time. The sum of the constants A + B describes the initial pressure, the constant A describes the long-term asymptotic pressure and T is the time constant of the function. The constants A and B were unique at every pressure level. t is the time elapsed from the onset of a decrease in pressure. The curve was determined using the least-square fitting method. The constant T determines the decay rate, $e^{-t/T}$ is reduced 50% for each 0.69T time interval (half-time).

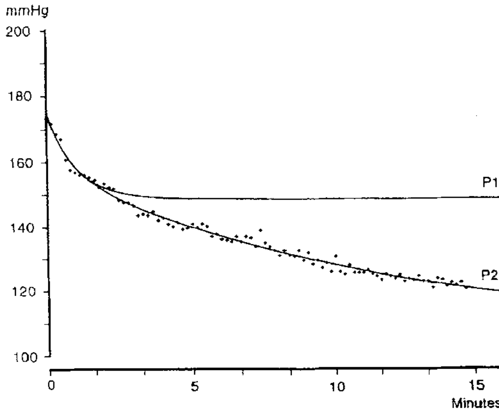

Figure 3. Pressure-time curve of a knee joint directly infused with saline to 170 mmHg and observed for 15 min. P1 is the function $A + Be^{-t/T}$ fitted to a 2 min interval and P2 is the function $A + Be^{-t/T} + Ce^{-t/T2}$ fitted to a 15 min interval.

In the three 15 min recordings, the function $p2 = A + Be^{-t/T} + Ce^{-t/T2}$ using two time constants, provided a better fit, because of altered pressure fall characteristics in the later part of the curve (Figure 3).

Results are given as the median and range. The slopes of the infusion curves and the relaxation curves from repeated infusions were analyzed by applying Wilcoxon's and Friedman's non-parametric tests. The correlation between joint volume and body length was determined by Spearman's test. Statistical significance was defined as $p < 0.05$.

All patients gave their informed consent to participate in the study, which was approved by the Ethics Committee at Huddinge University Hospital.

Results

The study was conducted without any signs of visible fluid leakage or capsular rupture in patients 1–13. In patients 1–10, the total amount of fluid infused was median 129 (SD 24) mL and the body height was 174 (10) cm (Table 1). There was a correlation between volume and height ($r = 0.74$).

At infusion, the pressure curve slope was positively correlated to the pressure levels 30–170 mmHg ($p = 0.0001$) (Table 2). At each pressure level, there was a significant difference between the infusion slopes of the pressure curves I and II, with the slope of II > I, indicating an increased capsular stiffness (Table 2).

In the pressure fall curves, the mean value of the 3 slope readings in the first half-minute period was used to compare curve characteristics. The slope of the I and II readings differed at 70 and 120 mmHg with I > II, but it was unchanged at 170 mmHg (Table 3).

In the 3 knees 11–13, which were filled to 170 mmHg IAP directly, the slope of the first 2 min of pressure fall was estimated not to differ from the 170 mmHg recordings in the knees examined with repeated infusions. Because of the small sample, a statistical analysis could not be utilized in this comparison (Table 3).

The mean volume in the 3 knees (patients 11–13) was 131 (39) mL. The mean viscoelastic expansion of the joint, expressed as the difference between the starting volume and the volume after refilling at 15 min, was 7.4% (Table 1).

In 2 knees (patients 14–15), there was a sudden loss of resistance during the infusion, followed by a sharp IAP fall. In both of these patients a puncture with a

Table 2. Data for repeated joint infusions to various pressure levels. IAP (mmHg) is the peak pressure of each level. I = first infusion. II = second infusion to the same pressure level. Time between all infusion levels 2 min. P is the pressure interval between start and end of infusion. V is the infusion volume. D is the mean derivative for the pressure/time curve (mmHg/sec) (= the slope)

IAP	30			70:I			70:II			120:I			120:II			170:I			170:II		
	P	V	D	P	V	D	P	V	D	P	V	D	P	V	D	P	V	D	P	V	D
1	4–31	58	0.5	28–76	22	2.2	58–72	3	4.7	65–116	17	3.0	99–122	4	5.8	107–177	11	6.4	133–175	5	8.4
2	1–36	78	0.4	33–75	18	2.3	63–88	7	3.6	76–133	11	5.2	108–128	2	10.0	113–177	10	6.4	149–180	2	15.5
3	0–37	61	0.7	31–73	16	2.6	61–92	6	5.2	73–124	9	5.7	94–118	2	12.0	100–186	14	6.1	139–172	4	8.3
4	0–48	76	0.6	34–72	14	2.7	58–73	3	5.0	66–123	13	4.4	100–123	4	5.8	111–169	9	6.4	144–170	4	6.5
5	0–35	90	0.4	28–71	32	1.3	63–78	5	3.0	69–127	21	2.8	102–133	6	5.2	112–168	12	4.7	139–194	9	6.1
6	0–40	50	0.8	30–76	16	2.9	60–80	3	6.7	65–120	12	4.6	99–131	5	6.4	93–180	10	8.7	122–177	5	11.0
7	3–36	46	0.7	32–71	15	2.6	55–82	5	5.4	62–121	10	5.9	84–128	5	8.8	91–169	10	7.8	110–182	7	10.3
8	2–32	73	0.4	29–66	28	1.3	53–71	5	3.6	62–112	19	2.6	93–119	4	6.5	106–169	14	4.5	147–186	6	6.5
9	2–42	92	0.4	34–76	20	2.1	66–81	5	3.0	74–125	15	3.4	100–127	4	6.8	108–168	13	4.6	129–171	6	7.0
10	0–36	62	0.6	31–70	21	1.9	66–82	6	2.7	73–124	14	3.6	105–125	2	10.0	109–186	16	4.8	150–177	5	5.4
						$p < 0.005$						$p < 0.005$						$p < 0.005$			

Wilcoxon's test for analysis of derivative of I and II curves. Friedman's test for analyzing of derivatives of 30–70:I–120:I–170:I curves, $p = 0.0001$

Table 3. Pressure fall characteristics for 13 knee joint capsules in the first half-minute after infusion to various intra-articular pressures (IAP mmHg), expressed as the mean derivative (mmHg/sec) of the pressure-time curves (= the slope). I = first infusion, II = repeated infusion to the same pressure level. In 3 knee joints, there was a single infusion directly to 170 mmHg IAP (170 s)

	IAP mmHg							
Pat	30	70:I	:II	120:I	:II	170:I	:II	170 s
1	0.16	0.67	0.12	0.26	0.16	1.75	0.46	
2	0.06	0.24	0.39	0.36	0.26	0.28	1.28	
3	0.07	0.14	0.26	0.60	0.26	0.91	0.42	
4	0.32	0.14	0.10	0.41	0.15	0.37	0.18	
5	0.16	0.15	0.10	0.39	0.28	0.39	0.49	
6	0.16	0.84	0.15	0.55	0.40	0.89	0.74	
7	0.18	0.20	0.29	0.56	0.53	0.91	0.92	
8	0.07	0.55	0.17	0.21	0.18	0.28	0.32	
9	0.16	0.18	0.11	0.37	0.21	0.50	0.45	
10	0.12	0.21	0.13	0.27	0.15	0.57	–	
11								0.56
12								0.56
13								0.47
Mean	0.15	0.33	0.18	0.39	0.26	0.68	0.58	0.53
P [a]		0.005		0.005		0.374		

[a] Wilcoxon test p-values for comparisons of first half-minute derivative between I and II recordings.

0.5-mm needle into the anterolateral compartment had been performed before the experiment to collect synovial fluid for another research project. In patient no. 16, the knee IAP could not be raised above 70 mmHg, in spite of a large infusion volume. The knee had been twisted 2 months earlier and arthroscopy revealed a grade II MCL rupture. In none of the 3 knee joints could a capsular rupture be identified at the subsequent arthroscopy (Table 1).

Discussion

Collagenous tissue is viscoelastic only at low loads (the physiological range), while plastic deformation will take place at higher loads, as characterized by the end of the second part of the nonlinear pressure-time curve (Figure 2). At maximal tissue strain, further distension will cause a rupture (Viidik 1968b). If the joint is regarded as a balloon, the wall tension per pressure unit will increase with the radius of the sphere, according to the formula $\Sigma = pr/2t$ (p = pressure, r = radius, t = wall thickness). The wall tension should accelerate faster than the pressure-volume ratio as an indication of increased stiffness. At all infusions in our experiment, the behavior of the capsule was in accordance with this model, which is indicative of unaltered capsular characteristics.

A stepwise increase in the IAP, as opposed to direct infusion to the maximal IAP, had no influence on capsular characteristics, which is in agreement with the low influence of the rate of increase in strain on hysteresis phenomena, as demonstrated by Fung (1967).

The pressure fall curve is typical of viscoelastic collagenous tissue subjected to deformation. After repeated infusions at 70 and 120 mmHg, there was a significant reduction in the slope, demonstrating a pressure fall to a higher asymptotic pressure. The same phenomenon was found by Viidik (1968a), who regarded it as a combined effect of the elastic, viscous and plastic components of the tissue. However, the slope of the pressure fall was identical in curves I and II at 170 mmHg, which could be an effect of fluid absorption across the synovial membrane, but also an indication of plastic deformation.

There may be two reasons for a pressure decrease in the knee joint. Apart from capsular expansion, a certain amount of fluid absorption into the periarticular space occurs. It is difficult, however, to measure the precise rate of absorption in humans, as the quantities are small.

Animal experiments have revealed an absorption of 0.49 µL/min/cm H_2O IAP (0.75 mmHg) in a rabbit knee, with a sixfold increase in absorption above 9 cm H_2O (6.8 mmHg) (Levick 1979). According to Pascal's principle, the IAP is uniform throughout a joint and, consequently, a large joint should show a higher extraarticular fluid absorption. As the synovial area in man is about 15 times larger than in a rabbit (Levick 1983), absorption volumes at 120 mm Hg IAP would be $6 \times (0.49 \times 10^{-6}) \times 170 \times 15 = 7.2$ mL/min, resulting in a total absorption of 107 mL in a 15 min period. The results of our study are in sharp contrast to the volume calculated above. Although only 3 joints were examined, the results were uniform; after15 min the joint volume had increased by 8–12 mL. These were absolute values resulting from a combined effect of capsular relaxation and extraarticular fluid absorption.

Since the data by Levick were obtained by a creep test, the values may not be representative of the stress-relaxation situation in our study. One cannot determine from this experiment the extent of extraarticular fluid absorption, but it is likely that the major factor in pressure which decreases after infusion is capsular relaxation.

In knees showing no signs of inflammatory disease or osteoarthritis, capsular rupture mainly occurs in the upper part of the joint, which is the weak point regarding resistance to tension caused by an increase in IAP (Dixon and Grant 1964, Noyes and Spievack 1982). In any arthroscopic procedure involving difficulties in maintaining the desired IAP, a capsular rup-

ture should be suspected (Noyes and Spievack 1982, Dandy 1987) and the 2 capsular ruptures observed in our study show that even small lesions, such as punctures, may result in vulnerability to increased IAP.

Joint position significantly affects the IAP. The pattern of IAP variations in the knee joint during motion shows minimum IAP at intermediate angles around 45° and maximum pressures at flexion and extension (Eyring and Murray 1964, Jayson and Dixon 1970a, Myers and Palmer 1970, Pedowitz et al. 1989, Funk et al. 1991). These pressures rise significantly in loaded joint motion (Machan 1983) and during changes in the position of a distended joint (Jayson and Dixon 1970b, Jensen and Graf 1993).

A high inadvertent pressure is not likely to be induced during arthroscopy so long as a low rate of change in the position of the knee is maintained. Although this study showed no certain plastic deformation of the joint capsule, it is important to perform fluid infusions carefully. Repeated infusions of small volumes to maintain a desired pressure are less detrimental to the capsule than single large infusions, since stiffness increases with repeated infusions. In routine knee arthroscopy, these findings should be taken into consideration and therefore we are against use of an IAP above 120 mmHg.

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