Abnormal Echogenic Findings Detected by Transesophageal Echocardiography and Cardiorespiratory Impairment during Total Knee Arthroplasty with Tourniquet

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Background: *In patients undergoing total knee arthroplasty, intraoperative pulmonary embolic events are rare, and most occur following tourniquet deflation. This embolization can be observed using transesophageal echocardiography. However, the authors have encountered sudden decreases in arterial oxygen partial pressure while a tourniquet is still inflated. Therefore, the current investigation was designed to detect emboli during the tourniquet inflation phase and to identify the composition of the echogenic material.*

Methods: *Forty-six patients were randomly assigned to undergo total knee arthroplasty without (control, n = 24) or with a tourniquet (n = 22). Hemodynamic monitoring, blood gas analysis, and continuous transesophageal echocardiography were performed during the total knee arthroplasty procedure. Right jugular blood specimens were collected whenever echogenic material was seen in the atrium.*

Results: *In the tourniquet group, embolic events occurred in 27% of patients during femoral reaming and in 100% after tourniquet deflation. In the control group, emboli were detected in 54% of patients during femoral reaming. Most of the patients exhibited cardiopulmonary impairment after severe echogenic embolism, even while the tourniquet was inflated (two patients). None of the blood samples aspirated from the central catheters contained detectable material.*

Conclusions: *This prospective study showed that embolic events occurred during total knee arthroplasty, even while a tourniquet was inflated. An inflated tourniquet does not completely prevent pulmonary emboli.*

PREVIOUS studies have shown that the embolism of air, fat, bone marrow, and thrombi often occurs during total hip arthroplasty,[1-4] especially during cemented femoral insertion and reduction of the hip joint. The resulting pulmonary emboli can cause hypoxemia, hypotension, and sudden death. The increase of intramedullary pressure in the femur seems to be the most crucial pathogenic factor.[1]

In patients undergoing total knee arthroplasty (TKA), intraoperative pulmonary embolic events are unusual, and even when they do occur, most of them follow tourniquet deflation.[5-7] After deflating the tourniquet, typical echogenic findings consist of a miliary pattern or one in which large discrete particles are superimposed on a miliary pattern.[8] It is commonly believed that pulmonary embolic events cannot occur while the tourniquet is inflated.

We have encountered sudden decreases in oxygen saturation during TKA, even while a tourniquet is still inflated. This appears to be most common after intramedullary manipulation of the femur.

However, there have been no reports of cardiopulmonary impairment while the tourniquet is inflated. Accordingly, we designed this study to determine whether cardiopulmonary impairment during the period of tourniquet inflation was related to echogenic findings detected by transesophageal echocardiography (TEE) and to identify the composition of the echogenic material.

Methods

After we obtained approval from the Institutional Review Board of the Nippon Medical School (Tokyo, Japan), written informed consent to participate in the current study was obtained from 46 patients scheduled to undergo TKA between May 1999 and March 2000. We randomly assigned patients to undergo TKA without a tourniquet (control group, n = 24) or with tourniquet (n = 22).

Anesthesia was induced with intravenous propofol (1.5 mg/kg) and fentanyl citrate (0.1 mg). Tracheal intubation was facilitated with vecuronium bromide (0.1 mg/kg), and anesthesia was maintained with 66% nitrous oxide in 33% oxygen and sevoflurane. During the operation, all patients were ventilated with a tidal volume of 10 ml/kg and a respiratory rate of 10 breaths/min. In the tourniquet group, the involved limb was exsanguinated by elevation and an esmarch bandage, after which a pneumatic thigh tourniquet was applied to the limb and inflated to a pressure of 350 mmHg. No tourniquet was applied to the legs of the control patients. The same surgeon performed all of the procedures, and a similar surgical technique was used in each patient. The femur was reamed to a depth of about 20 cm using an intramedullary rod. A Hy–Flex II Total Knee System (DePuy International Ltd., Leeds, United Kingdom), which has 20-mm pegs, was then implanted with cement in all but two of the patients. The two excep-
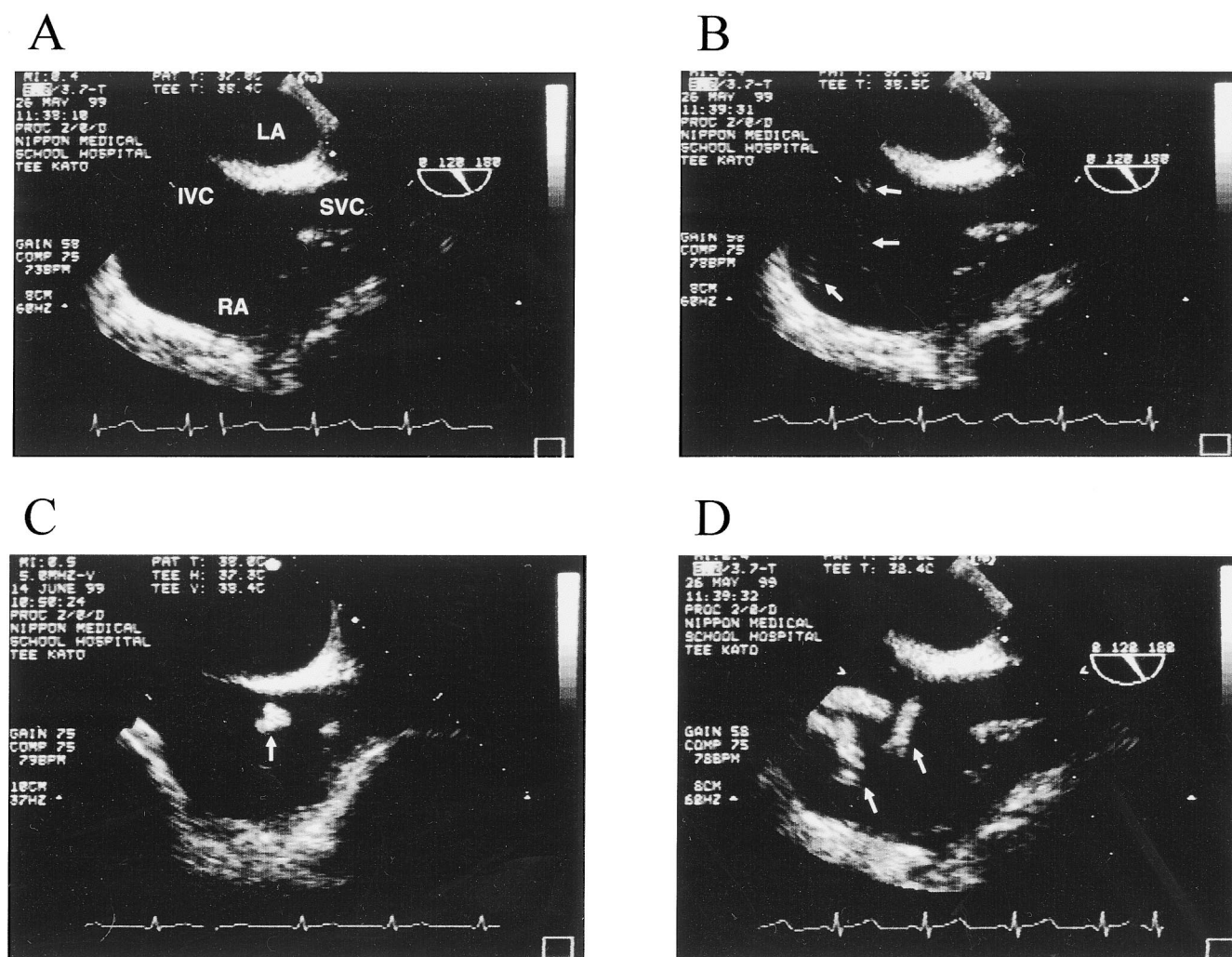
A

B

C

D

Fig. 1. The main echogenic patterns during total knee arthroplasty with the transesophageal echocardiography in upper esophageal plane. (*A*) Grade 0: no emboli. LA = left atrium; RA = right atrium; SVC = superior vena cava; IVC = inferior vena cava. (*B*) Grade 1: a few fine emboli (arrow). This picture is the image observed after femoral reaming in the tourniquet use group. (*C*) Grade 2: embolic masses less than 5 mm in diameter (arrow) with fine masses. This picture is the image observed after femoral reaming in the tourniquet group. (*D*) Grade 3: large embolic masses greater than 5 mm in diameter (arrow) with fine masses. This is the image observed after prosthesis with a long-stem insertion into the femur in the tourniquet group.

tions received the PFC Sigma (DePuy Orthopedics Inc., Warsaw, IN), which has a 130-mm-long stem, and this prosthesis was bonded with cement. The tibial component of PFC Sigma has a 70-mm stem.

An arterial catheter was inserted into the radial artery of all patients for intraoperative blood gas analysis and blood pressure determinations. A continuous three-lead electrocardiogram was recorded, and end-tidal carbon dioxide concentration and pulse oxygen saturation were measured (Solar 7000; Nihon Kohden, Tokyo, Japan).

A central venous catheter with a 14-gauge (2.33-mm) lumen was inserted *via* the right jugular vein into the right atrium of seven patients in the control group and five in the tourniquet group. Under TEE guidance, its tip was positioned above the tricuspid valve, and a blood sample was collected before the operation and again if echogenic embolic material was detected in the right

atrium. After centrifuging the blood samples at 3,500 rpm for 10 min, the supernatant was discarded, and the rest of the specimen was filtered through a milk-sediment disc with a pore size of 100 μm. To identify the residue, it was Sudan-stained to detect fat and Giemsa-stained to detect thrombus and bone marrow. We prospectively monitored patients with a 5.0-MHz biplane TEE probe (Sonos2000; Hewlett-Packard, Andover, MA) with an upper esophageal longitudinal view during the operation. The TEE image was recorded on VHS videotape and analyzed by an observer who was unaware of the surgical procedure. Because high-flow infusions from the upper limb created small and low-echogenic artifacts in the TEE image, we administered no fluids while making cardiopulmonary measurements. The echogenic patterns were classified according to a simplification of the established criteria[1,4,9]: grade 0 (fig. 1A), no emboli;

Table 1. Patient Background

	Control Group (n = 24)	Tourniquet Group (n = 22)
Gender: male, female	1, 23	2, 20
Age (yr)	63 ± 8	65 ± 10
Weight (kg)	50 ± 7	49 ± 8
Duration of operation (min)	111 ± 13	111 ± 41
Duration of tourniquet inflation (min)		108 ± 35
Blood loss (g)	510 ± 244*	67 ± 120
Transfusion (ml)	409 ± 150	54 ± 151
No. of patients with preoperative blood: stored, autologous	17, 2	2, 1
No. of patients of physical status: Class 1, 2, 3, 4	5, 17, 2, 0	5, 16, 1, 0

Physical status was determined according to the American Society of Anesthesiologists.

* $P < 0.05$ *versus* tourniquet group. Values are mean ± SD.

grade 1 (fig. 1B), a few fine emboli; grade 2 (fig. 1C), a cascade of fine emboli or embolic masses less than 5 mm in diameter and the right atrium opacified with echogenic materials; and grade 3 (fig. 1D), fine emboli mixed with large embolic masses greater than 5 mm in diameter or serpentine emboli.

Because most of the decrease in pulse oximeter saturation or blood pressure recovered within 5 min, we performed blood gas analysis and circulatory measurements frequently: at the stable point after incision as a baseline; after exsanguination by esmarch; after femoral osteotomy; 2.5, 5, and 10 min after femoral reaming; 2.5, 5, and 10 min after prosthesis insertion into the femur; after tibial osteotomy; 2.5, 5, and 10 min after tibial punching; 2.5, 5, and 10 min after prosthesis insertion into the tibia; after tourniquet deflation; and after relocation of the knee joint. In the control group, we performed measurements at the same points except after exsanguination by the esmarch and after tourniquet deflation.

We started transfusion when blood pressure could not recover (less than 80 mmHg) with fluid and intravenous vosoconstriction drug administration or when hemoglobin concentration was less than 7 mg/dl. Heparin at 5,000 U/d was administered postoperatively to all patients for 3 weeks.

Statistical Analysis

Before beginning the study, a sample-size calculation was performed. We hypothesized that we could observe at least a 10% reduction in arterial oxygen partial pressure (Pao_2). The α error was set at 0.05 (two-sided) and the β error at 0.20. Analysis showed that 22 patients per groups would be sufficient. For statistical analysis, repeated-measure one-way analysis of variance and Tukey test were performed to distinguish within-group differences over time. Repeated-measure two-way analysis of variance and unpaired t tests were performed to evaluate

differences within the same time period between the groups. All values are reported as the mean ± SD, and P values < 0.05 were considered to be statistically significant.

Results

The patients' backgrounds are summarized in table 1. Blood loss was higher in the control group than in the tourniquet group. Four patients underwent a bilateral procedure during the same anesthesia session, but the cardiopulmonary data collected during the second procedure were not included in this study. All patients were extubated in the operating room and transferred to the recovery room, where cardiopulmonary function returned to its preoperative state in all patients who had evidence of pulmonary embolism. None of the patients had atrial septal defects or neurologic alterations.

In three patients of the tourniquet group, clinically relevant pulmonary embolism was suspected by a postoperative decrease in Pao_2, and one of these patients had a positive perfusion lung scan. Only one patient in the control group was suspected to have clinical pulmonary embolism, but this was not confirmed by lung scan. There was no statistically significant difference in hospitalization period, and all patients were discharged without difficulty.

Results of TEE are shown in table 2. In the tourniquet group, the embolic events were observed in the right atrium 10–30 s after the femoral side operation and persisted for less than 5 min. Grade 2 or 3 material was detected after prosthesis insertion into the femur in the two patients in whom a femoral component with a long stem (130 mm) was inserted with cement (fig. 1D). TEE revealed echogenic material 10–20 s after tourniquet deflation in every patient; this peaked in intensity within 1 min and was present for less than 5 min in 16 patients, but lasted longer than 10 min in 6 patients. In the control group, echogenic findings were observed not only during the femoral but also during tibial side action. These echogenic responses appeared 10–30 s after femoral and tibial operation, and the echogenic materials circulated for several seconds in the right atrium and then floated into the lung stream. The appearance of findings after relocation of the knee joint was related to the severity of the echogenic showers that occurred during the femoral or tibial surgery. After tibial punching and after prosthesis insertion into the tibia, the control group had a significantly higher incidence of emboli than the tourniquet group ($P < 0.05$, Mann–Whitney U test).

Circulatory and respiratory results are shown in table 3. We presented only 2.5-min values after each manipulation because no other measurement point was statistically different. In the tourniquet group, all patients with grade 1 emboli were stable, one patient with a grade 2

Table 2. Embolic Grade on Transesophageal Echocardiography during Total Knee Arthroplasty

Grade	Control Group (n = 24)				Tourniquet Group (n = 22)			
	0	1	2	3	0	1	2	3
Exsanguination by eamarch					22 (100%)			
Femoral osteotomy	24 (100%)				22 (100%)			
Femoral reaming	11 (46%)	11 (46%)	1 (4%)	1 (4%)	16 (73%)	4 (18%)	2 (9%)	
Prosthesis insertion into femur	15 (63%)	8 (33%)	1 (4%)		16 (73%)	2 (9%)	3 (14%)	1 (4%)
Tibial osteotomy	24 (100%)				22 (100%)			
Tibial punching*	19 (79%)	5 (21%)			22 (100%)			
Prosthesis insertion into tibia*	20 (83%)	3 (13%)	1 (4%)		22 (100%)			
Tourniquet deflation						4 (18%)	12 (55%)	6 (27%)
Relocation of knee	10 (42%)	13 (54%)	1 (4%)		5 (23%)	12 (54%)	5 (23%)	

* = significant difference between groups in the frequency of appearance of the echogenic materials ($P < 0.05$).

Grade 0 = no emboli; grade 1 = a few fine emboli; grade 2 = a cascade of fine emboli or embolic masses with diameter of < 5 mm and the right atrium opacified with echogenic materials; grade 3 = fine emboli mixed with large embolic masses with a diameter of > 5 mm or serpentine emboli.

embolus after the prosthesis insertion into the femur had a 20% decrease in mean arterial pressure (from 90 to 72 mmHg) for about 3 min, and one patient who showed grade 3 material after the prosthesis insertion into the femur developed transient hypotension (mean arterial pressure = 45 mmHg) but recovered within 10 min after treatment with intravenous ephedrine. Pa_{O_2} decreased in four patients (18%) after femoral reaming or insertion of the prosthesis into the femur. These four patients consisted of one patient with grade 1 emboli, two patients with grade 2 emboli, and one patient with grade 3 emboli. Decreased Pa_{O_2} after tourniquet release was reversed by increasing the inspired oxygen concentration to 100%, and these Pa_{O_2} values were excluded from this study. In the control group, only one patient had a decrease in mean arterial pressure of more than 20 mmHg after femoral reaming following detection of grade 3 masses by TEE. Heart rates remained stable during surgery in both groups, and none of the patients had persistent impairment of circulatory function after the operation. Pa_{O_2} decreased only in the patients who had grade 2 and 3 masses. Most of these decreases in Pa_{O_2} were transient, but the decreases in Pa_{O_2} due to grade 3 masses persisted until the end of operation. End-tidal carbon dioxide increased sharply 1 min after

the tourniquet was deflated in nearly all of the patients, but was unchanged or tended to decrease in patients in whom grade 3 materials were observed.

None of the 26 blood samples aspirated from a central catheter when echogenic materials were detected in the right atrium contained significant findings.

Discussion

The first aim of this clinical study was to determine whether cardiopulmonary impairment during the period of tourniquet inflation was related to echogenic findings detected by TEE. This study showed that grade 3 echogenic findings caused hypotension and decreases in Pa_{O_2}. Even while the tourniquet was inflated, we detected abnormal echogenic findings along with cardio-respiratory impairment. Moreover, we detected echogenic material in the right atrium and found none in the left atrium during the entire study period. This suggests that embolic materials had been trapped in the pulmonary capillary vessels. A previous study showed that both femoral and tibial prosthesis cementing continuously caused small echogenic emboli during TKA without tourniquet.[10] We also observed low-density small parti-

Table 3. Circulatory and Respiratory Changes

	Control Group (n = 24)				Tourniquet Group (n = 22)			
	MAP	HR	Pa_{O_2}	ET_{CO_2}	MAP	HR	Pa_{O_2}	ET_{CO_2}
Baseline	86 ± 8	70 ± 6	130 ± 12	38 ± 3	88 ± 10	72 ± 9	138 ± 15	37 ± 3
Exsanguination by esmarch					91 ± 11	65 ± 8	139 ± 13	37 ± 4
Femoral osteotomy	86 ± 11	75 ± 10	130 ± 19	36 ± 3	94 ± 12	74 ± 6	140 ± 15	37 ± 3
Femoral reaming	89 ± 12	83 ± 9	111 ± 21	32 ± 6	93 ± 11	84 ± 12	128 ± 23	34 ± 3
Prosthesis insertion into femur	84 ± 14	77 ± 6	115 ± 19	33 ± 4	85 ± 16	81 ± 10	130 ± 21	32 ± 5
Tibial osteotomy	91 ± 10	74 ± 4	123 ± 15	35 ± 3	95 ± 13	78 ± 9	134 ± 19	34 ± 4
Tibial punching	92 ± 8	76 ± 7	131 ± 15	34 ± 3	95 ± 15	79 ± 8	135 ± 13	33 ± 3
Prosthesis insertion into tibia	95 ± 10	80 ± 11	137 ± 12	33 ± 4	95 ± 12	80 ± 11	141 ± 10	34 ± 3
Tourniquet deflation					81 ± 17*	86 ± 12	128 ± 17*	43 ± 5*
Relocation of knee	912 ± 13	85 ± 10	126 ± 18	35 ± 3	87 ± 14	85 ± 11	130 ± 18	40 ± 3

* $P < 0.05$ *versus* baseline value.

MAP = mean arterial pressure (mmHg); HR = heart rate (beats/min); Pa_{O_2} = arterial oxygen tension (mmHg); ET_{CO_2} = end-tidal carbon dioxide tension (mmHg).

cles up to grade 1 during reaming and insertion of prosthesis without the tourniquet. The material observed on TEE after deflation of the tourniquet was mixture of various sizes, from grade 1 to 3. This is similar to a previous study that revealed two patterns of echogenic materials: a miliary pattern or one in which large discrete particles are superimposed on a miliary pattern.[5,8] In particular, the large material classified as grade 3 was strongly suspected, based on its inhomogeneous internal structure, of being thrombus, and it seemed to have formed while the tourniquet was inflated. The material seen on TEE after deflation of the tourniquet seemed to be a mixture of material seen during reaming and insertion of the prosthesis without the tourniquet and the material formed while the tourniquet was inflated. Pneumatic tourniquet inflation compresses the femoral artery and vein, leading to venous stasis and acidosis. Furthermore, endtherial disruption plus additional tissue thromboplastin forced into the femoral vein from the femoral cavity account for thrombosis. This hypercoaguable state completes the Virchow triad of thrombus formation. However, the current study does not permit tissue characterization of embolic material.

The intraoperative infusion fluid exhibited a fine and low-echogenic pattern on TEE, and it was also observed for a period after the infusion was stopped. It was necessary to distinguish whether the echogenic material originated in the infusion or in the vicinity of the surgery. Since it would have transited through the superior vena cava if it had been the former and *via* the inferior vena cava if the latter, we monitored it on a plane capable of visualizing both veins at the same time (upper esophageal longitudinal view).

The patient who had Pa_{O_2} decrease with grade 1 emboli while the tourniquet was inflated had pulmonary fibrosis due to rheumatoid arthritis and preoperative hypoxemia. This impairment might be subclinical for those with good respiratory reserve but could be clinically threatening for those with poor reserve. More studies are needed to determine the frequency of cases of clinically insignificant pulmonary embolism. After tourniquet deflation, end-tidal carbon dioxide increased as a result of the return of deoxygenated blood from the ischemic limb. Shift of perfusion caused by grade 1 or 2 emboli might result in redistribution of perfusion with a functional gas exchange and preserve carbon dioxide excretion. In contrast, end-tidal carbon dioxide in patients with grade 3 material was unchanged or tended to decrease; this seemed to be the result of a total that was the balance of the increase for the above reason and the decrease due to pulmonary embolism.

Among the hemodynamic changes, we found a shift of the atrial septum toward the left atrium in a patient with grade 3 embolism. The increase in right ventricular afterload produced back pressure on right atrium. Furthermore, the blood pressure decreased more than 20% in one of the five patients with grade 2 masses while the tourniquet was inflated. Considering reports that emboli reduce the cross-sectional area of the pulmonary arterial bed by at least 40% to produce hemodynamic changes,[11,12] we agreed with the hypothesis that these phenomena may have been caused not only by mechanical obstruction but also vasoconstriction of the pulmonary vasculature due to the release of neurohumoral substances, such as serotonin released from platelets adhering to the embolus.[13]

There are two possible factors in the cause of intravasation of embolic material with a tourniquet. Echogenic material could flow from the drainage veins to the inferior vena cava. Anatomically, the blood that enters the femur can be drained to the surface through the emissary or perforating vein.[14] Furthermore, some authors have shown that fluid and even methylmethacrylate monomer particles leave cancellous bone and enter the systemic venous system.[15-18] Because it was impossible to increase the inner pressure of the femur by tourniquet inflation, some of the materials that migrated into the vessels in the medullary cavity could flow centrally through the venous network and exit to the surface of the femur *via* the drainage veins that were central to the site of application of the tourniquet. Then the material flowed into the inferior vena cava and reached the right atrium. When ipsilateral TKA operations were performed (with a tourniquet) on patients who had previously undergone total hip arthroplasty (n = 2), no foreign materials could be confirmed by TEE during maneuvers on the femoral side. This seemed to show that migration of foreign material through the marrow of the femur is impossible because of an artificial substance that has already been inserted into the bone marrow on the central side of the femur. However, movement of echogenic material larger than the diameter of the drainage veins cannot be explained by this mechanism. Perhaps thrombi formed in veins at sites of blood flow congestion proximal to the femur as a result of tourniquet inflation might have been sheared off the vessel walls by foreign material washed out of the blood stream above it, and they both might have arrived in the right atrium together.

Another possible etiologic factor was insufficient compression pressure by the tourniquet. Similarly to Parmet *et al.*,[10] we detected echogenic material in the control group not only after surgery on the femoral side (54%) but also on the tibial side (17%). If the compression pressure of the tourniquet was insufficient to prevent blood flow, we should have detected the echogenic materials after insertion of the prosthesis into both the femur and tibia in the tourniquet group, but echogenic materials appeared only after the operation on the femoral side in our study. We therefore concluded that the inflation pressure was sufficient to compress the vessels.

Echogenic materials could consist of fat, bone cement, thrombus, air, or cold blood from the ischemic limb. Pell

et al.[19] reported that the echogenic masses inside the heart were not sampled at the moment of embolism; subsequent histologic studies showed widespread pulmonary and systemic intravascular fat deposition consistent with fat embolism. Our current study also could not demonstrate fat. The central catheter might have been too small to aspirate materials larger than 2.33 mm in diameter that we thought were thrombus. Thus, we speculate that the observed miliary materials represent air or cold blood.

Deflation of the tourniquet caused a high incidence of grade 3 embolic events (27%), but without a tourniquet events of the same severity were observed only in one patient (4%) after femoral reaming. There are numerous concerns regarding the relation between echogenic emboli and tourniquet use.[10,20] A 5.33-fold greater risk of large venous embolism accompanied the use of a tourniquet during TKA.[10] Avoiding tourniquet inflation decreased the occurrence of large emboli. Thus, the current study suggests that TKA should be performed without a tourniquet, especially in patients with cardiopulmonary impairment. On the other hand, because we did not perform a lung scan in all patients, the actual incidence rate of pulmonary embolism was not confirmed. Furthermore, because currently available methods of prophylaxis reduce the incidence of venous thromboembolism,[21,22] it could be possible to use the tourniquet when we want to avoid blood transfusion.

Anesthesiologists and surgeons should be aware of the possibility of acute pulmonary embolism even while the tourniquet is inflated.

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