

Chronic Exertional Compartment Syndrome in Lower Legs: Localization and Follow-up with Thallium-201 SPECT Imaging

Shigeo Takebayashi, Haruo Takazawa, Ryosuke Sasaki, Hideyuki Miki, Ryotaku Soh and Junichi Nishimura
Departments of Radiology and Orthopedics, Yokohama City Kowan Hospital, Yokohama; and Department of Radiology, Yokohama City University School of Medicine, Yokohama, Japan

The purpose of this study was to ascertain whether ^{201}Tl SPECT imaging of the leg is useful in precise localization of the ischemic compartment involved in chronic exertional compartment syndrome (CECS). **Methods:** Imaging and quantitative analyses of postexercise ^{201}Tl SPECT leg examinations were retrospectively performed in nine patients with clinically diagnosed CECS and eight control subjects. Imaging and quantitative criteria for the ischemic compartment were decreased ^{201}Tl perfusion less than the lower limits of normal, which were defined as 2 s.d. below the mean percentage uptake of the control subjects. The SPECT imaging results were compared with those of quantitative analysis, postoperative SPECT images and clinical diagnoses. **Results:** Postexercise normal legs had nonuniform ^{201}Tl distribution in both legs and in the four compartments. Lower limits of normal mean percentage ^{201}Tl uptake were about 60% for the anterior compartment and about 50% for the other three compartments. Redistribution was observed in 67% of normal compartments in the control subjects. The SPECT images demonstrated 16 ischemic compartments in eight of the nine patients. The SPECT results were consistent with those of quantitative analysis. There were discrepancies between the clinical and SPECT diagnoses in six legs (33% of the 18 legs) of five patients. Postoperative SPECT demonstrated ^{201}Tl perfusion was improved in all involved compartments for that fasciotomy was performed. **Conclusion:** Thallium-201 SPECT imaging of the legs can easily provide precise localization of the ischemic compartment, which is demonstrated as decreased ^{201}Tl distribution on the stress image. This technique is promising for the screening and follow-up of CECS.

Key Words: sports injuries; chronic exertional compartment syndrome; thallium-201; SPECT

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The lower legs are commonly susceptible to compartment syndromes because muscles, nerves, blood vessels and bones are surrounded and protected by fascia. Chronic exertional compartment syndrome (CECS) is a condition in which pain occurs with exertional activity. Muscle hypertrophy may act to decrease the relative space available for the obligatory muscle swelling that occurs after exercise (1). Elevation of compartment pressure within a limited space reduces local blood flow, causing ischemia, which results in pain and neuromuscular dysfunction (2). The symptoms of CECS may often be reproduced after a defined period of exercise or distance, but the pain characteristically subsides after a period of rest (3). Accurate localization of CECS by clinical examination has been limited to 35% of cases (4). Measurement of compartment pressure by muscle puncture has been used in the diagnosis of CECS. However, this method is problematic because it is an invasive

procedure (3,5) and there is confusion as to how to take and interpret the measurements. Thallium-201 SPECT has been used to assess ischemic heart disease and peripheral arterial occlusive disease in the legs (6-8). Recently, Hayes et al. (5) reported that ^{201}Tl SPECT imaging of the leg can localize anterior or posterior ischemic regions involved by CECS quantitatively. They compared images of the lesions with normal leg images which have uniform uptake on stress images and no redistribution on delayed images. However, there has been a need for an imaging technique that precisely localizes and determines the number of affected compartments for evaluation of the severity of CECS and its treatment. The purpose of this study was to define ^{201}Tl distribution in postexercise normal legs and ascertain whether ^{201}Tl SPECT imaging of the leg is useful in the precise localization (anterior, lateral, superficial posterior and deep posterior compartments) of ischemic compartments involved by CECS.

MATERIALS AND METHODS

We performed ^{201}Tl SPECT imaging of the leg on nine athletes who had indications of CECS and eight normal asymptomatic volunteers from 1994 to 1995. The volunteers, all nonsmokers, consisted of five men and three women aged 21-28 yr (mean age, 23 yr). The patient group consisted of six men and three women aged 18-24 yr (mean age, 22 yr). The patients were four long distance runners, two jumpers, two soccer players and one basketball player. An experienced orthopedist diagnosed CECS in the nine patients who had pain in a particular compartment after a defined period of exercise. Bilateral lower legs were clinically involved in three patients and the unilateral lower leg was involved in six patients. Clinical diagnoses of the 18 legs were as follows: normal findings in five legs, anterolateral CECS in one leg, anterior CECS in three legs, lateral CECS in three legs and posterior CECS in four legs (Table 1).

In all patients, compartment pressures were measured in an operating room before surgical fasciotomy. The measurements were limited to the clinically involved compartment and its contralateral compartment served as a control because puncturing the muscle is an invasive technique that has the potential risk of neurovascular damage or muscular hernia (3,5). The pressures were measured with a simple 18-gauge needle at rest, during stress and 1 and 5 min after isometric foot dorsi-flexion for 1 min. Increasing compartment pressure was defined as fulfillment of the following three criteria: greater than 15 mmHg at rest, greater than 30 mmHg 1 min after stress and greater than 20 mmHg 5 min after stress (3). Equivocally increased pressure was defined as filling one or two of the three criteria.

All patients underwent surgical fasciotomy as treatment for CECS. Fasciotomy for decompressing anterior and lateral compartments was simultaneously performed through two anterolateral incisions in the anterior, lateral or both CECS. Surgical decompression of superficial posterior compartment was performed

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For correspondence or reprints contact: Shigeo Takebayashi, MD, Department of Radiology, Yokohama City Kowan Hospital, 3-2-3, Shin-Yamashita, Naka-ku, Yokohama 231, Japan.

TABLE 1
Pre- and Postoperative Thallium-201 SPECT Results in Nine Patients with Clinical CECS

Patient no.	Clinically involved compartments	Ischemic compartments on SPECT	Fasciotomy for compartments	Ischemic compartment on postoperative SPECT	Clinical result of fasciotomies
1*	Bil. lat.	Bil. lat.	Bil. ant. lat.	None	Excellent
2*	Bil. post.	Bil. sup. and deep post.	Bil. sup. post.	Bil. deep post.	Fair
3	Left lat.	Normal	Left ant. lat.	None	Fair
4	Right ant.	Right ant. lat. deep post.	Right ant. lat.	Right deep post.	Good
5	Left ant. lat.	Bil. ant. lat. deep post.	Bil. ant. lat.	Left deep post.	Good
6*	Right ant.	Right ant.	Right ant. lat.	None	Excellent
7	Left post.	Left lat.	Left sup. post.	Left lat.	Fair
8	Right ant.	Right lat.	Right ant. lat.	None	Excellent
9*	Left post.	Left deep post.	Left deep post.	None	Good

*Patients with clinical localization of affected compartments that were consistent with SPECT findings.

Bil. lat. = bilateral; bil. post. = bilateral posterior; bil. sup. = bilateral superior; deep post. = deep posterior; sup. post. = superior posterior.

through two posteromedial incisions. The tibialis posterior muscle compartment was decompressed in the deep posterior CECS. The fasciotomy results were evaluated by modified classification of Abramowitz and Schepesis criteria (3): excellent: no pain during or after exercise; good: minimal discomfort or soreness during or after exercise; fair: pain with running or exercise or afterward. All patients also underwent follow-up ²⁰¹Tl SPECT imaging 3 mo postsurgery.

Thallium-201 SPECT Leg Imaging

Thallium-201 SPECT leg imaging was performed in all patients and normal volunteers after they ran on a flat treadmill at a speed of 5.0 km/hr. Thallium-201-chloride (74 MBq) was intravenously injected in the patients when their leg symptoms had been reproduced during exercise (approximately 12 min). Exercise was continued for 1 min to allow tracer distribution at stress. In the control group, the same tracer dosage was injected after 12 min of exercise, which was the time at which leg symptoms had been reproduced during exercise for the patient group. SPECT images were obtained 5 and 180 min postinjection (stress and delayed images) with the patients in the supine position. A dual-head SPECT gamma camera was used to acquire 90 views over 360° with step-and-shoot methodology for 20 sec per stop through an elliptical orbit. Low-energy, high-resolution collimation was used with the camera peaked at 70 keV using a 20% window and at 166 keV using a 15% window. A Butterworth reconstruction filter with a 0.5 cutoff was used. The images were collected on 64 × 64 matrices and reconstructed to obtain both transaxial and coronal images. Transaxial and coronal slices were produced with a 10-mm of slice thickness. The images were displayed by 10-step color scales indicating 0%–10% to 90%–100% of maximum radionuclide uptake.

Quantitative Analysis

The lower leg was divided into anterior, lateral, superficial posterior and deep posterior compartments (Fig. 1). The border between the anterior and lateral compartment was delineated by extending a horizontal line from the ventral border of the fibula. The deep posterior compartment corresponded with tracer uptake between the tibia and fibula. Quantitative analyses were performed in 11 serial transaxial images of which the midcalf was center. Maximum uptake in both calves was obtained after a region of interest (ROI) was drawn manually over the area of 90%–100% uptake (white code area). In each compartment, the mean percentage of the maximum uptake was calculated after ROIs were drawn manually over each compartment (Fig. 2). The percent uptakes were displayed as “profile” curves generated from the stress images. Quantitative criterion for ischemic compartment is that the stress profile curve drops lower than the lower limit of normal stress curve. Profile curves of 2 s.d. below the mean percentage

uptake from the control subjects provided reference standards for quantitative analysis. The lowest uptake in the profile curve of each compartment was defined as an approximately lower limit of normal. Student’s test was used to determine any significant difference in the mean values of the profile curves among the four compartments. We also obtained the degree of redistribution according to the following formula:

$$\frac{(\text{Mean counts delayed image} - \text{mean counts stress image})}{\text{Mean counts stress image}}$$

In the formula, the mean counts of both stress and delayed images were corrected by subtracting the mean count of the background.

Imaging Analysis

The patient images were analyzed visually by two radiologists who knew the SPECT results of the control group but were blinded to the patients’ clinical and scintigraphic data. The reviewers evaluated ²⁰¹Tl perfusion in each compartment that were displayed as 10-step color scales indicating 0%–10% to 90%–100% of maximum radionuclide uptake. The imaging criterion for the ischemic compartment is decreased ²⁰¹Tl uptake less than the lower limit of normal obtained by quantitative analysis of control subject images. Therefore, the legs with heterogeneous uptake and

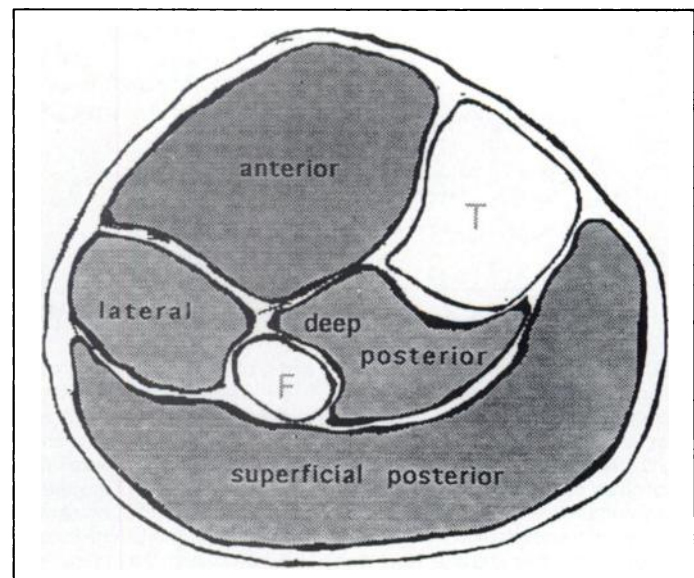


FIGURE 1. Cross-section of right calf at midlevel demonstrates the four compartments. T = tibia, F = fibula.

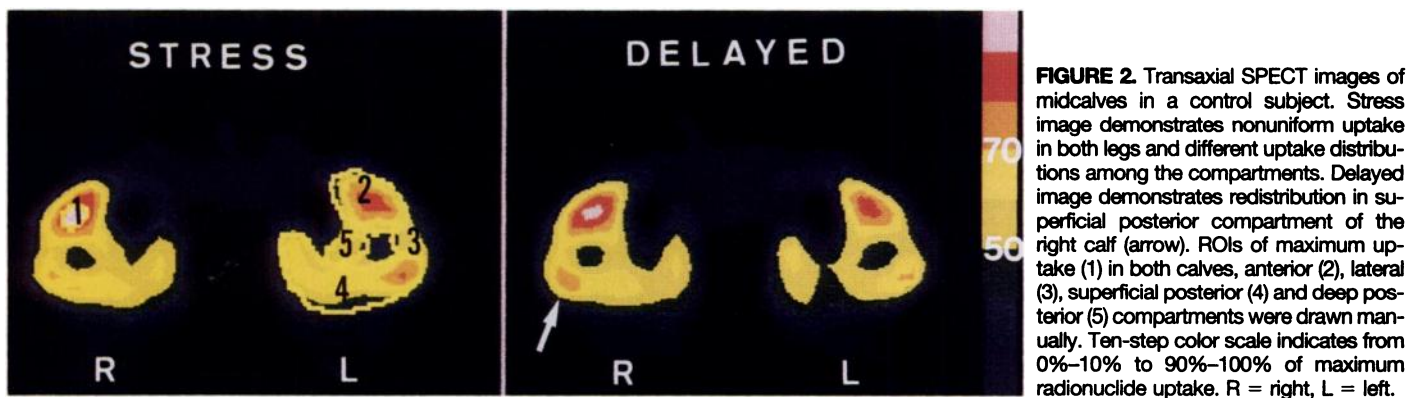


FIGURE 2. Transaxial SPECT images of midcalves in a control subject. Stress image demonstrates nonuniform uptake in both legs and different uptake distributions among the compartments. Delayed image demonstrates redistribution in superficial posterior compartment of the right calf (arrow). ROIs of maximum uptake (1) in both calves, anterior (2), lateral (3), superficial posterior (4) and deep posterior (5) compartments were drawn manually. Ten-step color scale indicates from 0%–10% to 90%–100% of maximum radionuclide uptake. R = right, L = left.

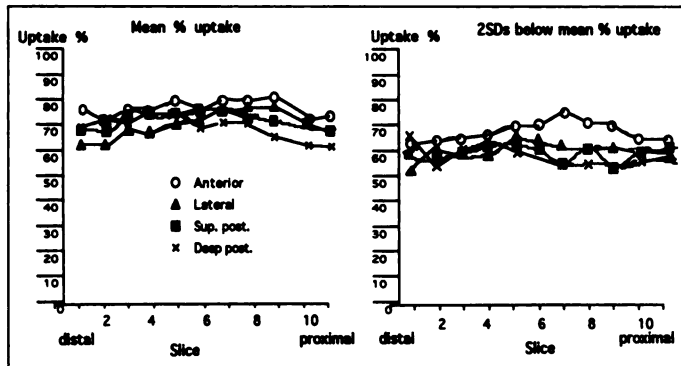


FIGURE 3. Profile curves of mean percent uptake and 2 s.d. below mean percent uptake in the four compartments of the control group. Lowest values of 2 s.d. below the uptake representing the lower limits of normal were approximately 60% for the anterior compartment and approximately 50% for the lateral, superficial posterior and deep posterior compartments.

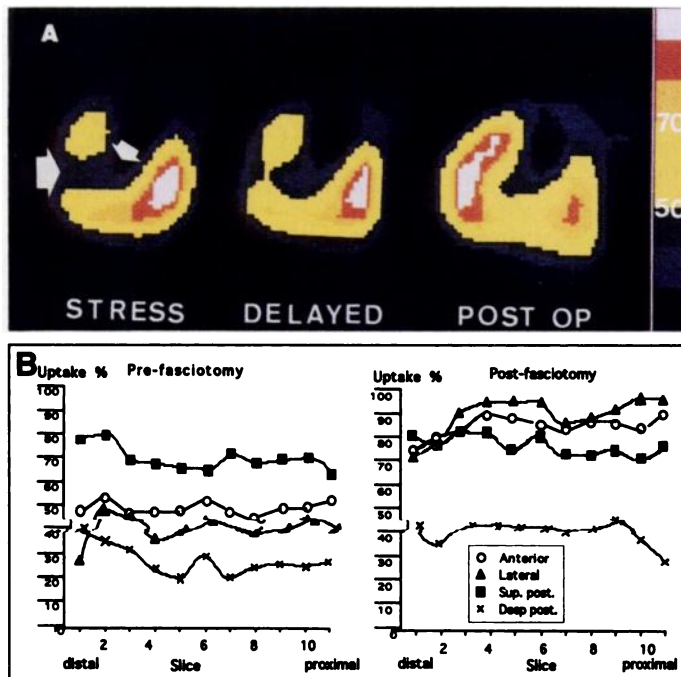


FIGURE 4. Transaxial SPECT images (A) and profile curves (B) of right calf with clinical involvement of anterior CECS. (A) Thallium-201 distribution is decreased in the lateral (large arrow) and deep posterior compartments (small arrow) on the stress image. Uptake in the anterior compartment is slightly decreased than normal. Lateral compartment has incomplete redistribution on the delayed image. Stress image after fasciotomy of the anterolateral compartment demonstrates marked improvement of ^{201}Tl distribution in the anterior and lateral compartments. (B) Image findings are confirmed on profile curves before and after fasciotomy. Clinical results of fasciotomy were good. Thallium-201 distribution in the deep posterior compartment is also slightly improved after fasciotomy for decompression of the adjacent compartment.

redistribution were diagnosed as normal legs unless they had abnormally decreased ^{201}Tl uptake. Disagreements were resolved with the help of a third observer and finally by consensus. The SPECT findings were compared with the results from quantitative analyses, compartment pressure and clinical diagnoses. They were also compared with the postoperative SPECT image findings and the clinical results from fasciotomy.

RESULTS

Normal Asymptomatic Volunteers

Transaxial stress SPECT images of the lower leg demonstrated that a large anterior defect indicates the tibia and a small posterior defect indicates the fibula. The postexercise SPECT images defined each compartment, but there was nonuniform ^{201}Tl distribution in both legs and in the four compartments (Fig. 2). Figure 3 demonstrates the profile curves with mean percentage uptake and 2 s.d. below the mean percentage uptake in each compartment. Mean values of the mean percentage uptake were 75% (s.d., 3.1%) in anterior compartment, 69% (s.d., 5.3%) in the lateral compartment, 72% (s.d., 3.4%) in the

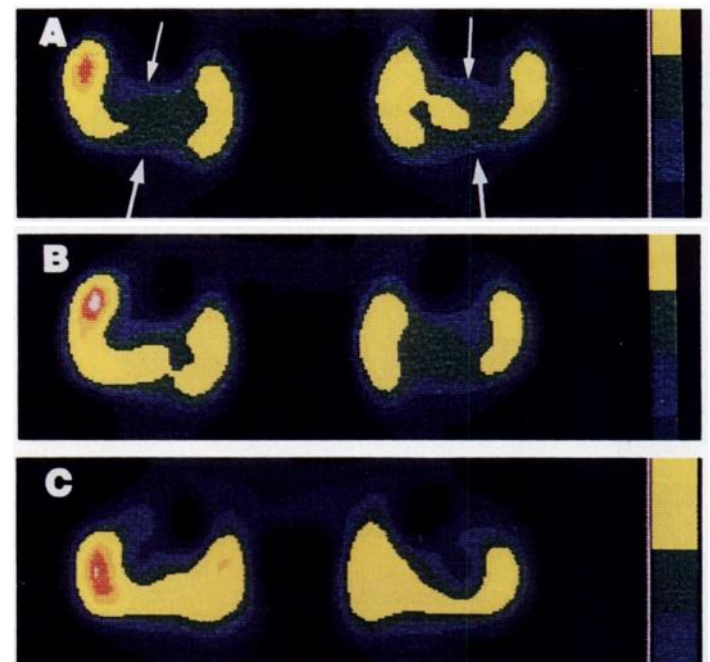


FIGURE 5. Transaxial SPECT images of calves clinically involved by posterior CECS. (A) Decreased ^{201}Tl perfusion in both superficial (large arrows) and deep (small arrows) posterior compartments is observed on the stress image. (B) Redistribution is observed in the right superficial and anterior compartments on the delayed image. (C) Thallium-201 distribution in the bilateral superficial compartments is improved on the stress image after fasciotomy of the bilateral superficial posterior compartments. Clinical result for fasciotomy was poor.

superficial posterior compartment and 68% (s.d., 4.3%) in the deep posterior compartment. Those compartments 2 s.d. below the mean percentage uptake were: 66% (range: 61%–75%, s.d.: 4.3%) anterior compartment, 59% (range: 51%–65%, s.d.: 3.6%) lateral compartment, 57% (range: 51%–62%, s.d.: 3.6%) superficial posterior compartment and 56% (range: 51%–62%, s.d.: 4.0%) deep posterior compartment. There were statistical differences in the mean values between the anterior and other compartments ($p < 0.001$). The lower limits of normal for the percent uptake values were estimated as approximately 60% for the anterior compartment and approximately 50% for other the compartments. Redistribution was observed in 69% (11 compartments) of the anterior compartments, 67% (12 compartments) of the lateral compartments, 44% (7 compartments) of the superficial posterior compartments and 81% (13 compartments) of the deep posterior compartments. The mean redistribution ratios were 6.8% (range: 1.0%–13%, s.d.: 4.8%) in the anterior compartments, 7.5% (range: 0.5%–18%, s.d.: 6.0%) in the lateral compartments, 3.0% (range: 0.4%–8.2%, s.d.: 2.3%) in the superficial posterior compartments, 5.6% (range: 0.4%–17%, s.d.: 4.2%) in the deep posterior compartments.

Patients

The SPECT images demonstrated 16 ischemic compartments in 10 legs of 8 patients. In the one remaining patient, lateral CECS was clinically diagnosed, but the SPECT image demonstrated normal ^{201}Tl perfusion in the legs. The 16 ischemic compartments were four anterior compartments, 7 lateral compartments, 2 superficial posterior compartments and 6 deep posterior compartments. Four (40%) of the 10 legs had two or three ischemic compartments (Figs. 4, 5). Ischemic compartments on the SPECT images were consistent with those determined by quantitative analysis. The mean values of the percent uptake in the ischemic compartments ranged from 25% to 48% (mean: 37%, s.d.: 5.9%). Redistribution was observed in 12 of 16 compartments with decreased ^{201}Tl perfusion on stress SPECT images. However, the finding was observed in all ischemic compartments by quantitative analysis. The degree of redistribution in the compartments ranged from 4.0% to 33% (mean: 13%, s.d. 7.1%).

There were discrepancies between the clinical and SPECT findings in six legs (33% of the 18 legs) of five patients (Table 1). The SPECT image demonstrated abnormally decreased ^{201}Tl uptake in the adjacent compartment in one leg, an additional ischemic compartment in four legs and normal ^{201}Tl uptake in the one remaining leg. Compartment pressures were measured in 18 compartments (Table 2). Thallium-201 uptake in the 18 compartments was decreased in 9 and normal in 9. Compartment pressures in the nine ischemic compartments were increased in six and equivocally increased in three. All of the nine compartments with normal ^{201}Tl uptake had normal pressures. The nine compartments with decreased ^{201}Tl uptake had increased pressure in six and equivocally increased pressure in three. Postoperative SPECT demonstrated improved ^{201}Tl uptake in all ischemic compartments in which fasciotomy was performed (Figs. 4, 5). The clinical results of fasciotomy were good or excellent in seven legs. In two of the seven legs, ^{201}Tl uptake in the ischemic deep posterior compartments was slightly improved after fasciotomy for decompressing adjacent compartments, although fasciotomy for the deep posterior compartment was not performed (Fig. 4). Clinical results of fasciotomy in three legs that had equivocally increased compartment pressure and ischemic SPECT scans were: excellent—one leg with equivocally increased pressure in the anterior compartment; good—one leg with pressure in the lateral

compartment and the remaining one leg with pressure in the deep posterior compartment.

DISCUSSION

The precise pathogenesis of CECS is not known. However, muscle hypertrophy may act to decrease the relative space available for obligatory muscle occurring after exercise (1). Typical history of CECS of the lower leg is that of an athlete who describes recurrent pain in the area of the affected compartment during physical activity. The symptoms often may be reproduced after a defined period of exercise or distance, but the pain characteristically subsides after a period of rest (3). The symptoms of soreness behind the tibia in CECS involving the deep posterior compartment mimics that of shin splint, which pathogenesis is suggested to be periostitis in athletes (9). The accurate localization of CECS by clinical examination is limited to 35% (4) because the typical characteristic of CECS during physical examination is the scarcity of any definite finding (3). MRI has been evaluated as a noninvasive technique for diagnosis of CECS. There may be a relationship between compartment pressure and proton relaxation time constants (10), but the practical value of MRI is not indicated in routine assessment of CECS. The role of ultrasound in diagnosing CECS has been limited to measurements of enlarged muscles before and after exercise (11).

The measurement of pre- and postexercise compartment pressures by puncturing the muscles has been commonly used and is considered to be a definitive method to confirm the diagnosis of CECS. This technique is problematic because of a lack of consensus on optimal methodologic and diagnostic criteria (3,12). Measurement of compartment pressure in all four compartments of each leg is required because multiple compartments in a leg are affected in about a half of CECS and symptoms in the bilateral compartments occur in approximately 75% of cases (4). The measurements are time-consuming for both patients and physicians because in pressure measurements only one compartment at a time can be examined dynamically. The pressure in the anterior, lateral and superficial compartments is easily measured under local anesthesia. However, puncturing the muscles is an invasive technique that has the potential risks of neurovascular damage or muscular hernia (3). On occasion, it may impair the athlete's ability to exercise for dynamic pressure measurements (5). In the measurement of deep posterior compartment pressure, the catheter needs to be positioned just behind and parallel to the posterior surface of the tibia. The measurement may be less reliable and more invasive than that of other compartmental pressure measurements because the technique is not easy.

In skeletal muscle, intravenous distribution of ^{201}Tl is affected by the fraction of cardiac output and is related to regional

TABLE 2
Correlation Between Thallium-201 Perfusion and Compartment Pressure in 18 Compartments

Compartment	^{201}Tl perfusion (no. of compartments)	Compartment pressure		
		Normal	Equivocally increased	Increased
Anterior/lateral	Normal (6)	6	0	0
	Ischemia (6)	0	2	4
Superficial posterior	Normal (2)	2	0	0
	Ischemia (2)	0	0	2
Deep posterior	Normal (1)	1	0	0
	Ischemia (1)	0	1	0
	Total (18)	9	3	6

blood flow. After exercise, normal muscles in the lower legs have an immediate reactive increased flow of up to 20-fold, but this subsides in 2–5 min (7). If ^{201}Tl is administered at peak exercise, the ischemic muscle area has decreased tracer activity because the vessels in the affected compartment are compressed and less muscle is exposed to the tracer. Vigorous exercise may result in sufficient muscle swelling and microscopic hemorrhage to raise compartment pressure (1). When the pressure is greater than 20 mmHg below the diastolic pressure, decreased blood flow and ischemias occur (13).

Hayes et al. (5) have demonstrated the utility of ^{201}Tl SPECT for diagnosing CECS and localizing either the anterior or posterior portion of the calf. Their criteria for normal muscles are uniform ^{201}Tl uptake on postexercise SPECT scans and no redistribution on the delayed image. The criteria for CECS are reduction of local muscle blood flow and redistribution. However, it is important to know the precise localization and number of affected compartments in order to evaluate the severity of CECS and various treatment modalities. The present study demonstrates that color SPECT images have enough resolution to define each of the four compartments, including the deep posterior compartment. Thallium-201 SPECT has definite advantages over compartment pressure measurements. The non-invasive technique can be performed after exercise, which is sufficient for reproducing CECS symptoms. A single SPECT study can evaluate blood perfusion in each compartment of the postexercise legs.

Ischemic findings on the SPECT scans are also observed in peripheral arterial occlusive disease (8), but CECS is strongly suggested in young athletes with ischemic legs because of their limited likelihood of having arterial disease.

An initial experimental study of thallium distribution has demonstrated that thallium concentration in rest skeletal muscle rises with time, although the concentration is initially high and declines with time in resting myocardium (14). The average thallium concentration in the heart at 4 hr postinjection is about one-fifth of the concentration at 10 min postinjection, whereas that in the muscle at 4 hr is about 1.5 the concentration at 10 min (14). Therefore, redistribution is not an abnormal finding in ^{201}Tl SPECT images of the leg. Our study demonstrates that normal leg muscles after exercise have nonuniform activity in both legs with differences in distribution in the compartments. Legs with heterogeneous uptake and redistribution are diag-

nosed as normal unless they have compartments with abnormally decreased ^{201}Tl uptake.

There is no uniform agreement for treatment of CECS. Some authors stressed that surgical decompression of the involved compartment is recommended once a diagnosis of CECS is established (3). However, Hutchinson and Ireland (12) recommend that fasciotomy be performed if symptoms persist for more than 3–6 mo on conservative therapy. The present study suggests that ^{201}Tl SPECT has promise for diagnosing and localizing CECS, although a larger group of patients need to be studied and a reference standard needs to be developed. In time, this noninvasive technique may replace compartment pressure measurement in the screening and follow-up of CECS.

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REFERENCES

1. Strahley D, Jones WW. Acute compartment syndrome (anterior, lateral and superficial posterior) following tear of the medial head of gastrocnemius muscle. *Am J Sports Med* 1986;14:96–99.
2. Styf J. Chronic exercise-induced pain in the anterior aspect of the lower leg: an overview of diagnosis. *Sports Med* 1989;7:331–339.
3. Abramowitz AJ, Schepisis AA. Chronic exertional compartment syndrome of the lower leg. *Orthop Rev* 1994;23:219–225.
4. Moeyersoons JP, Mertens M. Chronic compartment syndrome. Diagnosis and management. *Acta Orthopædica Belgica* 1992;58:23–27.
5. Hayes AA, Bower GD, Pitstock KL. Chronic (exertional) compartment syndrome of the legs diagnosed with thallous chloride scintigraphy. *J Nucl Med* 1995;36:1618–1624.
6. Alazraki NP, Krawczyńska EG, DePuey EG, et al. Reproducibility of thallium-201 exercise SPECT studies. *J Nucl Med* 1994;35:1237–1244.
7. Seder JS, Botvinick EH, Rahimtoola SH, Goldstone J, Price DC. Detecting and localizing peripheral arterial disease: assessment of ^{201}Tl scintigraphy. *Am J Roentgenol* 1981;137:373–380.
8. Oshima M, Akanabe H, Sakuma S, Yano T, Nishikimi N, Shinoyama S. Quantification of leg muscle perfusion using thallium-201 single-photon emission computed tomography. *J Nucl Med* 1989;30:458–465.
9. Holder LE, Michael RH. The specific scintigraphic pattern of shin splint in the lower leg: concise communication. *J Nucl Med* 1984;25:865–869.
10. Amendola A, Rorabeck CH, Velleit D, Vezina W, Rutt B, Nott L. The use of magnetic resonance imaging in exertional compartment syndrome. *Am J Sports Med* 1990;18:29–34.
11. van Holsbeeck M, Introcaso JM. Musculoskeletal ultrasonography. *Radiol North Clin Am* 1992;30:907–925.
12. Hutchinson MR, Ireland ML. Common compartment syndromes in athletes: treatment and rehabilitation. *Sports Med* 1994;17:200–208.
13. Matava MJ, Whitesides TE Jr, Seiler JG, Hewan-Lowe K, Hutton WC. Determination of the compartment pressure threshold of muscle ischemia in a canine model. *J Trauma* 1994;37:50–58.
14. Gehring PJ, Hammond PB. The interrelationship between thallium and potassium in animals. *J Pharmacol Exp Ther* 1967;155:187–210.