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The Value of Thermal Imaging for Knee Arthritis: A Single-Center Observational Study

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Purpose: To compare (non-contact) thermal imaging with power Doppler (PD) for the evaluation of knee arthritis with joint effusion.
Materials and Methods: We enrolled patients with knee arthritis who were scheduled to undergo an arthrocentesis of the knee from April to December 2020 at a single tertiary hospital. A thermography camera, FLIR ONE Pro, was used to obtain both thermographic and digital images on subjects. For each subject, thermography, ultrasonography, arthrocentesis, and blood tests were conducted at the same study visit. Thermal imaging findings and clinical characteristics were compared by dividing the subjects into PD-positive and PD-negative groups on ultrasound. The receiver operating characteristic (ROC) curve analysis was used to determine the accuracy of PD positivity.
Results: A total of 30 knee arthritis patients were enrolled in this study. Knee temperature was significantly higher in PD-positive group compared to PD-negative group [maximum temperature (T max): 33.2°C vs. 30.5°C, p=0.025; minimum temperature (T min): 30.7°C vs. 27.0°C, p=0.015; average temperature (T ave): 32.1°C vs. 29.1°C, p=0.016]. Also, the joint fluid white blood cell count was considerably higher in PD-positive group than in PD-negative group (24556 cells/mm^3 vs. 7840 cells/mm^3, p=0.010). The area under the ROC curve of the point measurement of T max, T min, and T ave ranged between 0.764 and 0.790.
Conclusion: In this study, we found that high thermographic temperatures of the knee suggest a positive PD signal. Thus, thermography might be used as an adjuvant tool of PD for non-invasive evaluation of knee arthritis.

Key Words: Thermography, ultrasonography, synovial fluid, arthrocentesis, knee, arthritis

INTRODUCTION

Inflammatory arthritis is characterized by cardinal signs of inflammation on physical examination, such as warmth, redness, swelling, and tenderness.[1,2] Also, synovial fluid analysis is helpful for the diagnosis of inflammatory arthritis. The white blood cell (WBC) count of synovial fluid is classified as inflammatory arthritis when it exceeds 2000 cells/mm^3.[3] Ultrasound is a valuable, non-invasive tool to evaluate the activity of inflammatory arthritis.[4] Notably, the power Doppler (PD) of ultrasound detects pathological blood flow in the synovium, which reflects joint inflammation.[5,6] However, ultrasound is operator-dependent and requires professional knowledge, such as musculoskeletal anatomy.[7] Thermography is a technique that measures the temperature of an object without physical contact by capturing the infrared radiation energy of an object using a thermographic camera.[8] Attempts to use thermal imaging systems as medical diagnostic tool began in the 1960s.[9] Thermography has been used to diagnose and evaluate several diseases that cause changes in local body temperature, including Raynaud's

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phenomenon, scleroderma, burns, and diabetic feet.[10,11] Inflammation, infection, or malignancy can cause a local temperature rise that can be detected by thermal imaging. Thermography has also emerged as another non-invasive imaging tool for evaluating arthritis in that it reflects increased pathological blood flow associated with inflamed joints.[12,13]

Therefore, we studied the role of non-invasive thermographic evaluation as an adjuvant diagnostic tool by comparing thermographic findings, ultrasound PD findings, and joint fluid analysis in patients with knee arthritis.

MATERIALS AND METHODS

Study population

Patients with swollen knee joints were prospectively enrolled in this study from April to December 2020 at the rheumatology clinic, a tertiary referral hospital in Seoul, Korea. All patients undergoing arthrocentesis of the knee joints were eligible. The exclusion criteria were as follows: 1) patients with peripheral arterial disease and autonomic neuropathy; 2) patients who have used cosmetics, creams, deodorants, acupuncture, hot packs on their knees that may affect local body temperature; and 3) patients who have undergone total knee replacement arthroplasty.

This study was approved by the Institutional Review Board (IRB) of Asan Medical Center, Seoul, Korea (IRB No. 2020-0691), and all patients were enrolled after providing written informed consent.

Baseline characteristics

The following data of patients were collected from the electronic medical records: age, sex, diagnosis, and medication use [including disease-modifying anti-rheumatic drugs (DMARDs) and corticosteroids] at the time of enrollment.

Thermographic image acquiring and image processing

Participants were examined after being rested for 20 min in the examination room. The ambient temperature of the room was maintained at 22°C±1.0°C and the humidity at 55%, with stable airflow. Both thermography image and digital image of the subject were taken with FLIR ONE Pro thermal imaging camera attached to a smartphone. Photographs were taken using a tripod at the same magnification and the same distance (1 m) from the knees. The pictures were transferred to a computer, and thermal data were processed in the FLIR Tools software program and analyzed by two-blinded evaluators. The knee region was assessed by a circle involving the entire anterior knee (Fig. 1). The knee region of interest (ROI) was defined as a circle that was at least 5.5 cm in diameter, including the medial and lateral epicondyle of the femur in surface anatomy with-

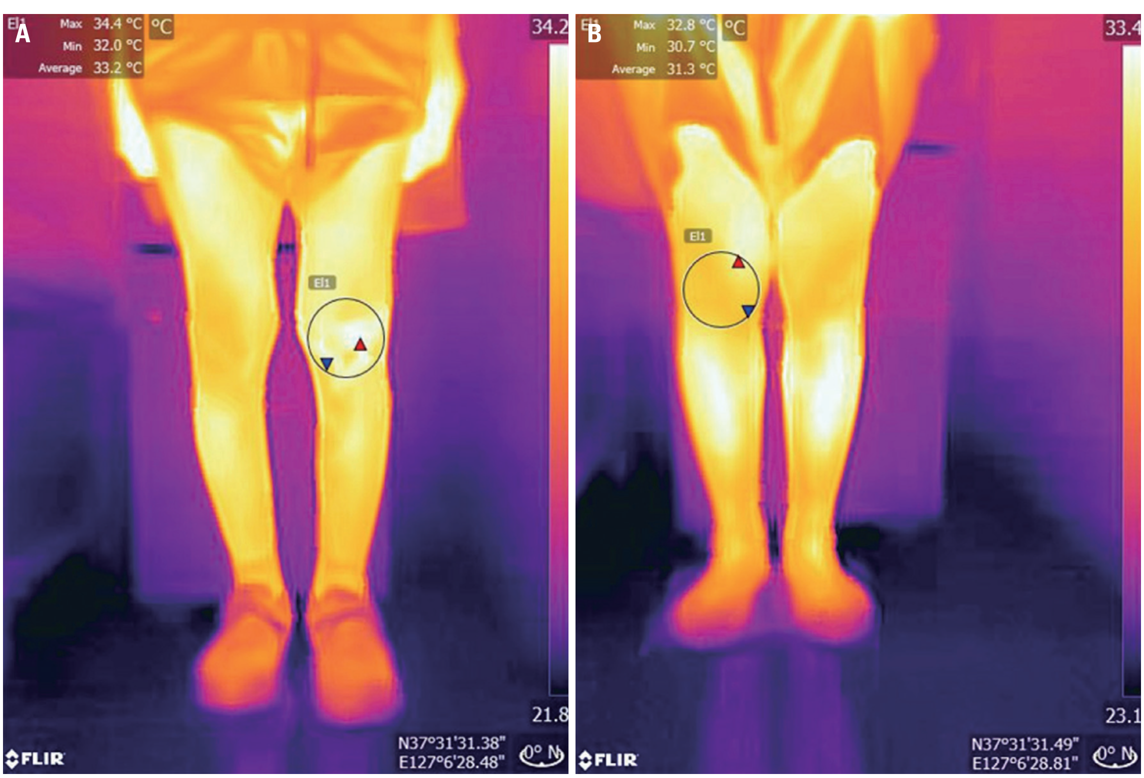

Fig. 1. Thermal images of the patients with knee arthritis. This figure shows an example of how a region of interest was manually selected from the thermal image by using a circle box placed over the knee of the patient. (A) Rheumatoid arthritis (left-knee arthritis). (B) Osteoarthritis (right-knee arthritis). The red and blue arrowheads indicate the highest and lowest temperature regions, respectively.

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in the knee contour range of the patella center. The maximum temperature (T max), minimum temperature (T min), average temperature (T ave), and gap of temperature (T max–T min) in degrees Celsius (°C) were recorded at ROI.

Evaluation of knee joint fluid, ultrasound, and blood samples

For each subject, thermography, ultrasonography, arthrocentesis, and blood tests were performed during the same study visit. Standardized knee ultrasound scanning was conducted following the European Alliance of Associations for Rheumatology guideline.[14] Knee ultrasound was performed using an RS80A (Samsung Medison, Co., Ltd., Seoul, Korea) with an L3-12A linear probe. The presence (PD grade 1 to 3) or absence of PD (PD grade 0) signal in the parapatellar recess was evaluated.[6] Ultrasound-guided arthrocentesis was conducted at the affected knee after taking a thermographic photograph. A synovial fluid sample was tested for gram-stain, bacterial culture, crystal examination, and cell counts, including the differential count. A venous blood sample was obtained from each patient to measure the WBC, hemoglobin, platelet counts, erythrocyte sedimentation rate (ESR), and C-reactive protein (CRP).

Statistical analyses

The chi-square test or Fisher's exact test was used to compare categorical data. Continuous values are expressed as means (standard deviations) or median (interquartile range), and they were compared using Student's t-test for parametric data or Mann-Whitney U test for nonparametric data. Intra-class correlation coefficient (ICC) was used to analyze the reliability of the measured temperature between inter-observers. ICC values were interpreted with the following cutoff points: <0.5, poor; 0.5−0.75, moderate; 0.75−0.9, good; and >0.9, excellent reliability.[15] The receiver operating characteristic (ROC) curve was used to determine the diagnostic accuracy [area under the ROC curve (AUC)]. The cut-off value for each variable was determined at the level at which Youden's index was the maximum.[16] The Spearman rank correlation coefficient was used to describe the correlation between joint fluid WBC counts and other baseline characteristics, including T max. Statistical significance was set at $p<0.05$. All statistical analyses were conducted in IBM SPSS, v.21.0 (IBM Corp., Armonk, NY, USA).

RESULTS

Baseline characteristics

A total of 30 patients with knee arthritis were enrolled in this study. The baseline characteristics of these patients are shown in Table 1. The mean age was 51.6 years, and 19 (63.3%) patients were female. The most common disease was rheumatoid arthritis (RA) (40.0%), followed by spondyloarthritis (36.7%), other inflammatory arthritis (16.7%), and osteoarthritis (6.7%). At the time of enrollment, 18 of 30 patients (60.0%)

Table 1. Baseline Characteristics of the 30 Study Patients

Characteristics	Total (n=30)	Doppler (-) (n=22)	Doppler (+) (n=8)	*p* value
Age, yr	51.6±13.0	51.7±11.6	51.3±17.1	0.931
Female	19 (63.3)	12 (54.5)	7 (87.5)	0.199
Diagnosis				>0.999
Rheumatoid arthritis	12 (40.0)	8 (36.4)	4 (50.0)	
Spondyloarthritis	11 (36.7)	8 (36.4)	3 (37.5)	
Other inflammatory arthritis	5 (16.7)	4 (18.2)	1 (12.5)	
Osteoarthritis	2 (6.7)	2 (9.1)	0	
Thermographic findings, °C				
T max	31.2±3.0	30.5±2.9	33.2±2.4	0.025
T min	28.0±3.8	27.0±3.8	30.7±2.6	0.015
T ave	29.9±3.1	29.1±3.0	32.1±2.3	0.016
T max–T min	2.7 (2.1–3.0)	2.7 (2.1–3.5)	2.6 (2.1–2.8)	0.496
Laboratory findings				
Joint fluid WBC counts, mm^3	10355 (2884–26157)	7840 (1175–19811)	24556 (15998–38158)	0.010
Inflammatory arthritis	24 (80.0)	16 (72.7)	8 (100)	0.155
Blood WBC counts, μL	8207±2429	8157±2575	8338±2152	0.851
Hemoglobin, g/dL	12.6±1.9	12.7±2.1	12.5±1.5	0.821
Platelet, $\times 10^9$/L	300±84	281±73	351±95	0.044
ESR, mm/hr	32 (13–78)	24 (9–65)	51 (20–89)	0.204
CRP, mg/dL	1.3 (0.3–3.3)	0.7 (0.3–3.0)	2.5 (0.5–3.6)	0.449

T max, maximum temperature; T min, minimum temperature; T ave, average temperature; WBC, white blood cell; ESR, erythrocyte sedimentation rate; CRP, C-reactive protein.
Data are presented as mean±standard deviation, n (%) or median (interquartile range).

were on one or more DMARDs (methotrexate, hydroxychloroquine, sulfasalazine, and/or biologics), while eight of 30 patients (26.7%) were on corticosteroids.

Thermographic findings

There was excellent inter-observer consistency for T max, T min, T ave, and T max–T min. The ICC between the two observers was 0.999 [95% confidence interval (CI) 0.998–1.000] for T max, 0.993 (95% CI 0.985–0.997) for T min, 1.000 (95% CI 0,999–1.000) for T ave, and 0.973 (95% CI 0.943–0.987) for T max–T min. The mean T max, mean T min, mean T ave, and median T max–T min of the mean temperature values of the study patients measured by two observers were 31.2°C, 28.0°C, 29.9°C, and 2.7°C, respectively. The median WBC count in the joint fluid was 10355 cells/mm^3. Twenty-four (80%) patients had inflammatory arthritis, defined as a joint fluid WBC above 2000 cells/mm^3. In all patients, no bacteria or crystals were found in the synovial fluid.

Thermographic findings and inflammatory parameters of knee arthritis

Eight (26.7%) patients showed positive PD findings on ultrasound. The T max, T min, and T ave were significantly higher in PD-positive group than in PD-negative group (T max: 33.2°C vs. 30.5°C, p=0.025; T min: 30.7°C vs. 27.0°C, p=0.015; T ave: 32.1°C vs. 29.1°C, p=0.016). Also, the joint fluid WBC count was significantly higher in PD-positive group than in PD-negative group (24556 cells/mm^3 vs. 7840 cells/mm^3, p=0.010).

Fig. 2 shows the ROC curve for the temperature values to predict PD positivity. Table 2 shows the accuracy values of thermographic temperature, best cut-off point, sensitivity, and specificity. T max had an AUC of 0.764 (95% CI 0.570–0.958) at a cut-off value of 32.8°C, T min (AUC=0.790, 95% CI 0.615–0.964, a cut-off value 28.6°C), and T ave (AUC=0.770, 95% CI 0.581–0.959, cut-off value 30.1°C) showed similar results to T max. When the subjects were divided into two groups based on thermographic temperature cut-off values, the PD-positive rate was significantly higher in the higher temperature group in all T max, T min, and T ave (T max: 75.0% vs. 25.0%, p=0.028; T min: 87.5% vs. 12.5%, p=0.012; T ave: 87.5% vs. 12.5%, p=0.012). In an initial cross-sectional analysis, joint fluid WBC count did not correlate with T max (r=0.063, p=0.739), T min (r=0.036, p=0.849), and T ave (r=0.060, p=0.752).

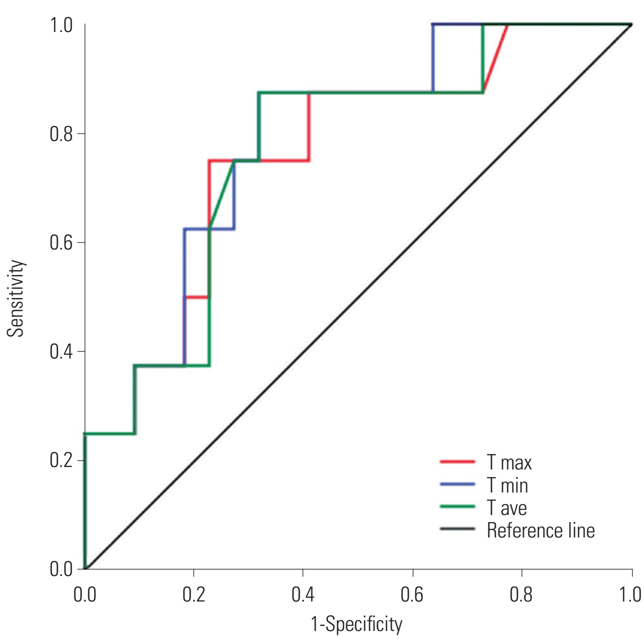

Fig. 2. Receiver operating characteristic curve of power Doppler-positive and negative knee temperature.

DISCUSSION

This study aimed to compare thermographic findings with PD-ultrasound in patients with knee arthritis. It showed that the temperature of knee arthritis measured by thermography could reflect PD positivity on ultrasound.

Thermography is a technique that can be applied in conditions where thermal temperature changes may indicate a problem.[11] In inflammatory arthritis, the local temperature increases due to increased vascularity in the inflamed tissue area. Since the 1980s, there have been studies using thermography to diagnose inflammatory arthritis.[17,18] The results of several studies on whether the thermal imaging findings reflect the inflammatory status of inflammatory arthritis are controversial (Table 3).[13,18-22] There have been reports that the joint thermographic results of patients with RA are higher than those of healthy participants, suggesting that thermography can be used as a supportive tool for RA.[21,22] Tan, et al. reported that a high thermographic temperature in PD-positive RA joint, and the use of combined thermal and ultrasound imaging in RA showed superiority to both imaging alone in correlation with disease activity score assessed by disease activity score in 28 joints.[13,23] Similarly, Jones, et al.[20] also reported that hand joint

Table 2. AUC, Best Cut-Off Point, Sensitivity, and Specificity of Infrared Thermography of the Knee

	AUC (95% CI)	Cut-off (°C)	Sensitivity (%)	Specificity (%)
T max	0.764 (0.570–0.958)	32.8	75.0	77.3
T min	0.790 (0.615–0.964)	28.6	87.5	68.2
T ave	0.770 (0.581–0.959)	30.1	87.5	68.2

AUC, area under the receiver operating characteristic curve; T max, maximum temperature; T min, minimum temperature; T ave, average temperature; CI, confidence interval.

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Table 3. Summary of Literature Included in the Review

Authors	Participant	Findings
Ahn et al. (current study)	Knee arthritis (n=30) - Rheumatoid arthritis (n=12) - Spondyloarthritis (n=11) - Other inflammatory arthritis (n= 5) - Osteoarthritis (n=2)	High thermographic temperatures of the knee were suggestive of the presence of positive power Doppler signal. The temperature on thermography was elevated in patients with positive power Doppler on ultrasound. White blood cell count in the joint fluid did not correlate with thermal imaging parameters.
Devereaux, et al.[18]	Rheumatoid arthritis (n=20)	Thermographic findings showed significant correlation with rheumatoid arthritis disease activity (pain score, grip strength, and ESR).
Pauk, et al.[22]	Rheumatoid arthritis (n=66) - High disease activity (n=50) - Moderate disease activity (n=16) Healthy participants (n=42)	Thermography detects the rheumatoid arthritis disease activity level and can be used in clinical practice as a supportive tool in diagnosis due to several reasons.
Gatt, et al.[21]	Rheumatoid arthritis (n=31) Healthy participants (n=51)	In rheumatoid arthritis patients without active inflammation, the hand temperature was significantly higher than that of healthy individuals.
Tan, et al.[13]	Rheumatoid arthritis (n=37)	The use of combined thermal and ultrasound imaging in rheumatoid arthritis demonstrated superiority to both imaging alone.
Jones, et al.[20]	Rheumatoid arthritis (n=49) Healthy participants (n=30)	Joint temperature was higher in rheumatoid arthritis patients than in healthy participants for both MCP and PIP joints. However, no significant relationship between thermographic findings and clinical measurements, including HAQ, swollen joints, serum CRP, and ESR, in rheumatoid arthritis patients.
Capo, et al.[19]	Psoriatic arthritis (n=13) Rheumatoid arthritis (n=10) Healthy participants (n=11)	Compared to the healthy control group, rheumatoid patients showed lower thermal parameters, and psoriatic arthritis patients showed higher thermal parameters.

ESR, erythrocyte sedimentation rate; MCP, metacarpophalangeal; PIP, proximal interphalangeal; HAQ, Health Assessment Questionnaire; CRP, C-reactive protein.

thermographic findings of patients with RA were higher than those in healthy participants, though there was no significant relationship between thermographic results and clinical measures, including the Health Assessment Questionnaire score, swollen joints, serum CRP, and ESR, in patients with RA. Instead, there was a report that the thermographic results of the joints of patients with RA were lower than those of healthy participants and psoriatic arthritis patients, possibly due to excessive tissue growth characteristic of the RA inflammatory process.[19] In this study, the temperature of the knee arthritis site measured by thermography did not correlate with WBC count in the joint fluid. However, along with WBC count in the joint fluid, thermographic temperature was significantly higher in PD-positive group on ultrasound than in PD-negative group, suggesting a value of thermographic examination. Synovial fluid analysis through arthrocentesis is an essential test for diagnosing inflammatory arthritis. Arthrocentesis is a procedure with rare complications if appropriately performed. However, arthrocentesis is contraindicated if cellulitis is suspected at the needle entry, and caution is required in patients receiving anticoagulant medications or patients with coagulopathy.[24] Additionally, since arthrocentesis is an invasive test, it is accompanied by pain.

Ultrasonography is an essential tool in the clinical rheumatology practice, as it provides immediate diagnostic information and can be used to support interventional procedures.[25] Ultrasound PD signal is a reliable method for qualitatively grading synovial tissue vascularity in the knee joint of RA, and it has shown correlation with disease activity score in 28 joints.[26,27] However, ultrasonography is limited in that it is an operator-dependent technique that requires a significant period of technical skills training as well as expensive machines.[7,28] The recently developed smartphone thermal imaging camera used in this study has the advantage of being inexpensive and easy-to-use, with a small size that can fit into a pocket.[29] This has led to increased use of smartphone thermal imaging for various medical purposes over the past few years.[29,30] Additionally, thermography allows objective evaluation without direct skin contact, and it is free from the risk of infection from contact. Due to these non-invasive and easily accessible advantages, thermal imaging along with ultrasound can be recommended for patients with suspected inflammatory arthritis.

This study had some limitations. First, there may have been inherent limitations related to its single-center design, as well as the relatively small number of patients and diverse patient populations. Therefore, further research with a larger number of patients for each disease is needed. Second, since only the FLIR ONE Pro thermal imaging camera was used in our study, there may be limitations in generalizing the results. Each type of thermal imaging camera has different resolution and image quality. The FLIR ONE Pro thermal imaging camera has a resolution of 160×120 pixels, which is lower than the resolution of other thermal imaging cameras; however, it has been used in various medical studies due to its higher image quality, small size, light weight, and low price.[29,31] Despite these limitations, this study is the first study to evaluate joint inflammation by comparing PD signal on ultrasound and WBC counts in joint fluid with thermographic findings.

In this study, we found that on ultrasound, the temperature of thermography is high when PD is positive in knee arthritis patients. Although thermography cannot replace joint fluid analysis or ultrasound, it has many advantages of being non-invasive, non-contact, and simple; therefore, it may be used as an adjuvant tool to evaluate knee arthritis.

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AUTHOR CONTRIBUTIONS

Conceptualization: Soo Min Ahn, Joo Hyang Chun, Ji Seon Oh, and Yong-Gil Kim. Data curation: Joo Hyang Chun. Formal analysis: Soo Min Ahn and Ji Seon Oh. Funding acquisition: Yong-Gil Kim. Investigation: Soo Min Ahn and Joo Hyang Chun. Methodology: Joo Hyang Chun, Ji Seon Oh, and Yong-Gil Kim. Project administration: Ji Seon Oh and Yong-Gil Kim. Resources: Seokchan Hong, Chang-Keun Lee, and Bin Yoo. Software: Soo Min Ahn. Supervision: Seokchan Hong, Chang-Keun Lee, Bin Yoo, Ji Seon Oh, and Yong-Gil Kim. Validation: Seokchan Hong, Chang-Keun Lee, and Bin Yoo. Visualization: Soo Min Ahn. Writing—original draft: Soo Min Ahn. Writing—review & editing: Ji Seon Oh and Yong-Gil Kim. Approval of final manuscript: all authors.

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