Application of 3-Dimensional Ultrasonography in Assessing Carpal Tunnel Syndrome

Sung Bum Pyun, MD, Chang Ho Kang, MD, Joon Shik Yoon, MD, Hee Kyu Kwon, MD, Jung Hyuk Kim, MD, Kyoo Byung Chung, MD, Yu Whan Oh, MD

Objectives—The aim of study was to assess the usefulness of 3D ultrasonography (3DUS) in the diagnosis of carpal tunnel syndrome.

Methods—Fifty patients with carpal tunnel syndrome confirmed by electromyography and 37 healthy control participants underwent 3DUS of the wrists. The mean times per participant for the 3DUS examination and review of the 3D volume set were recorded. The cross-sectional area at the proximal carpal tunnel and the maximum swelling point were measured. Data from patients and controls were compared for determination of statistical significance. The accuracy of the 3DUS diagnostic criteria for carpal tunnel syndrome was evaluated using receiver operating characteristic analysis, and changes in the median nerve shape, including the maximum swelling point, were assessed by review of the 3D volume data.

Results—The mean times for examination of a participant and review in each wrist were 56 seconds and 5.7 minutes, respectively. Significant differences were observed in the mean cross-sectional areas of the median nerve between patients and controls. The mean cross-sectional areas ± SD were 16.7 ± 6.7 mm² in patients and 8.3 ± 1.9 mm² in controls. Using the receiver operating characteristic curve, a cutoff value of greater than 10.5 mm² provided diagnostic sensitivity of 84% and specificity of 86%. In 42 of 73 wrists with carpal tunnel syndrome, the median nerve showed fusiform morphologic abnormalities and maximum swelling points.

Conclusions—Our results show that 3DUS could markedly decrease scanning time, and measurement of the median nerve cross-sectional area combined with morphologic analysis using 3DUS is a promising supplementary method for the diagnosis of carpal tunnel syndrome.

Key Words—carpal tunnel syndrome; median nerve; 3-dimensional ultrasonography

Carpal tunnel syndrome is a common entrapment neuropathy of the median nerve. It is characterized by pain and sensory disturbance along the distribution of the median nerve as well as thenar muscle atrophy in advanced stages. Diagnosis may be made clinically¹ and with electromyography (EMG).² Ultrasonography (US) may also be valuable for the diagnosis of carpal tunnel syndrome.³ Several studies⁴, ⁵, ⁶ have shown that the combination of carpal tunnel US with clinical features and EMG was more sensitive and specific than clinical evaluation or EMG in isolation. However, EMG is time-consuming, slightly invasive, and generally not well tolerated for repeated evaluations.⁷ The attraction of US for the
The diagnosis of carpal tunnel syndrome lies in its wide availability, noninvasiveness, and shorter examination time. The ability of 2-dimensional ultrasonography (2DUS) to depict normal and pathologic nerves, including anatomic variants and abnormalities associated with carpal tunnel syndrome, has been proven.

In the last decade, research investigators and commercial companies have further advanced US imaging with the development of 3-dimensional ultrasonography (3DUS). This new imaging approach is rapidly achieving widespread use in numerous applications. In a conventional US examination, the transducer is manipulated to obtain a series of 2D images, which are mentally combined by the operator to form a subjective impression of the anatomy and pathologic features. Mental transformation of multiple 2D images to form a 3D impression is not only time-consuming and inefficient but also variable and subjective and can lead to incorrect diagnostic decisions. Thus, the success of the diagnostic procedure is largely dependent on the skill and experience of the operator.

The aim of the study was to present a new application of modern 3DUS using mechanical scanning techniques and to assess the usefulness of 3DUS in the diagnosis of carpal tunnel syndrome.

Materials and Methods

Study Population

Institutional Review Board approval was obtained for this study. Informed consent was provided by all participants before the examinations. Fifty-one patients who underwent 3DUS (LOGIQ 9; GE Healthcare, Milwaukee, WI) between May 2008 and February 2009 were referred from the physical medicine and rehabilitation clinic after confirmation of the clinical diagnosis with EMG in a consecutive fashion. Studies in all patients were performed sequentially on the same day, beginning with EMG and ending with 3DUS. One patient with a bifid median nerve was excluded from the final analysis after 3DUS revealed this anatomic variation. Therefore, the patient group consisted of 73 wrists in 50 patients (5 men and 45 women; mean age, 55.7 years; range, 31–73 years).

Electromyography was performed using a Dantec Counterpoint MK2 system (Medtronic, Minneapolis, MN). Median compound muscle action potentials were recorded from the abductor pollicis brevis with stimulation of the median nerve 8 cm proximally at the wrist. Median sensory nerve action potentials were recorded from the third digit, with stimulation of the median nerve in the mid palm and wrist at distances of 7 and 14 cm proximal to the recording electrode, respectively. To rule out the possibility of peripheral neuropathy, ulnar motor, sensory, and sural sensory nerves were evaluated using a standard conduction technique. Needle EMG was also performed to rule out cervical radiculopathy. The skin temperature was maintained at 32°C or higher. Carpal tunnel syndrome was diagnosed if the nerve conduction study fulfilled 3 of the following criteria: (1) median sensory nerve action potential peak latency greater than 3.7 milliseconds; (2) sensory nerve action potential peak latency of the proximal 7-cm segment greater than peak latency of the distal 7-cm segment; (3) sensory nerve action potential amplitude drop of greater than 50% with wrist stimulation compared to palm stimulation; (4) median compound muscle action potential distal latency greater than 4.2 milliseconds; and (5) compound muscle action potential amplitude less than 4.5 mV. To include idiopathic carpal tunnel syndrome only, patients with a history of underlying diseases (such as gout, rheumatoid arthritis, and diabetes mellitus), pregnancy, previously performed wrist surgery, and previous wrist fracture were excluded from the study.

Seventy-four wrists in 37 healthy participants (3 men and 34 women; mean age, 52.8 years; range, 28–78 years) with no signs or symptoms of carpal tunnel syndrome were included as a control group. All control participants were screened to exclude the above-described systemic and orthopedic conditions. Both wrists of each control participant were evaluated by 3DUS. Electromyography was not performed in the control group.

Three-Dimensional US Imaging and Measurement

Using a dedicated mechanical 3D volume transducer with a variable high frequency (8–15 MHz), all examinations were performed by a fourth-year radiology resident with less than 1 year of experience in musculoskeletal US. Participants were seated with the forearm lying on a table, wrist in supination, and fingers extended during the examination. A 3DUS transducer was placed on the volar aspect of the wrist, including the distal wrist crease, which is a useful surface landmark for identification of the entrance to the proximal carpal tunnel (Figure 1). Participants were discharged immediately after the examination and before review by a radiologist. The time from the participant’s entrance into the US room to exit from the room was measured.
Three-dimensional US data were transferred to a separate workstation (Centricity Radiology RA 600, version 7.0; GE Healthcare), allowing display and interactive analysis of the 3D data. The radiologist retrieved the 3D volume data sets, which were randomly distributed in the study folder on the workstation, reviewed images, and performed cross-sectional area measurements without knowledge of the study groups (patient versus control) and electrodiagnostic test results. The full course of the median nerve from the distal radius to the proximal carpal tunnel was evaluated in 3 orthogonal planes (Figures 2–4). The 3 views are displayed along with graphic lines and dots that show how each section projection cuts the volume. Changes in the shape of the median nerve through the full scanning field were qualitatively assessed by review of 3D volume data for determination of whether the maximum nerve swelling points could be shown; if shown, a determination of whether these points were located in the wrist or forearm was made.

Figure 1. Three-dimensional ultrasonographic examination of the median nerve. Participants were seated with the forearm lying on a table. A 3-dimensional volume transducer was placed in the volar aspect of the wrist and oriented perpendicular to the wrist crease.

Figure 2. Multiplanar display of a 3-dimensional ultrasonographic volume from a healthy individual showing the median nerve in 3 orientations at right angles to each other as well as bony landmarks of the proximal carpal tunnel. The planes are interactive and permit a complete trace of the median nerve from the distal radius to the proximal carpal tunnel, which is defined with a line intersecting the scaphoid tubercle (S) and the pisiform (P). In all 3 planes, dots indicate an identical voxel that represents the median nerve in the proximal carpal tunnel, which can be identified in every activated plane of the volume of interest.

Figure 3. Swollen median nerve in a 56-year-old woman with carpal tunnel syndrome. In this case, the median nerve (stars) shows fusiform enlargement, and the location of the point of maximum nerve swelling within the proximal carpal tunnel could be determined using bony landmarks such as the scaphoid tubercle (S) and pisiform (P). Dots indicate an identical voxel that represents the median nerve in the proximal carpal tunnel. Multiplanar imaging provides the coronal view, enabling better visualization of bony landmarks in the proximal carpal tunnel. In this case, however, the coronal view actually does not show the median nerve because it is located above the coronal plane intersecting the bony landmarks.
within or proximal to the proximal carpal tunnel was made by the consensus of 2 radiologists (C.H.K. and J.H.K.; Figures 3 and 4).

Cross-sectional area measurements were performed by a musculoskeletal radiologist (C.H.K.) with 10 years of US experience. For assessment of intraobserver variance, measurements of all wrists after greater than 1 month were repeated by the same radiologist. Measurements of the median nerve cross-sectional area were performed at the point of maximum nerve swelling or the proximal carpal tunnel (scaphoid-pisiform level) using the indirect technique (Figure 5). In this measurement, the formula of an ellipsoid area was used ($D_1 \times D_2 \times 3.14/4$, where $D$ is diameter). No measurements were taken in the distal carpal tunnel (trapezium-hamate level), which was not fully covered by the scanning field. Semik et al$^{12}$ reported a high correlation ($r = 0.99$) between the areas calculated by the indirect and direct methods; consequently, we used the easier indirect method in our study.

**Statistical Analysis**

Median nerve cross-sectional area measurements in patients and controls were compared using unpaired t tests. The receiver operating characteristic curve was used to define optimal US measurement threshold values for the diagnosis of carpal tunnel syndrome. Sensitivity and specificity values were calculated for each cutoff point defined for US. Intraobserver variance in cross-sectional area measurements was quantified with an intraclass correlation coefficient. Statistical software (SPSS version 10.0; SPSS Inc, Chicago, IL) was used in all statistical analyses.

**Results**

The mean time per participant for US was 56 seconds. In addition, the mean time ± SD for review of the 3D volume set and median cross-sectional area measurement of the median nerve in each wrist by the musculoskeletal radiologist (C.H.K.) was 5.7 ± 1.76 minutes. In no case did the
radiologist consider the median nerve in question incompletely imaged and unmeasurable. Identification of the exact boundaries of the median nerve reconstructed from the 3DUS volume was clear in the distal radius to the proximal carpal tunnel but became more difficult at the distal carpal tunnel where the nerve was deeper, oblique to the transducer, and not fully included in the scanning field. Using the distal wrist crease as the external landmark simplified scanning by allowing consistent placement of the proximal carpal tunnel and distal radius. Intraobserver reproducibility in the median nerve cross-sectional area measurements was high (intraclass $r = 0.987$).

In the patient group, the mean cross-sectional area of the median nerve was $16.7 \pm 6.7 \text{ mm}^2$. In 42 of 73 wrists with carpal tunnel syndrome, the median nerve showed fusiform morphologic abnormalities and maximum swelling points (Figures 3 and 4 and Video 1). In 25 of 42 cases with fusiform swelling, the maximum nerve swelling point was located more proximal to the scaphoid-pisiform level rather than at that level (Figure 4). An increase in the duration of symptoms was significantly associated with fusiform swelling of the median nerve on reconstructed 3DUS images ($P < .005$). In the control group, the mean cross-sectional area of the median nerve was $8.3 \pm 1.9 \text{ mm}^2$. All wrists in the control group showed no fusiform morphologic abnormalities. Using the $t$ test, there were significant differences in median nerve cross-sectional areas between both groups ($P < .001$). Using clinical diagnosis with a positive EMG test result as the reference standard, the diagnostic accuracy of US measurement of the median nerve cross-sectional area was determined using the receiver operating characteristic curve. The sensitivity and specificity values of 3DUS-measured cross-sectional areas for the diagnosis of carpal tunnel syndrome are presented in Table 1. The best diagnostic discrimination was achieved by using a cross-sectional area threshold of $10.5 \text{ mm}^2$, for which the sensitivity, specificity, false-positive, and false-negative rates were 84% (61 of 73), 86% (64 of 74), 14% (10 of 71), and 16% (12 of 76), respectively.

**Discussion**

To the best of our knowledge, a prospective study of the application of 3DUS in patients with carpal tunnel syndrome has not been reported previously. In general, the diagnosis of carpal tunnel syndrome is usually based on typical signs and symptoms, can be confirmed with EMG, and, at least in typical cases, does not require an imaging study. However, progressive development of US transducer technology has enhanced the ability to depict the median nerve in the carpal tunnel, and US is now widely used as an additional approach for the diagnosis of carpal tunnel syndrome.$^{2,13-16}$

In the hands of an experienced operator, 2DUS would have very few limitations in evaluation of patients with carpal tunnel syndrome. However, the major advantage of 3D or "volume" US is its potential to change the practice of US by making it far less operator dependent and markedly decreasing scanning time. In addition, 3DUS has new flexibility for reconstruction of volumes in any plane at any location to obtain an optimal cross section for organ measurement. In this study, using the multiplanar reconstruction technique, we applied this 3D approach to cross-sectional area measurement and morphologic analysis of the median nerve in patients with carpal tunnel syndrome.

**Table 1.** Sensitivity and Specificity of Cross-Sectional Area Measurements in Diagnosis of Carpal Tunnel Syndrome

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<tr>
<th>Cross-Sectional Area, mm²</th>
<th>Sensitivity, %</th>
<th>Specificity, %</th>
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<tr>
<td>7.5</td>
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<td>41</td>
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<td>8.5</td>
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The 3DUS technique described here allowed considerable shortening of the US examination time, which could potentially be as quick as less than 1 minute. Of course, this was counterbalanced by the greater time needed for evaluation of the image and measurement of the median nerve cross-sectional area on a separate workstation. We do not believe that the entire time needed to perform a scan, review the volume data, and measure the median nerve cross-sectional using 3DUS would be reduced when compared with 2DUS. However, the use of 3DUS is novel, and we believe that it offers benefits in that it can be performed by an inexperienced operator and measurements can be calculated offline by the reporting radiologist.

The main US findings in carpal tunnel syndrome include changes in the shape and echo texture of the median nerve and abnormalities in the transverse carpal ligament. When detectable changes are present on US, the median nerve appears swollen at the proximal carpal tunnel and flattened at the distal tunnel.5,10 Enlargement of the median nerve may be evident on a subjective evaluation. In this study, fusiform swelling of the median nerve was shown in 42 of 73 wrists with carpal tunnel syndrome (58%). This result is compatible with findings from the surgical literature17 showing swelling of the median nerve in 66% of cases. Some studies have reported that the increase in the median nerve cross-sectional area is at its maximum, and most easily distinguishable, at the level of the proximal tunnel.16–20 Nakamichi and Tachibana19 also showed that the maximum swelling was at the distal carpal tunnel; however, in their study, the mean cross-sectional areas at the proximal level (14.4 mm²) and distal level (14.7 mm²) were nearly equal. Of importance in our study was the finding that the median nerve in carpal tunnel syndrome showed maximum enlargement behind the proximal edge of the transverse carpal ligament as well as within the proximal carpal tunnel. Therefore, the greater difference in median nerve cross-sectional areas between patients and controls seems to have been more reliably obtained by consideration of the maximum nerve swelling point. Multiple-level swelling of the median nerve in or proximal to the carpal tunnel seems to be the rule in patients with carpal tunnel syndrome. Neither the caliber or swelling is a continuum, and attempts to define single universal threshold values will always have limited success. Therefore, we believe that 3D-based assessment would be more useful than operator-dependent and arbitrary evaluation using 2DUS.

Wong et al15 measured the cross-sectional area of the median nerve at 3 different levels: immediately proximal to the carpal tunnel inlet, at the carpal tunnel inlet, and at the carpal tunnel outlet. Using a classification and regression tree,10 they determined optimal threshold values for each of these levels and suggested diagnostic algorithms based on a combination of fixed cutoffs at 2 levels of the median nerve that differed for the left and right hands; however, this is controversial among specialists.21 Using the largest cross-sectional area as a single diagnostic indicator may be preferable for clinical practice. On the basis of our 3DUS protocol, which appears more feasible in routine settings, we obtained comparable diagnostic accuracy at a single cutoff, which was obtained at the carpal tunnel inlet with consideration of the point of maximum nerve swelling. In most previously published studies, values ranging from 9 to 12 mm² were reported.3,4,15,16,20,22–24 The results of this study showed that 10.5 mm² was the most adequate cutoff point; this was in agreement with previous findings13,15 and revealed similar sensitivity and specificity for US evaluation of carpal tunnel syndrome with EMG as the reference standard.4,15,16

This study had some limitations. First, there was no comparison of live 2DUS and 3DUS for scanning time, radiologist review time, and diagnostic accuracy. In particular, the time difference would be that between the time required for acquisition of a 2D image set and the time required for acquisition of a 3D data set and reconstruction of the 3D images. These times need to be calculated and compared to give support to the use of 3DUS for the diagnosis of carpal tunnel syndrome, and although we recorded the 3DUS scanning and review times, they were not compared with a 2DUS examination.

Second, no US parameters other than the median nerve cross-sectional area were evaluated, including median nerve echogenicity, mobility, the flattening ratio in the distal carpal tunnel, and abnormalities in the transverse carpal ligament. Although these are useful parameters that yield additional information in the diagnosis of carpal tunnel syndrome, the focus of this study was evaluation of a recently developed 3DUS application for measurement of the median nerve size. In terms of median nerve echogenicity and the clarity of the median nerve boundary, it is apparent from the images that the orthogonal planes obtained using our 3DUS technique do not have the type of resolution that one can obtain with 2DUS. Currently, the mechanical sweep necessary to obtain the volume makes the resolution and acquisition speed trade-offs. Therefore, median nerve echogenic abnormalities could be difficult to evaluate with the lower spatial resolution of an acquired 3D volume. Another potential problem with 3DUS is that it would be most applicable in the musculoskeletal system when the structure imaged is
that our 3D protocol would be applicable to the diagnosis of carpal tunnel syndrome. Although further studies covering supplementary modality for use in the diagnosis of carpal tunnel syndrome.25 Yao and Gai26 suggested a trend toward a stronger correlation of body mass index. However, they stated that the implications of this observation were unclear.

Fourth, there was a limitation with regard to use of the indirect technique for measurement of the median nerve cross-sectional area, which resulted from anteroposterior measurement and the transverse distance of the median nerve. Sometimes the median nerve is bilobed, which can make use of the ellipsoid technique less accurate. Duncan et al4 reported that use of the direct technique showed more accurate results than use of the indirect technique. However, findings from a recent report showed the accuracy of both the direct and indirect techniques in the diagnosis of carpal tunnel syndrome.12

Finally, this study could have been limited by the lack of information on the body mass index. Both obesity and age have been established as risk factors for carpal tunnel syndrome.25 Yao and Gai26 suggested a trend toward a larger median nerve cross-sectional area at the proximal carpal tunnel level in older patients and those with a higher body mass index. However, they stated that the implications of this observation were unclear.

In conclusion, this study shows that 3DUS is a promising supplementary modality for use in the diagnosis of carpal tunnel syndrome. Although further studies covering the full carpal tunnel with 3DUS and comparing the time efficiency of 2DUS and 3DUS are needed, we believe that our 3D protocol would be applicable to the diagnosis of carpal tunnel syndrome in routine clinical settings.

References