Int Arch Occup Environ Health (2008) 81:661–669
DOI 10.1007/s00420-007-0268-y

ORIGINAL ARTICLE

Syndromes from segmental vibration and nerve entrapment: observations on case definitions for carpal tunnel syndrome

Martin Cherniack · Anthony J. Brammer · Ronnie Lundstrom · Tim F. Morse · Greg Neely · Tohr Nilsson · Donald Peterson · Esko Toppila · Nicholas Warren · Ulysses Diva · Marc Croteau · Jeffrey Dussetschleger

Received: 15 August 2007 / Accepted: 19 September 2007 / Published online: 2 October 2007

Abstract
Objectives The purpose of this paper is to assess the overlap and stability of two different case definitions of carpal tunnel syndrome CTS. The analysis considers the association between different case definitions and objective tests (sensory nerve conduction velocities, SNCVs and vibrotactile perception thresholds, TTS), and the natural history of CTS, in the context of two vibration-exposed cohorts.
Methods Clinical CTS cases were defined in two ways: (1) by the study physician using fixed criteria, and; (2) by questionnaire and hand diagram. SNCV in median and ulnar nerves was measured for digital, transpalmar, and transcarpal segments, and conventionally as from wrist-digit. Skin temperature was assessed as a point measurement by thermistor and regionally by thermal imaging. VTTs were determined at the bilateral fingertips of the third and fifth digits using a tactometer meeting the requirements of ISO 13091-1 (ISO 2001). The subjects were cohorts of shipyard workers in 2001 and 2004, and dental hygienists in 2002 and 2004.
Results Results are reported for 214 shipyard workers in 2001 and 135 in 2004, and for 94 dental hygienists in 2002 and 66 in 2004. In 2001, 50% of shipyard workers were diagnosed as CTS cases by at least one of the diagnostic schemes, but only 20% were positive by both criteria. Among study physician diagnosed cases, 64% were CTS negative in 2001, 76% were negative in 2004, 13% were positive in both years, 22% became negative after being positive, and 11% became positive after being negative. For only study physician diagnosed CTS did VTTs differ between cases differ and non-cases in digit 3; there was no such distinction in digit 5. The dental hygienists had little CTS.
Conclusion Clinical case definitions of CTS based on diagrams and self-assessment, and clinical evaluation have limited overlap. Combining clinical criteria to create a more narrow or specific case definition of CTS does not appear to predict SNCV. The natural history of CTS suggests a protean disorder with considerable flux in case status over time.

Keywords Hand–arm vibration · Carpal tunnel syndrome · Sensory nerve conduction velocity · Vibrotactile thresholds

Introduction

Whether or not hand–arm vibration (HAV) exposure predisposes workers to carpal tunnel syndrome (CTS) inspires several competing perspectives. Some studies of CTS in working populations have uncovered unexpected vibration exposure (Cannon et al. 1981; Silverstein et al. 1987). Others have shown sensory nerve conduction velocity (SNCV) deficits in the median nerves of vibration-exposed workers, whether or not CTS symptoms were present (Seppäläinen 1972; Chatterjee et al. 1982). However, Rosén et al. (1993) described a pattern of electrophysiological abnormalities in vibration-exposed workers experiencing paresthesias that was not consistent with "classical" CTS cases, nor with the pattern displayed by controls. Several investigators have described a distal pattern of reduced SNCV either localized to the digits (Sakakibara et al. 1994, 1998; Hirata et al. 2002) or to hand-localized segments of the median, ulnar and radial nerves (Rosén et al. 1993; Giannini et al. 1999;

M. Cherniack (✉) · A. J. Brammer · R. Lundstrom · T. F. Morse · G. Neely · T. Nilsson · D. Peterson · E. Toppila · N. Warren · U. Diva · M. Croteau · J. Dussetschleger
University of Connecticut Health Center, Farmington, USA
e-mail: wojtusik@up.uchc.edu

Bovenzi et al. 2000). While differing in their emphases, a common theme of these studies is that HAV-related neuropathy covers a wider spectrum than classical CTS (Brammer and Pyykkö 1987). Although vibration exposure reportedly produces a pattern of injury to digital nerves that can be detected by segmental nerve conduction (Sakakibara et al. 1998; Cherniack et al. 2004a), this has either not been observed in all studies (Cherniack et al. 1992), or, when present, has been included in a broader pattern of multinerve distal slowing (Bovenzi et al. 2000). As a result, nerve conduction studies have been both discarded as a definitive diagnostic tool for neurosensory evaluation (McGeough and Gilmour 2000; McGeough et al. 2005), or endorsed for their power to differentiate between vibration-induced and other neuropathies (Sakakibara et al. 1998; Cherniack et al. 2004a).

When information from quantitative sensory tests, such as the vibrotactile threshold (VTT), is added to the diversity of CTS presentations, the association between paresthesias and median nerve conduction delays is further complicated. Virokannas (1992) measured VTTs and nerve conduction in railway and forest workers. When the clear-cut CTS cases were excluded, there was a strong association between vibration exposure and VTT, but not with NCV. Strömberg et al. (1998) found high levels of neurosensory abnormality, measured as an elevated VTT, in 57.3% of symptomatic vibration-exposed workers, whether or not the actual symptoms included neurological complaints. Thus, nerve injury distal to the carpal tunnel may either confound or muddle the classification of CTS. In a small study of vibration-exposed and non-exposed manual workers, and of subjects with clinical CTS, Brismar and Ekenvall (1992) measured SNCV in the median and ulnar nerves using segmented transcarpal and palm-to-digit measurements. Effects on SNCV from exposure to vibration could not be differentiated among asymptomatic manual workers. Vibration-exposed workers with symptoms had focal median nerve slowing, but it was less severe than for classical CTS patients. Other authors have described a more disabling functional pattern in vibration-exposed workers with CTS than in non-vibration exposed CTS cases (Strömberg et al. 1997).

Because vibration exposure is often concurrent with a range of biomechanical stresses associated with CTS (Silverstein et al. 1986; Nilsson et al. 1994; Fagarasanu and Kumar 2003), an argument has emerged that the coupling of postural risk and force loading with vibratory exposure produces an aggravated CTS clinical profile (Bovenzi et al. 2000; Koskimies et al. 1990). In addition to this more customary emphasis on confounding and interactive factors affecting exposure classification, the role of different pathologies producing similar symptoms is also important. There is no particular reason to presume that symptoms associated with a mix of exposures are the product of a single disease.

The purpose of this paper is to assess the overlap and stability of two different case definitions of CTS. The analysis considers the association between different case definitions and objective tests (SNCVs and VTTs), and the natural history of CTS, in the context of two vibration-exposed cohorts. The work was performed by HAVIC (Hand–Arm Vibration International Consortium), which is a multi-national research group organized to better define exposure–response relationships for exposure to segmental vibration through application of longitudinal study design (Cherniack et al. 2006b). The populations were shipyard workers, and dental hygienists. The cohorts, which were studied in 2001/2002, and 2004, provided a platform for addressing several unanswered questions about the relationship between vibration exposure and CTS. The longitudinal design provided a basis for evaluating CTS natural history, providing there were cases at the baseline. Vibrotactile perception thresholds were determined so that mechanoreceptor function could be assessed independently of nerve conduction. Fractionated nerve conduction was performed to provide comparisons of SNCV in the digits with cross-wrist and longer track measurements. The variety of assessment tools—questionnaire and hand diagrams, diagnosis by study physician, past treatment history, and electrophysiological studies—allows for comparative and contingent case definitions of CTS.

Study population and methods

Study populations

Table 1 presents basic demographic information for the shipyard and dental hygiene workers when they were re-evaluated in 2004. Shipyard workers were engaged in metal trades, most often with moderate to frequent use of manual and power tools. In the United States, dental hygiene involves small instruments, and is largely restricted to manual and ultrasonic scaling and polishing. There were nine shipyard workers and two dental hygienists with historic exposure to vibration, who were not exposed during the inter-study interval. They are included in the analysis due to their cumulative exposure. The follow-up/retention rate for these two populations was not especially high. In October–December of 2001, 214 shipyard workforce members (199 males and 15 females) participated in the baseline assessment and completed all tests: 135 (127 male and 8 females) were re-evaluated in February–April 2004 (retest rate = 63%). The reasons for dropping out were established for 55 participants, and included: long-term travel or temporary re-assignment to other shipyards ($n = 12$); withdrawal for

Table 1 Demographics-shipyard workers and dental hygienists (2004 evaluation)

Variable	Shipyard workers $n = 135$			Dental hygienists $n = 66$		
	Mean	SD	Min–Max	Mean	SD	Min–Max
Age (year)	50.6	6.3	24–62	42.7	12.6	21–72
Height (cm)	174.6	8.6	152–194	164.5	6.6	140–179
Weight (kg)	93.8	22.2	54–162	68.6	15.7	42–118
3rd finger circumference (mm)	72.6	5.6	58–85	62.3	5.6	50–80
5th finger circumference (mm)	61.0	5.9	47–76	52.2	5.3	43–68
Years worked in trade/profession	24.0	6.8	2.5–42	18.2	12.1	8–42
Vibration hours/week	9.3	11.5	0 to >40[a]	7.7	6.7	0–32

[a] Self-report of overtime workers

specified reasons such as off-site assignment ($n = 12$); termination of employment ($n = 11$); disability and medical leave ($n = 10$); documentation problems within the shipyard ($n = 9$), and; retirement ($n = 1$). Among the dental hygienists (all females), 66 out of 94 were retested (retest rate = 70%). The initial testing was in April–June 2002 and retesting took place 24 months later. The reasons for the failure to follow-up could not be documented, as almost all dropouts were unreachable or failed to respond to solicitations.

Nerve conduction studies

SNCVs were measured in both upper extremities. All studies were performed using a Nicolet Viking Quest® device. SNCV testing followed the approach of Sakakibara et al. (1994, 1998). The technique is fully described elsewhere (Cherniack et al. 2004a). The following median and ulnar nerve segments were assessed: (1) Proximal digit–distal digit; (2) Palm–proximal digit; (3) Wrist–palm; (4) Wrist–distal digit, and (5) Wrist–proximal digit.

Before nerve stimulation, sub-maximal exercise took place on a bicycle ergometer (12 min, ramped at 50–100 Ws) (Sandén et al. 2005), followed by testing within a temperature-controlled environment. The workload was linked to heart rate, which was continuously monitored, and/or discomfort. The room temperature was thermostatically controlled at 22°C, with an acceptable range of ±1°C. All testing was performed in the sitting position. Subjects were draped with a thermal blanket during nerve conduction testing to maintain core temperature. Studies did not proceed until the temperature at the base of the second digit was ≥31°C.

Vibrotactile threshold (VTT) testing

Vibrotactile thresholds were determined at the fingertips of the third and fifth digits of both upper extremities using a laboratory tactometer meeting the requirements of ISO 13091-1 (2001). This consists of a vibration stimulator and sensor suspended so that they may be lowered onto a fingertip, a means to support the hand and arm under investigation, and specialised electronic circuits under computer control. The measurement procedure requires the arm be supported horizontally, with the fingers in a relaxed, curved position (palm upward). A 4 mm diameter-stimulating probe is lowered onto a fingertip from above, and contacts the skin with a controlled, compressive force (0.15 N). Sinusoidal bursts of vibration, each of different intensity, are applied to the skin at a selected frequency, with the subject signalling by pressing a switch when the stimulus is detected. Details of the measurement procedure are software controlled. Inconsistencies and errors in the subject's performance are detected by a patented procedure and displayed to the operator during the measurement (Brammer and Piercy 1995).

For the purposes of the present study, measurements were performed at the fingertip of digits 3 and 5 of both hands to distinguish median from ulnar nerve innervations and to insure correspondence with the recording electrode sites used in the SNCV studies. The measurement protocol closely followed that proposed by ISO 139091-1 (2001), and required prior to testing that a subject was: not be exposed to hand-transmitted vibration, did not engage in activity involving repetitive hand/arm motion for at least 1 h; did not consume a vasoactive or neuroactive agent (e.g., smoke cigarettes, drink caffeine containing beverages), nor engaged in vigorous exercise for at least 60 min before the test, and; was present and resting seated for at least 5 min before the test commenced. In addition, VTT testing was temporally separated from SNCV testing and pre-test exercise. Measurements of VTT were conducted at frequencies of 4 Hz (believed mediated by SAI receptors); 32 Hz (believed mediated by FAI receptors), and; 125 Hz (believed mediated by FAII receptors) (Brammer and Piercy 2000). All results are reported as accelerations in units of decibels (dB) re 10^{-6} m/s^2.

Questionnaire and physical examination

Participants completed a self-administered questionnaire directed to vibration-specific and more general musculoskeletal disorders. Exposure-specific questions were developed

to profile each set of work tasks. The questionnaire has been previously described (Cherniack et al. 2004b). Symptom questions also included staging with the Stockholm Workshop Scale, a consensus instrument used for classifying sensorineural and vascular symptoms of HAVS (Gemne et al. 1987; Brammer et al. 1987). Questionnaire components pertinent to this study include estimates of vibration exposure and work history, neurological and vascular symptoms, and demographics. Manikin like drawings were used for the purposes of symptom localization, with emphasis on each upper extremity region (Viikari-Juntura et al. 1996), in order to better define CTS related symptoms (Katz and Stirrat 1990). The questionnaire also requested detailed clinical information on past treatment for selected conditions, including CTS.

A physical examination, including weight, height, and finger circumference was performed by a study physician. The standardized examination included more than 20 recognized clinical provocation tests, including the Adson's test, Roos test, Allen's test, Wright's test, Tinel's signs, Phalen's test, and Finkelstein's test. Each test procedure was reviewed for consistency with other standardized examinations (Nilsson 2002; Sluiter et al. 2001). The examining physician was also required to render clinical diagnoses that were restricted by rules.

Case definition of CTS

The questionnaire and physical examination were constructed to support two non-electrodiagnostic case definitions of CTS—one being study physician diagnosed, the other defined by symptoms described in hand diagrams (termed diagrammatically defined). The study physician diagnosis of CTS was based on criteria specifically established for the study: paresthesias in a median nerve or broader distribution, a characteristic history, and a positive Tinel's, or Phalen's test, or positive wrist compression test. Three physicians, including two of the authors (MC, MC) conducted all examinations in 2001 and 2004 and cross-trained to establish reliability. The diagrammatic definition of CTS was based on frequent paresthesias in the median nerve distribution, or frequent paresthesias affecting all digits, and nighttime paresthesias in the median nerve distribution. To provide clarification, "median nerve distribution" refers to digits 1–3 and the radial side of digit 4 while the "broader distribution" refers to the involvement of all digits. The study physician was blinded to the results of objective tests and questionnaire responses.

Data analysis and statistics

Analyses were performed using SPSS and SAS statistical packages. Continuous data were summarized as means, standard deviations, standard errors, and minimum and maximum values. Dichotomous variables were summarized as counts and proportions. Differences between group means were compared using t tests and F tests in analyses of variance, as appropriate. For t tests comparing two groups of unequal sizes, Satterwaithe approximations were used. The McNemar and Mantel–Haenzel Chi square test were used to test for association between variables in contingency tables. The term significant refers to two-tailed probability values (P value) < 0.05.

Results

Table 2 presents the baseline rate of CTS diagnoses by the study physician for each cohort and the self-reporting of hand paresthesias. In the shipyard cohort, hand paresthesias were at least two times more prevalent than physician-based CTS diagnosis. In contrast, in the dental hygienist cohort, hand paresthesias were three times more prevalent than CTS diagnoses. While the relatively small number of CTS cases among the dental hygienists limits inferences from the results, the very different quality of the workplace exposure provides an additional dimension to the assessment of work-related CTS. Nevertheless, of necessity, the following results and analyses are directed mainly to the shipyard population.

Use of different case definitions for CTS

Table 3 compares the two different case definitions for CTS among shipyard workers for 2001 and 2004. It should be noted that the +CTS subjects are designated by the clinical definitions, whereas in Table 2, the category of hand paresthesias is less narrowly defined and the subject numbers are greater.Table 3 compares the two different case definitions for CTS among shipyard workers for 2001 and 2004. It should be noted that the + CTS subjects are designated by the clinical definitions, whereas in Table 2, the category of hand paresthesias is less narrowly defined and the subject numbers are greater.

The study physician diagnosed 36% of the workforce with CTS in 2001, and 24% in 2004. CTS diagnosis by hand diagram and questionnaire response was confirmed on 34% of the participating workforce in 2001, and 32% in 2004. Most notably, the two case definitions are frequently discrepant, although statistically homogeneous ($\chi^2 = 0.40$ in 2001 and 3.46 in 2004). Robust negatives (no CTS by both diagnostic methods) made up only 50% of the tested workforce in 2001 and 59% in 2004. Looked at another way, 50% of all participants in 2001 and 41% in 2004 were positive for CTS by at least one diagnostic scheme, but only 20% in 2001 and 15% in 2004 were positively diagnosed by both case definitions.

Table 2 Symptoms and carpal tunnel syndrome (CTS) cases at baseline

Cohort	Baseline test year	Subjects tested	+ Hand paresthesias	CTS cases physician diagnosed dominant hand
Shipyard workers	2001	214	145 (68%)	77 (36%)
Dental hygienists	2002	94	42 (45%)	14 (15%)

Table 3 Effect of different case definitions of carpal tunnel syndrome (CTS) for shipyard workers

Study physician diagnosis	2001		Totals	2004		Totals
	Diagrammatic definition			Diagrammatic definition		
	No CTS	CTS		No CTS	CTS	
No CTS	108	29	137	80	23	103
CTS	34	43	77	12	20	32
Total	142	72	214	92	43	135

$\chi^2 = 0.40$ (1*df*, $P = 0.53$),
$\chi^2 = 3.46$ (1*df*, $P = 0.07$)

The lack of agreement between case definitions was also apparent in the dental hygienist cohort in 2004 (not shown), where six subjects were defined with CTS by physician diagnosis and seven subjects were defined by the diagrammatic method. However, there was limited overlap between the two groups of subjects. Four subjects met CTS case definition by both methods. In 2004, nine dental hygienists (14%) were positive for CTS by at least one diagnostic scheme, but only 4 (6% were positively diagnosed by both case definitions.

In Table 4, SNCVs for the median and ulnar nerves of the dominant hand are compared for the 2004 shipyard cohort by combinations of the CTS case definitions. The results are shown for diagnoses of no CTS (−CTS) and for positive diagnosis of CTS (+CTS) by either one or both of the case definitions. Overall, there is little apparent difference in SNCV, whether CTS cases are determined by a single or multiple case definitions. Only the SNCV in the wrist–palm segment differed significantly between CTS cases and non-cases when one case definition was used. The statistical significance was lost when the two diagnostic criteria were applied probably due to the reduction in the number of cases, although the actual velocities were unchanged from those recorded in cases with a single diagnosis of CTS. The SNCV in the ulnar nerve segments is unaffected by the method used to diagnose CTS.

Natural history of CTS in vibration exposed cohorts

Comparisons between tests provide a perspective on the stability of the CTS diagnosis. In Table 5, case consistency for shipyard workers is compared between the two testing intervals. A single case definition is used, namely study physicians diagnosed CTS, as this was less affected by selection or recall bias. For shipyard workers, 73 subjects were not CTS cases in both 2001 and 2004 (which we denote in future discussion by "−, −"); 18 were positively diagnosed in both years (denoted by "+, +"); 30 were formerly CTS positive and became non-cases (denoted by "+, −"); and 14 became new CTS cases in 2004 (denoted by "−, +"). Case classification volatility was substantial, but appeared to have limited association with changes in VTT, and two measures of altered habitus, namely third finger circumference and body mass index (BMI). It should be

Table 4 Sensory nerve conduction velocity (SNCV) on the dominant hand for carpal tunnel syndrome (CTS) based on combinations of clinical diagnoses for shipyard workers (2004)

Nerve	Segment	No CTS $n = 80$	+CTS 1 diagnosis $n = 55$	+CTS 2 diagnoses $n = 20$
Median	Proximal digit to distal digit	49.4 ± 6.4	49.6 ± 8.5	50.1 ± 10.5
	Wrist to palm	44.0 ± 7.2	*41.2 ± 6.8*	40.9 ± 7.4
	Wrist to distal digit	47.5 ± 5.5	45.9 ± 5.9	45.9 ± 6.5
Ulnar	Proximal digit to distal digit	51.5 ± 9.0	52.7 ± 8.2	51.3 ± 6.2
	Wrist to palm	51.6 ± 5.8	51.4 ± 5.8	51.0 ± 5.6
	Wrist to distal digit	52. 6 ± 4.1	52.7 ± 4.1	52.7 ± 3.8

SNCV is reported in m/s as mean and SD

Pr>|*t*| Test for significant change between cases and non-cases, where $Pr \geq |t| \leq 0.05$ (shown as *italics*)

Table 5 Interval change in key quantitative measures in the dominant hand for CTS diagnosed by the study physician. Data for shipyard workers

Dominant hand		No CTS in 2004		CTS in 2004	
		Mean (SE)	Pr>|t|	Mean (SE)	Pr>|t|
No CTS in 2001		$n = 73$		$n = 14$	
	Body mass index (BMI) change	1.5(0.5)	***0.0066***	0.7(0.4)	0.1084
	Median nerve, tactometry change (125 Hz) (dB)	1.7(1.2)	*0.0536*	5.4 (2.6)	*0.0675*
	3rd finger circumference change (mm)	2.4(0.5)	***0.0023***	1.2(1.0)	0.2695
CTS in 2001		$n = 30$		$n = 18$	
	Body mass index (BMI) change	0.2(0.7)	0.8012	0.8(0.4)	*0.0750*
	Median nerve, tactometry change (125 Hz) (dB)	−2.6(1.6)	0.1698	3.8(2.1)	0.1147
	3rd finger circumference change (mm)	−0.7(0.6)	0.3010	−0.4(0.8)	0.5972

Pr>|t| - Test for significant change between 2001 and 2004, where $Pr \geq |t| \leq 0.10$ (shown as *underlined italics*)

Pr>|t| - Test for significant change between 2001 and 2004, where $\boldsymbol{Pr \geq |t| \leq 0.05}$ (shown as *underlined bold italics*)

noted that VTT was measured at three frequencies, but only results at 125 Hz are reported. This was the frequency that generated the largest inter-test and inter-subject differences. The changes were either significant (BMI and finger circumference) or almost significant (VTT) for non-cases in 2001, and almost significant (VTT) for newly diagnosed CTS cases in 2004.

A comparable analysis has not been presented for the dental hygienist cohort because of the small number of CTS cases, but it should be noted that there were four newly diagnosed cases between 2001 and 2004 in the retested cohort, and 8 cases that had been positively diagnosed and were now negative. Fifty-two participants were not diagnosed with CTS at both visits and only two subjects were diagnosed with CTS at both evaluations.

Vibration neuropathy and CTS

The shipyard worker cohort had significant exposures to hand arm vibration, thus providing potential interactions between HAV syndrome and more "classical" CTS. In Table 6, the characteristics of generalized neurosensory symptoms and CTS symptoms is further examined by comparing changes in Stockholm Workshop Sensorineural (SN) stage between 2001 and 2004 and changes in study physician diagnosed CTS. The changes in the SN scale are summarized as: "−, −" stage 0 in 2001 and 2004; "−, +" from stage 0 in 2001 to any of stages 1,2, or 3 in 2004; "±" from stage 1,2, or 3, to stage 0, and; "+/+" from stage 1,2, or 3 to another symptomatic stage. The different trajectories of the CTS diagnosis and Stockholm Scale staging is captured by the Mantel–Haenzel test statistic ($\chi^2 = 32.98$ (9*df*, $P = 0.000135$).

The majority of shipyard workers were either SN +, + ($n = 72$) or SN −, − ($n = 32$) at both examinations. Change in CTS diagnosis roughly mirrors the change in SN stage when demarcated by the presence or absence of SN symptoms.

Table 6 Sensorineural symptoms by change in carpal tunnel syndrome (CTS) physician's diagnosis from 2001 to 2004

Sensorineural stage change (SN123c)	Study physician diagnosed CTS				Total
	+, +	+, −	−, +	−, −	
+, +	16	21	10	25	72
+, −	1	5	2	14	22
−, +	1	1	2	5	9
−, −	0	3	0	29	32
Total	18	30	14	73	135

$\chi^2 = 32.98$ (9*df*, $P = 0.000135$)

SN123c Stockholm scale 0 versus 1,2,3 change 2001/2004: −, −; −, +; +, −; +, +

However, movement between the different categories was less frequent for SN staging (22 +, − and 9 −, +) than for CTS diagnosis (30 +, − and 14 −, +). This is consistent with the observation that clinical CTS cases, independent of the method of diagnosis, typically have neurosensory symptoms, but not all neurosensory symptoms indicate CTS. Since SN status incorporates hand paresthesias, it is expected that CTS patterns and SN patterns will overlap. Nevertheless, the seemingly greater stability in SN symptom patterns is also mirrored in the modest changes in VTTs between studies (Table 5).

Discussion

This study has provided a number of observations on the relationships between vibration exposure, industrial work, and CTS.

1. Clinical case definitions of CTS based on self-assessments (questionnaires and diagrams and, and on clinical evaluation seem to have limited overlap (Table 3).

2. Combining clinical criteria to create a more narrow or specific case definition of CTS does not appear to influence, or predict, nerve conduction (Table 4).
3. The natural history of CTS suggests a protean disorder with considerable flux in case status over time (Tables 5, 6).

It should be noted that acknowledged risk factors for CTS include biodynamic, personal and demographic factors, and levels of vibratory exposure. These were accorded a secondary role in the analysis for two reasons. First, the results seem sufficiently provocative and clinically important to stand without further presumptive hypotheses. Second, the HAVIC study was designed to investigate exposure–response relationships for the HAV syndrome. The analyses of this multi-cohort study are incomplete, but already the integration of directly measured vibratory and biomechanical exposure variables presents sufficient complexity to discourage simplistic interpretations.

Shipyard workers

Both at baseline and at follow-up, there was limited overlap between the two methods of diagnosis–study physician and diagrammatic definition. The relative independence of method of diagnosis is further underlined in Table 4, where, for shipyard workers, the combination of diagnostic methods did not appreciably predict the SNCV results. Nevertheless, the study physician's diagnosis seemed to incorporate an enlarged clinical spectrum, which included raised VTTs in the third digit in 2001 and 2004 for shipyard workers. Self-assessment offered less differentiation between cases and non-cases for both the SNCV and VTT results.

It appeared that the study physician was better able to identify vibration specific components of hand paresthesias, often evidenced as increased VTTs and decreased digital SNCV. Since, as reported elsewhere, there appears to be no correlation between VTT and SNCV in the dental hygienists cohort (Cherniack et al. 2006a), it would seem that the broader clinical presentation, paresthesias and clinical signs, is at the root of the association between CTS and VTT found in the cases diagnosed by the examining physician. Reduced SNCVs in vibration-exposed workers compared to controls have been observed by Sakakibara et al. (1998), and in the HAVIC study (Cherniack et al. 2004a). Similar observations have been recorded by Rosén et al. (1993) and Giannini et al. (1999).

Dental hygienists

There are, of course, broad differences between the shipyard and dental hygiene study populations. Nevertheless, some validation of and exception from these results is provided by the dental hygienists. Only four new CTS cases emerged from 2002–2004, whereas eight cases no longer met the CTS case definition. This suggests a demarcation between symptoms and SNCV when viewed longitudinally. It also suggests a difference from the condition affecting shipyard workers. Our own laboratory evidence, to be reported elsewhere, indicates that the ISO-weighted acceleration produced by ultrasonic scalers is negligible. Survey evidence suggests that hand symptoms often motivate a change from hand scaling to the use of an ultrasonic scaling tool, in an effort to reduce the biomechanical stress on the upper extremity. One conclusion from these data is that CTS clinical patterns in working populations may be specific to work task rather than to a generic disease.

CTS and disease natural history

The results also highlight an apparent contradiction between cause and effect relationships for CTS, when comparing cross-sectional and longitudinal studies. Large cross-sectional studies have consistently shown an increase in CTS incidence and prevalence across age strata, and clear exposure gradients with manual jobs carrying greater risk than more sedentary employment (de Zwart et al.1997, 1999). Nathan et al. (1998, 2002) studied CTS prospectively in an open industrial cohort with significant turnover and replacement, using segmental nerve conduction measurements not unlike those used here. There were several seemingly anomalous observations: (1) CTS prevalence was extremely high, regardless of the intensity of the exposure, approaching 50% in workers doing the most forceful work; (2) the prevalence of symptoms did not seem to increase overall with retesting, but fluctuated widely at the individual level; (3) SNCV increased over time but was partially independent of symptoms, and; (4) workplace vibration appeared to aggravate symptoms. Similarities with our shipyard population include high clinical CTS rates at baseline, stable (even declining) symptom prevalence over time, and little association between symptoms and SNCVs. The disparity between cross-sectional and longitudinal studies of CTS is also supported by our work.

Unitary clinical definition of CTS

The protean nature of occupational CTS presentations in these vibration-exposed cohorts provides a basis for the diverse and sometimes contradictory reports from other investigators on the relationship of vibration exposure to CTS, and on the natural history of CTS. The observation that clinical diagnostic criteria for CTS appear to be categorical, rather than hierarchical or overlapping, is probably not limited to workers with HAV exposure. In fact, it parallels other reports on the ambiguities of CTS in working populations.

Moreover, in the longitudinal studies of Padua et al. (2001) and Padua and Mondelli (2005), the presence of clinical signs was one of the strongest predictors of deterioration in CTS patients, an observation that is distinctly contrary to the results from cross-sectional studies. The diagnostic confusion becomes even more absolute when VTT testing is added to the mix (Gerr et al. 1995; Borg and Lindblom 1986), although it is useful for identifying cases with vibration exposure particularly when confounded by CTS (Rosén et al. 1993).

The limited overlap between clinical definitions, the dissociation between SNCV and our clinical case definition, and the elusiveness of a composite and specific case definition is only disheartening if it is presumed, a priori, that CTS is a disease entity that progresses linearly over time, and is accelerated in a predictable way when intrinsic risks (e.g., sex, obesity, aging) and extrinsic risks (e.g., force, vibration, repetition) are introduced. A different perspective emerges if the relationship between clinical presentations and nerve conduction data is recognized as associative rather than causal or etiologic. If, as it appears, nerve conduction tests and clinical symptoms have different natural histories, further altered by HAV exposure, then the confusing observations on shipyard workers may be more understandable. The change in CTS case status between studies is not convincingly explained by either exposure attenuation or aging, as the gradual rise in VTTs in shipyard workers includes the effects of aging and ongoing vibratory exposure (and by implication ongoing biomechanical exposure). If, however, occupational CTS is not a simple cumulative condition but is, instead, a transitory diagnosis imposed on several semi-independent disease components, then each diagnostic medley is likely to "freeze" a particular component pathway at a point in time, rather than comply with an extended or inclusive case definition.

Conclusion

Clinical case definitions of CTS based on diagrams and self-assessment, and clinical evaluation have limited overlap. Combining clinical criteria to create a more narrow or specific case definition of CTS does not appear to predict SNCV. The natural history of CTS suggests a protean disorder with considerable flux in case status over time.

Acknowledgments This study-U01 OH 07312—was performed with support from the National Institute for Occupational Safety and Health.

References

Borg K, Lindblom U (1986) Increase of vibration threshold during wrist flexion in patients with carpal tunnel syndrome. Pain 26:211–219

Bovenzi M, Giannini F, Rossi S (2000) Vibration induced multifocal neuropathy in forestry workers: electrophysiological findings in relation to vibration exposure and finger circulation. Int Arch of Occup Environ Health 73:519–527

Brammer AJ, Pyykkö I (1987) Vibration-induced neuropathy: detection by nerve conduction measurements. Scand J Work Environ Health 13:317–322

Brammer AJ, Piercy JE (1995) Method and apparatus for identifying vibrotactile perception thresholds of nerve endings with subject inconsistency detection. U.S. Patent 5,433,211

Brammer AJ, Piercy JE (2000) Rationale for measuring vibrotactile perception at the fingertips as proposed for standardization in ISO-13091-1. Arbetslivsrapport 4:125–132

Brammer AJ, Taylor W, Lundborg G (1987) Sensorineural stages of the hand–arm vibration syndrome. Scand J Work Environ Health 13:279–283

Brismar T, Ekenvall L (1992) Nerve conduction in the hands of vibration exposed workers. Electroencephalogr Clin Neurophysiol 85(3):173–6

Cannon LJ, Bernacki EJ, Walther SD (1981) Personal and occupational factors associated with carpal tunnel syndrome. JOM 23:255–258

Chatterjee DS, Barrwick DD, Pertrie A (1982) Exploratory electromyography in the study of vibration-induced white fingers in rock driller. Brit J Indus Med 39:89–97

Cherniack MG, Letz C, Gerr F, Brammer A, Pace P (1992) Detailed clinical assessment of neurologic function in symptomatic shipyard workers. J Indust Med 47:566-572

Cherniack M, Brammer AJ, Lundström R, Meyer J, Morse TF, Neely G, Nilsson T, Peterson D, Toppila E, Warren N, Fu RW, Bruneau H (2004a) Segmental nerve conduction velocity in vibration exposed shipyard workers. Int Arch Occup Environ Health 77(3):159–176

Cherniack M, Morse TF, Brammer AJ, Lundström R, Meyer J, Nilsson T, Peterson D, Toppila E, Warren N, Fu RW, Bruneau H, Croteau M (2004b) Vibration exposure, workplace modification, and disease in a shipyard: a 13-year revisit. Am J Indus Med 45:500–512

Cherniack M, Brammer AJ, Lundström R, Meyer JD, Morse T, Neeley G, Nilsson T, Peterson D, Toppila E, Warren N, Atwood-Sanders M, Michalak-Turcotte C, Abbas U, Bruneau H, Croteau M, Fu RW (2006a) Sensory deficits and motor function in dental hygienists using high frequency ultrasound handpieces. AJIM 49:313–326

Cherniack M, Brammer AJ, Lundström R, Meyer JD, Morse TF, Neely G, Nilsson T, Peterson D, Toppila E, Warren N (2006b) The Hand–Arm Vibration International Consortium (HAVIC): prospective studies on the relationship between power tool exposure and health effects (in review)

de Zwart BCH, Broersen JPG, Frings-Dresen MHW, van Dijk FJH (1997) Repeated survey on changes in musculoskeletal complaints relative to age and work demands. Oem 54:793–799

de Zwart BC, Frings-Dresen MH, van Duivenbooden JC (1999) Senior workers in the Dutch construction industry: a search for age-related work and health issues. Exp Aging Res 25:385–391

Fagarasanu M, Kumar S (2003) Work-related carpal tunnel syndrome: current concepts. J Musculoskeletal Res 7:87–96

Gemne G, Pyykkö I, Taylor W, Pelmear PL (1987) The Stockholm Workshop scale for the classification of cold-induced Raynaud's phenomenon in the hand–arm vibration syndrome. Scand J Work Environ Health 13:275–278

Gerr F, Letz R, Harris-Abbot D, Hopkins L (1995) Sensitivity and specificity of vibrometry for detection of carpal tunnel syndrome. JOEM 37:1108–1115

Giannini F, Rossi S, Passeroa S, Bovenzi M, Cannava G, Mancini R, Cionia R, Battistini N (1999) Multifocal neural conduction impairment in forestry workers exposed and not exposed to vibration. Clin Neurophysiol 110:1276–1283

Hirata M, Sakakibara H, Abe M (2002) Reduced sensory nerve conduction velocity of the distal part of the radial nerve among patients with vibration syndrome. Electromyogr Clin Neurophysiol 42(2):113–8

ISO 13091-1 (2001) International Organization for Standardization. Mechanical vibration—vibrotactile perception thresholds for the assessment of nerve dysfunction: Part 1—Method of measurement at the fingertips

Katz JN, Stirrat CR (1990) A self-administered hand diagram for the diagnosis of carpal tunnel syndrome. J Hand Surg (AM) 15:360–363

Koskimies K, Farkilla M, Pyykko I, Jantti V, Aatola S, Starck J, Inaba R (1990) Carpal tunnel syndrome in vibration disease. Brit J Indus Med 47:411–416

McGeough KL, Gilmour WH (2000) Cross sectional study of a workforce exposed to hand–arm vibration: with objective tests and the Stockholm workshop scales. Occup Environ Med 57:35–42

McGeough KL, Lawson J, Burke F, Proud G, Miles J (2005) Use of sensorineural tests in a large volume of medico-legal compensation claims for HAVS. Occup Med 54:528–534

Nathan PA, Keniston RC, Myers LD, Meadows KD, Lockwood RS (1998) Natural history of median nerve sensory conduction in industry: relationship to symptoms and carpal tunnel syndrome in 558 hands over 11 years. Muscle Nerve 21(6):711–21

Nathan PA, Meadows KD, Istvan JA (2002) Predictors of carpal tunnel syndrome: an 11-year study of industrial workers. J Hand Surg (Am) 27:644–651

Nilsson T (2002) Neurological diagnosis: aspects of bedside and electrodiagnostic examinations in relation to hand–arm vibration syndrome. Int Arch Environ Health 75:55–67

Nilsson T, Hagberg M, Burström L, Kihlberg S (1994) Impaired nerve conduction in the carpal tunnel of platers and truck assembles exposed to hand–arm vibration. Scand J Work Environ Health 20:189–99

Padua L, Mondelli M (2005) Evaluation of hand dysfunction and symptoms in untreated carpal tunnel syndrome. Muscle Nerve 32:545–547

Padua L, Padua R, Aprile I, Pasqualetti P, Tonali P (2001) Multiperspective follow-up of untreated carpal tunnel syndrome: a multicenter study. Neurology 56:1459–1466

Rosén I, Stromberg T, Lundborg G (1993) Neurophysiological investigation of hands damaged by vibration: comparison with idiopathic carpal tunnel syndrome. Scand J Plast Reconstr Hand Surg 27:209–16

Sakakibara H, Kondo T, Miyao M, Yamada S (1994) Digital nerve conduction velocity as a sensitive indication of peripheral neuropathy in vibration syndrome. Am J Ind Med 26:359–366

Sakakibara H, Hirata M, Hashiguchi T, Toibana N, Koshiyama H, Zhu S-K, Kondo T, Miyao M, Yamada S (1998) Digital sensory nerve conduction velocity and vibration perception threshold in peripheral neurological test for hand-arm vibration syndrome. AJIM 30:219–224

Sandén H, Edblom HM, Hagberg M, Wallin BG (2005) Bicycle ergometer test to obtain adequate skin temperature when measuring nerve conduction velocity. Clin Neurophysiol 116:25–27

Seppäläinen A-M (1972) Peripheral neuropathy in forest workers. A field study. Work Environ Health 9:106–111

Silverstein BA, Fine LJ, Armstrong TJ (1986) Hand wrist cumulative trauma disorders in industry. Br J Indus Med 43:779–784

Silverstein BA, Fine LJ, Armstrong TJ (1987) Occupational factors and carpal tunnel syndrome. Am J Ind Med 11:343–358

Sluiter JK, Rest KM, Frings-Dresen MH (2001) Criteria document for evaluating the work-relatedness of upper-extremity musculoskeletal disorders. Scand J Work Environ Health 27(1):1–102

Strömberg T, Dahlin LB, Brun A, Lundborg G (1997) Structural nerve changes at wrist level in workers exposed to vibration. Occup Environ Med 54:307–311

Strömberg T, Dahlin LB, Lundborg G (1998) Vibrotactile sense in the hand-arm vibration syndrome. Scand J Work Environ Health 24(6):495–502

Viikari-Juntura E, Rauas S, Martikainen R, Kuosma E, Riihimaki H, Takala E-P, Sarrenmaa K (1996) Validity of self-reported physical work load in epidemiologic studies on musculoskeletal disorders. Scand J Work Environ Health 22:251–259

Virokannas H (1992) Dose–response relation between exposure to two types of hand–arm vibration and sensorineural perception of vibration. OEM 52:332–336