

Original Article

Thermal perception thresholds: assessing the level of human spinal cord injury

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Study design: Controlled, cross-sectional, observational.

Objectives: To investigate whether quantitative sensory testing (QST) is able to reveal subclinical deficits at the neurological level of lesion in subjects with chronic spinal cord injury (SCI).

Setting: National Spinal Injuries Centre, Stoke Mandeville Hospital and Imperial College London, UK.

Methods: QST and clinical assessments were carried out on 18 subjects with complete SCI (American Spinal Injury Association (ASIA) grade A) and 10 subjects with incomplete SCI (ASIA grades B, C or D). A total of 10 healthy subjects acted as controls.

Results: At the level of lesion perceptual thresholds to monofilaments, cold pain and heat pain were similar to values in control subjects but cool and warm thresholds were significantly raised. A correlation between cool and warm thresholds was observed at the level of lesion in complete SCI and between heat and cold pain thresholds at the level of lesion in complete SCI, incomplete SCI and in control subjects. In the zone of partial preservation in complete SCI and below the level of lesion in incomplete SCI, thresholds for all modalities were all different compared to controls.

Conclusion: QST reveals impaired thermal sensation in dermatomes clinically defined as normal with ASIA standards. Quantitative thermal testing therefore permits a discriminating assessment of preserved sensation and subclinical deficit and has the potential to improve upon the clinical detection of natural recovery or changes in level of injury following interventions designed to repair SCI.

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Introduction

Sensory dysfunction is a highly detrimental consequence of spinal cord injury (SCI). It may manifest itself as a loss of sensation, hypo- or hyperaesthesia, pain or allodynia. In addition to loss of sensory function below the level of lesion in complete SCI, sensory dysfunction may be found above the level of injury as a result of plasticity.¹ Changes rostral to a spinal cord lesion occur in the central nervous system,² including the thalamus^{3,4} and cortical areas.⁵

Chronic neuropathic pain, which has a major impact on quality of life in subjects with SCI, is also thought to

be associated with altered central processing of somatosensory function for dermatomes rostral to the segmental level of injury.⁶

Clinical neurological examination is a crude assessment and does not allow sensitive selective detection of subclinical deficits. Sensory deficit in SCI routinely assessed by the American Spinal Injury Association (ASIA) standards categorizes sensory scores as absent, impaired or normal, with the category of impaired including hypoaesthesia and hyperaesthesia, hypoalgesia and hyperalgesia. Quantitative sensory testing (QST) is a noninvasive method⁷ widely used in the screening of peripheral neuropathy, both for loss of sensation and increased cutaneous sensitivity, in monitoring disease progression and in evaluating response to therapy in adults and children.^{8–10} It has also proved useful in the

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assessment and characterisation of hypersensitive conditions such as hyperalgesia and allodynia.¹¹ Quantitative thermal testing as part of QST is a widely accepted psychophysical method of evaluating small nerve fibre function and refines the diagnosis of neuropathies.^{12,13} Quraishi *et al*¹⁴ used QST in patients with low back pain and lumbosacral spinal nerve root pain, to reveal significant elevations of warm, cool and touch perception thresholds in affected dermatomes. In clinically complete SCI, Finnerup *et al*,¹⁵ used QST to reveal retained sensory communication (sensory discomplete) although a cautionary note on the utility of QST in SCI¹⁶ has stressed the need for repeated measures to establish stable baseline values.

The principal aim of the present study was to establish the extent to which QST is able to reveal subclinical sensory deficits at the neurological level of SCI injury established by the ASIA impairment scale.¹⁷ Confirmation that QST is able to detect such abnormalities would merit consideration of the inclusion of QST as a means of assessing the outcome of future interventions designed to promote regeneration and recovery of spinal cord function. Factors such as the heterogeneity in the cause of lesion and the time elapsed since the occurrence of injury were expected to influence the interpretation of our findings. Therefore, in the present study we employed strict inclusion and exclusion criteria with

regard to SCI subjects. Preliminary results from a less selective group have appeared in a broad review of a clinical initiative designed to develop clinical, sensory, motor and autonomic tests for the assessment of recovery in SCI.¹⁸

Subjects and methods

The study was approved by the Aylesbury Vale Ethics Committee. All participants gave their informed consent and the study conformed to the guidelines of the Helsinki Convention.

A total of 28 subjects with chronic SCI and 10 healthy volunteers acting as controls participated in the study. Subjects were examined lying supine in a quiet room. Subjects with SCI were classified according to the ASIA impairment scale.¹⁷ The 28 SCI subjects were subclassified into two groups (Table 1). First group: 18 subjects with complete SCI (ASIA grade A), four cervical injury (levels C5–C8) and 14 thoracic injury (levels T4–T11), 15 male and three female, aged 33.3 ± 10 years (mean \pm SD). Most subjects had a zone of partial preservation (ZPP), a term used only with complete injuries, that refers to those dermatomes (and myotomes) caudal to the neurological level that remain partially innervated. The most caudal segment with some sensory and/or motor function defines the extent

Table 1 Spinal cord injury subject demographics

No	Age	Sex	ASIA	ZPP	Cause of injury	Injury (weeks)
1	21	F	C4 A	C5–T2	RTA	39
2	23	M	C5 A	C6–C7	RTA	32
3	20	M	C7 A	C8–T3	RTA	61
4	21	M	C8 A	T1	RTA	35
5	53	M	T4 A	None	Fall	16
6	40	M	T4 A	T5	RTA	28
7	47	M	T4 A	T5–T6	RTA	51
8	23	M	T5 A	T6	RTA	43
9	40	M	T6 A	T7	Fall	56
10	36	M	T6 A	T7–T8	RTA	38
11	43	M	T6 A	T7–T8	Fall	27
12	23	M	T6 A	T7–T9	RTA	23
13	33	F	T7 A	T8	RTA	35
14	37	M	T8 A	T9	RTA	30
15	29	M	T8 A	T9–T11	RTA	29
16	38	M	T8 A	T9–T10	RTA	28
17	29	F	T9 A	T10–T11	Fall	19
18	43	M	T11 A	T12	Sport	15
19	37	M	C3 D	NA	Sport	18
20	26	M	C4 C	NA	Sport	59
21	29	M	C5 C	NA	Sport	28
22	70	F	C6 C	NA	Fall	28
23	30	M	C7 C	NA	Sport	18
24	57	M	T9 B	NA	Fall	24
25	41	M	T12 D	NA	Fall	16
26	37	M	L1 C	NA	Fall	20
27	52	M	L3 C	NA	Fall	26
28	21	M	L4 C	NA	RTA	30

Age in years. ZPP, zone of partial preservation; NA, not applicable; RTA, road traffic accident; Sport, horse riding or skiing

of the ZPP. Second group: 10 subjects with incomplete SCI, with injury levels ranging from C3 to L4, grade B, C or D, nine male and one female, aged 40 ± 15.3 years. All subjects had suffered from traumatic SCI: in the majority of cases, the cause of injury was road traffic accident (RTA). Subjects with nontraumatic injury (spinal tumour, iatrogenic lesions, etc) were excluded from the study. Also, we included only those subjects with duration of injury between 15 and 61 weeks excluding all subjects with acute or longer-term injury.

QST included the following tests.

- Light touch threshold using Semmes-Weinstein monofilaments (A Ainsworth, University College London, UK). Threshold for light touch was taken as the number of the hair detected with the lowest force level. Sensation was regarded as normal for monofilaments \leq No 3 (0.0479 g) and abnormal for monofilaments No 4 and higher.¹⁰
- Thermal threshold to cool sensation, warm sensation, cold pain and heat pain were measured with a Medoc Thermal Sensory Analyser (TSA-2001, Israel) and thermode (30 × 30 mm) applied to the skin. Thermal sensory thresholds were measured using the method of limits. Sensation was regarded as abnormal for thresholds $>2SD$ from controls. Subjects received three successive, decreasing or increasing, stimuli starting from an adaptation temperature of 32°C, at a rate of 1°C/s. Subjects were required to arrest the changing stimulus intensity by pressing a button as soon as they perceived the specific thermal modality being tested. Alternatively, for those subjects with cervical lesions who were unable to use their hands, the assessor pressed the button immediately the subject reported a change in sensation. Since the rate of change of temperature of the probe was 1°C/s, any slight delay (<1 s) was not considered to materially affect the measure of threshold. Thresholds were taken as the average of three successive readings in each session.¹⁹ Innocuous and noxious thermal thresholds were tested in separate sessions. For noxious cold and heat, subjects were asked to arrest the increasing stimulus intensity when they perceived it to have become uncomfortable. The method of limits also allowed determination of abnormal patterns, such as thermal hypoaesthesia, hypoalgesia, hyperalgesia and combinations of these patterns as well as paradoxical thermal sensations, thermal dysaesthesias and paraesthesias.¹²

Monofilament and thermal QST was performed at the level of injury (most caudal segment of the spinal cord with normal sensory and motor function on both sides of the body) in the ZPP in appropriate cases of complete SCI, and below the level of injury. In a few SCI subjects, thermal sensitivity was additionally tested at one or more segments above the level of injury. Monofilaments and thermode were placed on the ASIA key sensory points of the dermatomes tested. In control subjects,

thermal thresholds were measured for all dermatomes from T2 to T12, with the thermode placed on the ASIA key sensory points.

Subjects were asked to report the nature of the perceived sensation irrespective of the actual modality under test. The study of neuropathic pain by means of questionnaires and visual analogue scale and inferences between neuropathic pain and sensory dysfunction were beyond the aims of the present study. Observations were limited to the perception thresholds of cold and heat pain. In appropriate cases, however, allodynia (pain evoked by non-noxious stimulation) to thermal stimuli was assessed with the Medoc TSA and to mechanical stimuli with monofilaments.

Results were analysed by using SigmaStat (Jandel) statistical software. Perceptual thresholds were not normally distributed. ANOVA rank (Kruskal–Wallis) tests were performed (P significant if <0.05) to analyse differences in sensory perception thresholds between complete SCI, incomplete SCI and control subjects. An all pair-wise multiple comparison procedure (Dunn's method) was used to isolate groups that differed from each other. Linear correlation was performed in order to establish any dependence between different modalities of sensation.

Results

Complete SCI

At the level of lesion (most caudal normal level) in subjects with complete SCI, monofilament threshold values were not different to control values. In contrast, thermal thresholds for perception of cool and warm stimuli were significantly ($P < 0.01$) raised above control values (Figure 1) and this was also the case when data were restricted to the 14 SCI subjects with thoracic injuries. Cold and heat pain thresholds were not significantly different between SCI subjects and controls. However, it should be noted that several subjects, both control and SCI, did not report cold pain even when the thermode had reached a temperature of 0°C, giving a large standard deviation to the cold threshold readings. No misinterpretation of sensation occurred and allodynia was not reported. Perceptual threshold results at the level of lesion are summarised in Table 2.

In a subgroup of five complete SCI subjects, cool and warm perception thresholds were additionally assessed at one or two dermatomes immediately above the neurological level of injury. Both thermal thresholds were significantly lower than those measured at the level of injury ($P < 0.05$) and not significantly different from normal control values. Thus, the raised thermal thresholds were observed only at the level of lesion.

In the ZPP (see Table 1), thresholds for monofilaments, cool and warm perception and heat and cold pain were significantly ($P < 0.05$) greater than control values (tactile and thermal hypo-aesthesia). In the ZPP, some subjects (one cervical and five thoracic SCI) reported a misinterpretation of sensation (cold for warm

or vice versa), or an undefined sensation rather than thermal. In addition, thermal allodynia was observed in three thoracic SCI subjects. No mechanical allodynia (to monofilament touch) was observed in any SCI subjects. Below the level of lesion (below the ZPP), there was a total sensory loss (beyond limits of tests).

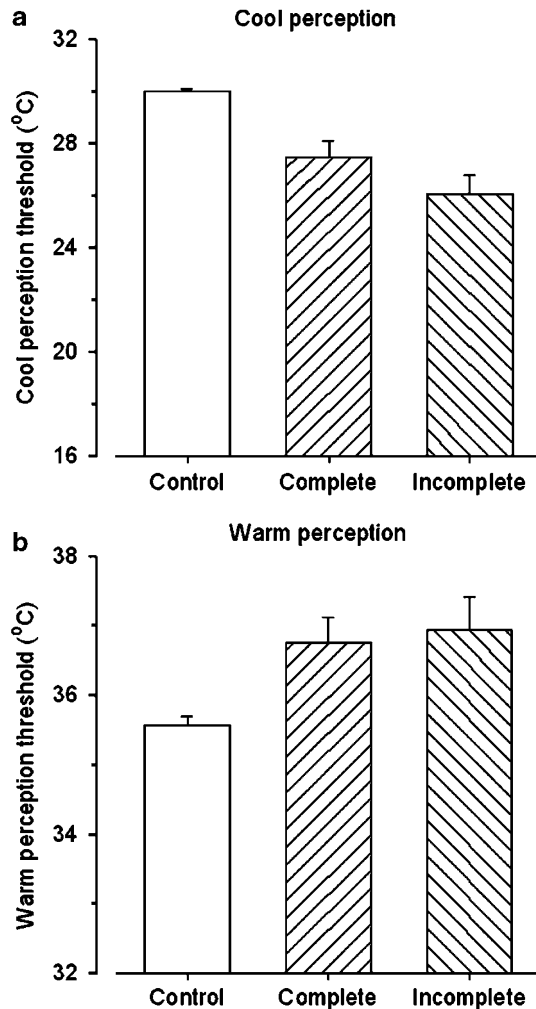


Figure 1 Thermal thresholds (mean ± SE) for cool (a) and warm (b) perception in control (open bars) and spinal cord-injured subjects (complete SCI – rising hatch; incomplete SCI – falling hatch). The mean thresholds for both thermal modalities are significantly different from control values for both complete and incomplete SCI subjects ($P < 0.01$)

Incomplete SCI

In subjects with incomplete SCI at the level of lesion, monofilament threshold, cold and heat pain threshold values were similar to controls. Cool and warm perception thresholds were however, significantly raised ($P < 0.001$) compared to controls (thermal hypo-aesthesia), as was observed for subjects with complete SCI (Figure 1). Perceptual threshold results above the level of lesion are summarised in Table 2.

In a subgroup of five incomplete SCI subjects, cool and warm perception thresholds were additionally assessed at one dermatome immediately above the neurological level of injury. Cool threshold was significantly lower than that measured at the level of injury ($P < 0.01$) and not significantly different from normal control values. Thus, the raised thermal threshold was observed only at the level of lesion.

Below the level of lesion, monofilament, cool perception and warm perception thresholds were all raised (hyposensitivity). One subject reported misinterpretation of thermal modalities and another reported thermal allodynia. No mechanical allodynia to monofilament stimulation was reported in any subject.

Correlation between sensory modalities

The raised thresholds to warm and cool sensory modalities, but not to nonthermal modalities, at the level of lesion (most caudal normal level) in complete and incomplete SCI raises the possibility that injury might affect centrally projecting pathways differently. We have therefore looked to see whether the thresholds for different modalities might be correlated. Linear regression analysis was carried out between threshold values for all combinations of types of stimuli used in QST: monofilaments, cool sensation, warm sensation, cold pain and heat pain. This was carried out in both complete and incomplete SCI subjects at the level of lesion, and in control subjects. There was a significant ($P < 0.01$) but weak positive correlation ($r = 0.46$) between thresholds for cool and warm sensation in complete SCI but not in incomplete SCI or control subjects (Figure 2). No correlations were observed for any other combinations of innocuous modalities of sensation. However, significant ($P < 0.01$) correlations were observed between heat and cold pain (Figure 2) for all three groups of subjects (complete SCI, $r = 0.58$;

Table 2 Perceptual thresholds (mean ± SE) for control subjects and for SCI subjects at the level of injury

Stimulus	Control subjects	Complete SCI subjects	Incomplete SCI subjects
Monofilaments (Filament No.)	Normal range 1–3		
Cool (°C)	30.0 ± 0.1	27.5 ± 0.6 ^a	26.0 ± 0.7 ^a
Warm (°C)	35.6 ± 0.1	36.7 ± 0.4 ^a	36.9 ± 0.5 ^a
Cold pain (°C)	12.2 ± 1.1	12.3 ± 2.0	12.8 ± 3.1
Heat pain (°C)	44.2 ± 0.4	44.2 ± 0.6	44.8 ± 1.0

^aSCI thresholds significantly ($P < 0.01$) elevated compared to control values

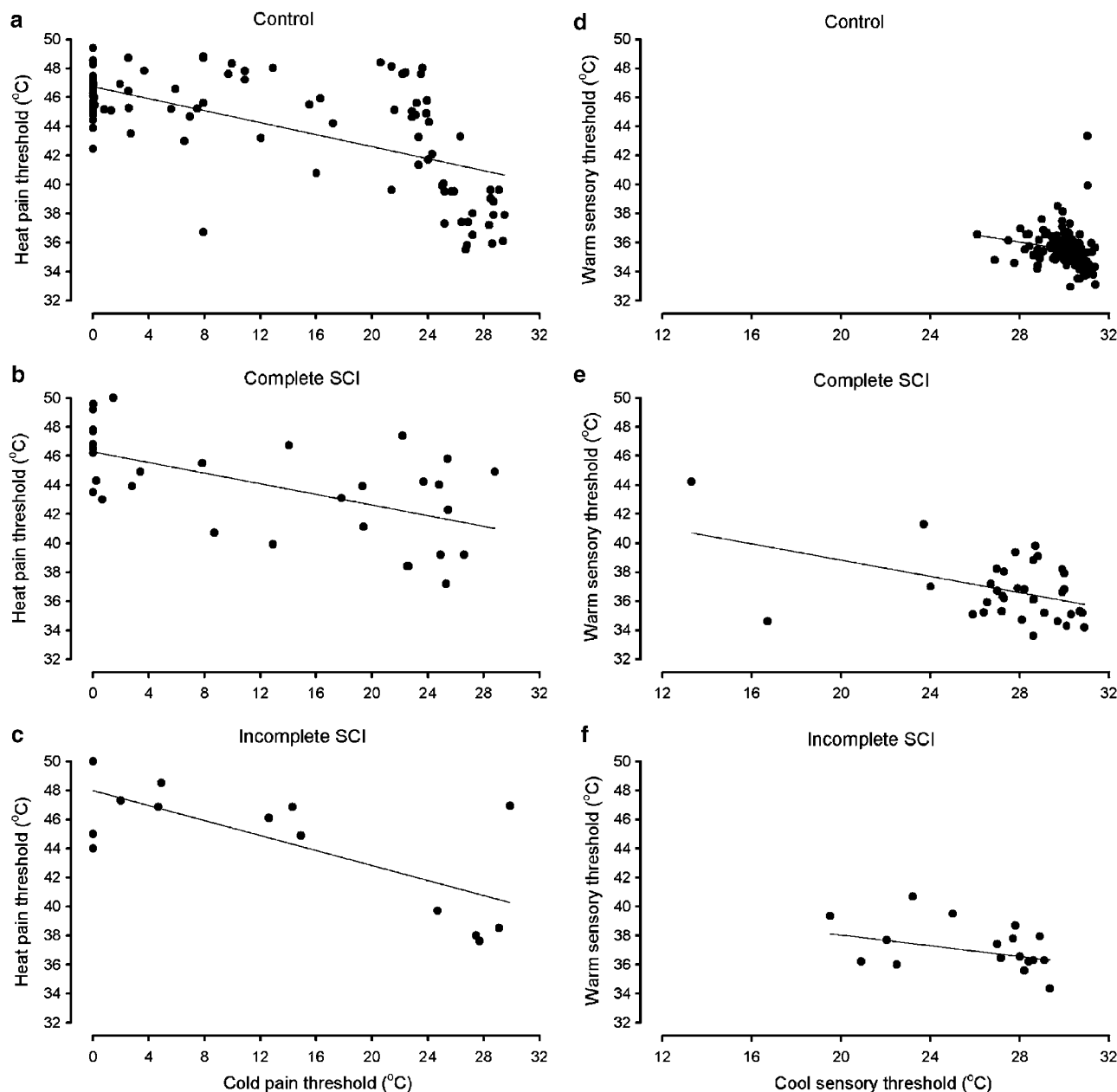


Figure 2 Relationships between thermal thresholds for control and SCI subjects. Measurements were made at T2–T12 thoracic dermatomes for control subjects and at the level of lesion (most-caudal normal vertebral level) on the left and the right for SCI subjects. (a–c) Relationship between heat and cold pain thresholds for control (a), complete SCI (b) and incomplete SCI (c) subjects. Note that many control and SCI subjects did not report discomfort to cold even at 0°C. (d–f) Relationship between warm and cool thresholds for control (d), complete SCI (e) and incomplete SCI (f) subjects. Linear regression analysis (solid lines) gave statistically significant correlations between heat and cold pain thresholds for all three groups and for warm and cool thresholds for complete SCI ($P < 0.01$)

incomplete SCI, $r = 0.74$; control, $r = 0.65$). No correlations were observed between any innocuous and noxious modality.

Discussion

The principal result of this study is that thermal thresholds to cool and warm stimuli at the level of

lesion, that is the most caudal normal level as determined by clinical ASIA criteria, are significantly higher in subjects with complete and incomplete SCI than normal control values. First, we consider whether this finding of raised thermal thresholds but normal tactile thresholds might have resulted from differences between the size of the thermode and that of the monofilaments. Dermatomes are not clearly demarcated

regions and overlap exists with some areas of the skin innervated by adjacent spinal roots. The point-like dimension of the tip of a monofilament would have ensured that stimulation (at the ASIA key sensory point) was confined to one dermatome. Although there was potential for the larger thermode (see Subjects and methods) to straddle an adjacent dermatome placement on the key ASIA points ensured that it did not. This being the case, it is relevant that thermal dermatomes are invariably smaller than tactile dermatomes and have minimal overlap,²⁰ making it unlikely that a thermode testing the lowest normal dermatome would also have contacted skin innervated by the next (lower) abnormal level.

Finnerup *et al.*¹ have also observed raised cool and warm thresholds above the level of SCI but only in those suffering from neuropathic pain. In the present study, thermal thresholds measured for one or two dermatomes immediately above the level of lesion appeared to be normal. Our findings thus reveal selective subclinical thermal sensory deficits for dermatomes clinically defined as normal (most caudal normal sensory level) by ASIA standards. One interpretation of our findings is that a lesion at a particular level and density may affect the inputs or relays to different ascending sensory pathways differently. In this study, at the most caudal normal level in SCI light touch as assessed clinically and by monofilament testing was normal. This would indicate that the axonal branching of primary afferents conveying touch via the dorsal column pathway is not disrupted. In contrast at the same level, the raised thermal thresholds suggests that the input to the spinothalamic tract via interneuronal connections from primary afferents involved in signalling thermal conditions is abnormal. This is to be expected since the pathology of the injury is likely to affect the core of the cord more than the surrounding white matter.²¹ Notwithstanding the reason, the finding indicates that QST is capable of revealing subclinical deficits in SCI. This would support the inclusion of QST as a tool that furnishes greater accuracy than ASIA assessments for tracking recovery of spinal cord function. Of particular clinical relevance would be its application in future interventions designed to promote regeneration since it is anticipated that functional recovery may be limited to only one or two segments in the first attempts at spinal cord repair.²²

The question in general of association between thresholds for different sensory modalities has been addressed frequently in the past, more particularly with regard to the different modalities of pain^{23,24} than for innocuous sensation, but with no clear consensus of opinion. Of particular interest in the present study was the possibility of association of sensory modalities tested at the level of lesion. A weak positive correlation between thresholds for cool and warm sensation was observed in complete SCI but not in incomplete SCI or control subjects. An association between innocuous cool and warm sensations is not expected on peripheral grounds since these modalities are subserved by different

receptors.²⁵ Furthermore, damage to the anterior spinothalamic tract at the rostral end of the lesion and extending into the most caudal clinically normal level is unlikely to account for the association since there was no association between thresholds for noxious and innocuous thermal stimuli, even though ascending fibres for these modalities share the same tract. Rather, we speculate that the weak association between cool and warm sensations suggests that some convergence may have developed between ascending projections. If this plasticity is labile then a reversal of the process might be expected if the level of SCI were to change during recovery. Monitoring any association between cool and warm thresholds in SCI might therefore be useful in tracking a recovery process.

The situation with regard to association between different sensory modalities is different for pain since, in addition to receptors with peripheral specificity, other receptors are polymodal, responding to heat, chemical and mechanical noxious stimuli. Although a significant correlation was observed between heat and cold pain thresholds, there was an association of equivalent degree in normal and SCI subjects. Such an association has not been reported consistently in the past^{23,24,26,27} possibly reflecting differences in body sites tested, rate of change of temperature and degree of exposure ranging from the tip of a thermode to whole arm immersion. Since, the association between heat and cold pain thresholds in our tests was not uniquely a feature of SCI at the level of injury, the relationship is unlikely to be useful in monitoring change during recovery. In addition, with respect to cold pain it is worth stressing the wide range of thresholds reported by SCI and control subjects alike. Several individuals failed to report discomfort at temperatures frequently acknowledged as painful by others. In some instances thermal pain was not reported even when the thermode reached 0°C. This would indicate that a cold pain test is less suitable as an indicator of abnormal sensory function and for monitoring change.

Warm perception thresholds reflect the activity of unmyelinated C-fibres, whereas cool perception thresholds indicate A δ fibre function and only to a lesser extent also the function of subgroups of C-fibres.^{12,28} Touch and vibration sensation are served mainly by larger cutaneous and proprioceptive myelinated afferents.²⁹ Cool and warm hypoesthesia have been found to dissociate from each other in patients with peripheral somatosensory dysfunction and may occur in the absence of abnormal tactile sensation sub-served by large myelinated afferents.¹² A similar dissociation evidenced by thermal hypoesthesia in the presence of normal tactile sensation was observed in the present study and may have occurred as result of the greater impact of the injury on the grey matter core of the spinal cord compared with the surrounding white matter. However, in the present study there was weak association rather than dissociation observed between the two modalities of thermal sensation (cool and warm thresholds) at the level of lesion in complete SCI. The

possibility is that reorganisation of spinal cord circuitry close to the level of the lesion altered the connectivity of C and A δ fibres creating increased convergence in their ascending pathways and a degree of association in sensation in some subjects.

Defrin *et al*³⁰ found that in areas lacking thermal sensibility, warm and cool stimuli produced a sensation of pricking pain, which had no thermal quality and was detected at significantly higher thresholds in subjects with SCI compared to controls. Misinterpretation of thermal sensation and thermal allodynia were found in the present study in the ZPP of subjects with complete lesions and below the level in subjects with incomplete lesions but not above the level of lesion in either group. Thermal allodynia may have an explanation similar to that proposed for mechanical allodynia³¹ whereby hyperexcitable dorsal horn neurones normally responding to noxious stimulation begin responding also to activity in low threshold mechanoreceptors. However, mechanical allodynia was not observed in any SCI subjects either above or below their injury.

Our study emphasises the ability of non-noxious thermal tests as a component of QST to reveal sensory dysfunction in dermatomes at the level of injury in chronic SCI. Irrespective of whether subclinical deficits are due to the natural progression of the original injury or the results of intervention, a considerable advantage of QST is that it offers a range of values compared to the standard clinical examination thus permitting a more objective, discriminating, and standardized evaluation of the degree and quality of preserved sensation or sub-clinical deficit. QST comprises non-invasive tools that are also well tolerated by SCI subjects. As such, QST will provide an important adjunct in the assessment of sensory systems in SCI, especially in the evaluation of natural recovery or small sensory changes in level of SCI anticipated following future interventions designed to promote regeneration within the spinal cord.

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