BJA

# Influence of ketamine and morphine on descending pain modulation in chronic pain patients: a randomized placebo-controlled cross-over proof-of-concept study

M. Niesters, L. Aarts, E. Sarton and A. Dahan*

Department of Anesthesiology, Leiden University Medical Center, 2300 RC Leiden, The Netherlands
* Corresponding author. E-mail: a.dahan@lumc.nl

### Editor's key points

- Dysfunction of central inhibition of pain processing has been implicated in the pathogenesis of chronic pain states.
- The effects of morphine and ketamine on conditioned pain modulation (CPM) were studied in 10 adults with chronic peripheral neuropathic pain.
- Morphine, ketamine, and placebo all provided CPM in proportion to their analgesic effects, suggesting a role for CPM in the treatment of chronic pain.

**Background.** Descending inhibition of pain, part of the endogenous pain modulation system, is important for normal pain processing. Dysfunction is associated with various chronic pain states. Here, the effect of ketamine and morphine on descending inhibition is examined using the conditioned pain modulation (CPM) paradigm in chronic neuropathic pain patients.

**Methods.** CPM responses were obtained in 10 adult neuropathic pain subjects (two men/ eight women). All subjects had peripheral neuropathy as defined by abnormal quantitative sensory testing. The effects of $S(+)$-ketamine (0.57 mg kg$^{-1}$ h$^{-1}$ for 1 h) and morphine (0.065 mg kg$^{-1}$ h$^{-1}$ for 1 h) were tested in a randomized, placebo-controlled double-blind study. CPM was measured at baseline and 100 min after the start of treatment and was induced by immersion of the leg into a cold-water bath. The test stimulus was a 30 s static thermal stimulus to the skin of the forearm.

**Results.** Without treatment, no CPM was detectable. Treatment with ketamine, morphine, and placebo produced CPM responses of 40.2 (10.9)%, 28.5 (7.0)%, and 22.1 (12.0)%, respectively (for all treatments, CPM effect $P<0.05$), with no statistical difference in the magnitude of CPM among treatments. The magnitude of CPM correlated positively with the magnitude and duration of spontaneous pain relief.

**Conclusions.** The observed treatment effects in chronic pain patients suggest a role for CPM engagement in analgesic efficacy of ketamine, morphine, and placebo treatment.

**Keywords:** diffuse noxious inhibitory control; ketamine; morphine; peripheral nervous system diseases; placebo effect

Accepted for publication: 17 December 2012

Normal pain processing involves modulation of pain signals in the central nervous system by the activation of endogenous inhibitory (analgesic) or facilitatory (algesic) mechanisms.[1–3] These modulatory mechanisms allow optimal functionality in response to an acute painful insult.[4] For example, activation of endogenous inhibition of pain allows for an evolutionary well-preserved fight or flight response;[5 6] facilitation of pain responses puts the emphasis on tissue damage and forces an individual to seek rest, medical attention, or both.[6] In recent years, various experimental (surrogate) expressions of endogenous modulation of pain gained increasing interest in chronic pain research.

Conditioned pain modulation (CPM, formerly known as diffuse noxious inhibitory controls or DNIC) has been investigated most intensively and induces central inhibition of a focal pain stimulus by administering a second noxious stimulus at a remote area.[7 8] In contrast to animals, where endogenous inhibition involves activation of spinal–medullary–spinal feedback loops (e.g. DNIC),[9] in humans more complex supraspinal mechanisms also play an important role (e.g. CPM).[7 10] Absent or impaired CPM responses have been observed in several chronic pain states.[8 11–13] Defects in CPM possibly reflect an inability to engage descending inhibition, either causing perseverance of pain symptoms or possibly even leading to the development of chronic pain. For example, recent animal data show that less efficient descending inhibition is associated with a high probability of chronic pain development after peripheral nerve injury.[14 15]

Few studies address the effect of analgesic medication on CPM responses in chronic pain patients. It can be hypothesized that chronic pain patients would benefit from analgesics that enhance descending inhibition as measured by CPM.[14 16] A recent study showed that duloxetine-induced improvement of CPM responses correlated with drug efficacy in patients with painful diabetic neuropathy.[16] Hence, the positive effect of analgesics on CPM might have a predictive

effect on their ability to cause (long-term) analgesia. In the current study, we assessed the effect of morphine and ketamine on CPM responses in a group of patients with chronic painful peripheral neuropathy. Both treatments are effective in chronic pain patients, but their effects on CPM responses have only been tested in volunteers, but not in chronic pain patients. We hypothesized that both drugs enhance CPM responses and that the magnitude of these responses correlates positively with the magnitude and duration of spontaneous pain relief.

## Methods

Approval of the study was obtained from the local human ethics committee, and written informed consent was obtained from all subjects. The study was registered in the Dutch Trial Register (www.trialregister.nl) under trial number NTR2005.

### Subjects

Ten patients with chronic pain were recruited to participate in the study. They were diagnosed with chronic peripheral neuropathic pain and were included on the basis of their symptoms, the results of quantitative sensory testing (QST), and a neurological examination.[17–19] Subjects were required to have at least two of the following symptoms in legs, arms, or both (in a stocking-glove distribution): (i) symmetrical dysesthesias or paresthesias; (ii) burning or painful feet with night-time worsening; or (iii) peripheral tactile allodynia. With respect to the QST, subjects were included if they had an abnormal warm and cold detection threshold, an abnormal warm and cold pain threshold, or allodynia.

Before participation, all subjects underwent physical examination. Exclusion criteria for the study were: age <18 or >80 yr; presence or history of a medical disease such as renal, cardiac, vascular (including hypertension), or infectious disease; presence or history of a neurological and psychiatric disease such as increased cranial pressure, epilepsy or psychosis; glaucoma; pregnancy; obesity (BMI>30); or use of strong opioid medication. Subjects were allowed to continue the following pain medications as long as they used a constant dose for at least 3 months before the start of the study and could be kept constant during the whole study period: acetaminophen, non-steroidal anti-inflammatory drugs, amitriptyline, gabapentin, and pregabalin.

### Pain assessment and CPM

As examined by Pud and colleagues,[7] noxious cold water is the most used pain modality as a conditioning stimulus combined, with different pain modalities used as test stimulus. We applied a heat pain stimulus as test stimulus and cold water as conditioning stimulus, in agreement with earlier studies from our laboratory and from King and colleagues.[8 20]

The test stimulus was a noxious thermal stimulus applied to clinically normal skin of the volar side of the dominant forearm (with normal warm and cold thresholds). The skin

was stimulated with a $3\times3$ cm thermal probe of the Pathway Neurosensory Analyzer (Medoc Ltd, Ramat Yishai, Israel). During the heat pain stimulus, subjects continuously quantified the pain intensity level of the stimulus using a slider on a computerized potentiometer that ranged from 0 (no pain) to 100 (worst pain imaginable), which allowed continuous, electronic monitoring of the visual analogue scale (eVAS). To overcome sensitization, a 3 min interval was incorporated between tests and the volar side of the arm was divided into three zones.[8] The thermode was moved from zone to zone between stimuli. The test stimulus was obtained by gradually increasing the thermode temperature from baseline (32°C) to the test temperature (at $1.5°C\ s^{-1}$). When the test temperature was reached, it remained constant for 30 s. Next, the temperature was rapidly decreased (at $6°C\ s^{-1}$) to baseline. Before the test, individual test and conditioning temperatures were determined. For the test stimulus, a series of heat stimuli was applied. Baseline temperature was set at 32°C after which temperature increased by $1.5°C\ s^{-1}$ to temperatures ranging from 42°C to 49°C for 10 s. The temperature evoking an eVAS of at least 50 mm was set as test temperature and used during the remainder of the study for the experimental stimulus. Before testing, the thermode was calibrated using a surface thermometer (K-Thermocouple thermometer, Hanna Instruments, Woonsocket, RI, USA).

The conditioning stimulus was cold water immersion in a cold-water bath which was filled and temperature adjusted using a rapid-water cooling system (IcyDip, IcySolutions BV, Delft, The Netherlands).[20] The subject's foot and lower leg were immersed into the cold water reservoir, which could be set at temperatures ranging from 6°C to 18°C. The temperature that produced an eVAS of at least 30 mm was used in the study for the conditioning stimulus. After exposure to cold water, the subject's extremity was immediately warmed to normal temperature using the warm water reservoir of the IcyDip system.

To measure CPM, eVAS responses to the test stimulus were obtained without ($n = 3$) and with the conditioning stimulus ($n = 3$). The conditioning stimulus was applied 25 s before the start of the test stimulus and ended simultaneously with the end of the test stimulus. The subject was instructed to only rate the pain intensity level of the test stimulus with the eVAS slider.

### Study design

Each subject visited the laboratory on 3 days, at least 2 weeks apart, in which placebo, morphine, and ketamine were tested using a double-blind, randomized cross-over study design. Initially, CPM was measured without treatment (baseline values). After a break, i.v. treatment was given (infusion duration 1 h), and 20 min later, the CPM responses were repeated. Treatments were as follows: (A) a 1 h i.v. infusion of 0.57 mg kg$^{-1}$ $S(+)$-ketamine (Ketanest-S, Pfizer BV, Capelle a/d IJssel, The Netherlands); (B) morphine bolus of 0.05 mg kg$^{-1}$ followed by 0.015 mg kg$^{-1}$ h$^{-1}$ for 1 h (Morphine HCl, Pharmachemie

BV, Haarlem, The Netherlands); and (C) a 1 h placebo (0.9% NaCl) infusion.

### Disease-related pain

The effect of treatment on disease-related or spontaneous pain scores was measured after treatment on a 0–10 numerical rating scale (NRS). Subjects were contacted after their treatment to determine the duration of pain relief. An arbitrary distinction was made between pain relief lasting 0–6 h post-treatment, 6–12 h post-treatment, and 12–24 h post-treatment.

### Data and statistical analyses

The difference between the eVAS response to the test stimulus without and with conditioning stimulus is the generated CPM. The eVAS data were averaged over 1 s periods. To quantify CPM, the area under the curve (AUC) of each eVAS response was calculated. For analysis of the relative amount of CPM, the mean of the three AUC responses per condition was calculated (i.e. the mean of the three AUCs without conditioning stimulus and the three AUCs with the conditioning stimulus). The percentage of CPM (CPM%) was calculated as: CPM% = [(mean AUC without CS stimulus−mean AUC with CS)/(mean AUC of without CS)]×100, which corrected for the variation in the magnitude of the peak response between sessions and between subjects.

The drug study was powered to detect a significant difference between treatment effects on CPM%. Assuming a difference between groups of 20% (derived from previous data)[20] with $sd$ 10%, $\alpha = 0.05$, and power = 0.9, we estimated a group size of 10 (SigmaPlot v12, Systat Software Inc., Chicago, IL, USA).

A linear mixed effect model was used to compare the AUCs of the eVAS responses with and without conditioning stimulus within each experimental session. The effect of treatment on CPM% and spontaneous pain scores was tested by one-way analysis of variance with the post hoc Bonferroni correction. Statistical analysis was performed in SigmaPlot version 12.0 for Windows (Systat Software Inc.). $P$-values of <0.05 were considered significant. Data are presented as mean ($sem$) unless otherwise stated.

## Results

### Subjects

All 10 subjects completed the protocol without major side-effects. The study population included two men, eight women, and had a mean age of 54.4 (4.2) yr and a mean weight of 83.6 (7.6) kg. All suffered from chronic neuropathy with signs of mixed small and large fibre neuropathy on the QST (significant abnormalities in cold detection threshold, warm detection threshold, paradoxal heat sensation, and vibration detection threshold, Fig. 1). Subjects were diagnosed with diabetes mellitus ($n = 4$), sarcoidosis ($n = 2$), and Sjögren's syndrome ($n = 1$). In three subjects, the origin of the pain was unknown. Feet were affected in all subjects; in four subjects, the hands were affected as well. Subjects

used the following medication during the study: acetaminophen, non-steroidal anti-inflammatory drugs, gabapentin, pregabalin, and amitriptyline.

### CPM responses

Average test and conditioning stimulus temperatures were 45.1 (0.1)°C and 9.8 (1.0)°C, respectively. At baseline, the average eVAS scores were 43.0 (2.4) mm and after treatment were 49.0 (3.4), 50.1 (2.9), and 51.1 (2.9) mm for ketamine, morphine, and placebo, respectively. No significant CPM responses were detected before treatment: AUC without conditioning stimulus 1180 (71) mm s compared with AUC with conditioning stimulus 1080 (79) mm s ($P>0.05$). After all three treatments, significant CPM was detected indicating an inhibitory effect of the cold water-conditioning stimulus on the experimental heat pain stimulus. Placebo AUCs were reduced by the conditioning stimulus from 1240 (209) to 862 (135) mm s ($P=0.001$); morphine AUCs were reduced from 1500 (224) to 1050 (185) mm s ($P<0.001$); ketamine reduced the AUCs from 1350 (118) to 809 (159) mm s ($P<0.0001$) (Fig. 2A). Ketamine caused the largest increase in CPM: mean CPM% after placebo 22.1 (12.0)% [95% confidence interval (95% CI): −5.1 to 49.3], after morphine 28.5 (7.0)% (95% CI: 12.8–44.3), and after ketamine 40.2 (10.9)% (95% CI: 15.6–64.6); however, no difference in CPM enhancement could be detected between the three treatment groups ($P>0.05$, see also Fig. 2B).

### Pain relief and magnitude of CPM

The mean NRS at baseline was 6.2 (0.5). In terms of magnitude, pain relief was greatest after ketamine [mean NRS after treatment: 0.3 (0.3), $P<0.01$ vs baseline], followed by morphine [1.8 (0.7)] and placebo [3.2 (0.7)]. In terms of duration of effect, ketamine had effects lasting >12 h in eight of 10 subjects and >6 h in the remaining two subjects. Morphine had effects lasting >12 h in zero of 10 subjects, >6 h in eight of 10 subjects, and <6 h in the remaining two subjects. After placebo, all analgesic effects had dissipated within 6 h of treatment. The magnitude of CPM correlated positively with that of pain relief (Fig. 3) and duration of spontaneous pain relief.

### Side-effects after analgesic treatment

Minor side-effects occurred with nausea in four subjects (two of whom vomited) during ketamine infusion and in seven subjects (four of whom vomited) during morphine infusion. No nausea or vomiting was observed during placebo infusion. At the end of the infusion, the mean drug high scores were 7.2 (0.6) for ketamine, 2.4 (0.5) for morphine, and 0.4 (0.2) for placebo.

## Discussion

We tested CPM responses in a relatively homogenous population (in terms of QST abnormalities) of subjects with chronic pain related to peripheral neuropathy. The main findings of our explorative studies are that CPM responses were
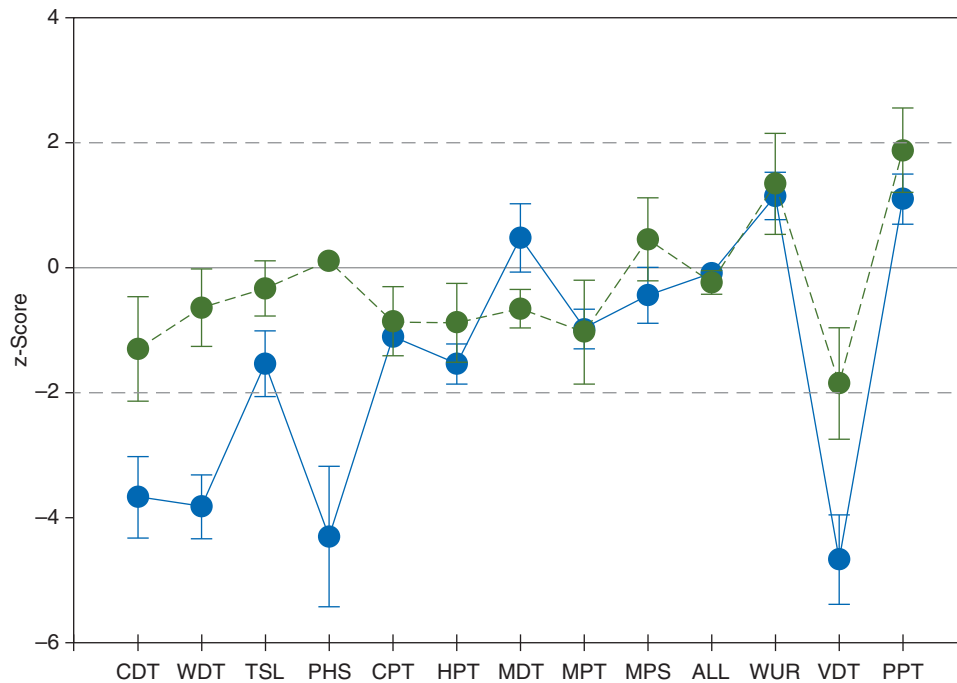
**Fig 1** Quantitative sensory testing. The test site was the site most affected by pain (either hand or foot; blue symbols), the control site was the face (green symbols). Data are the population mean *z*-scores (SEM). *z*-scores were calculated in relation to a population of healthy subjects as determined by Rolke and colleagues.[39] The horizontal broken lines indicate the +2 and −2 *z*-score boundaries. A specific QST test is considered abnormal if the test-value lies above the upper or below the lower boundary. CDT, cold detection threshold; WDT, warm detection threshold; TSL, thermal sensory limen; PHS, paradoxal heat sensation; CPT, cold pain threshold; HPT, heat pain threshold; MDT, mechanical detection threshold; MPT, mechanical pain threshold; MPS, mechanical pain sensitivity; ALL, dynamic mechanical allodynia; WUR, windup ratio; VDT, vibration detection threshold; PPT, pressure pain threshold.
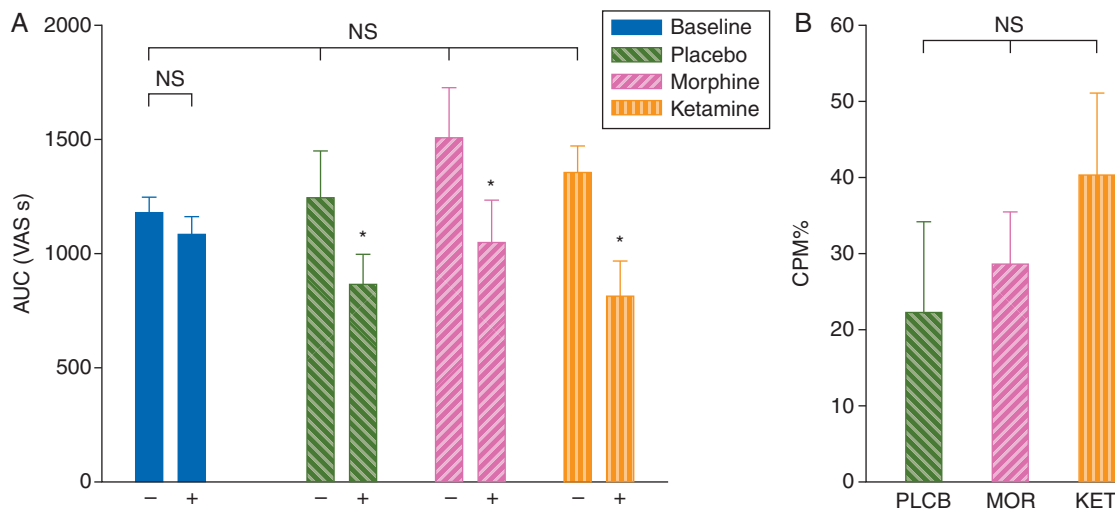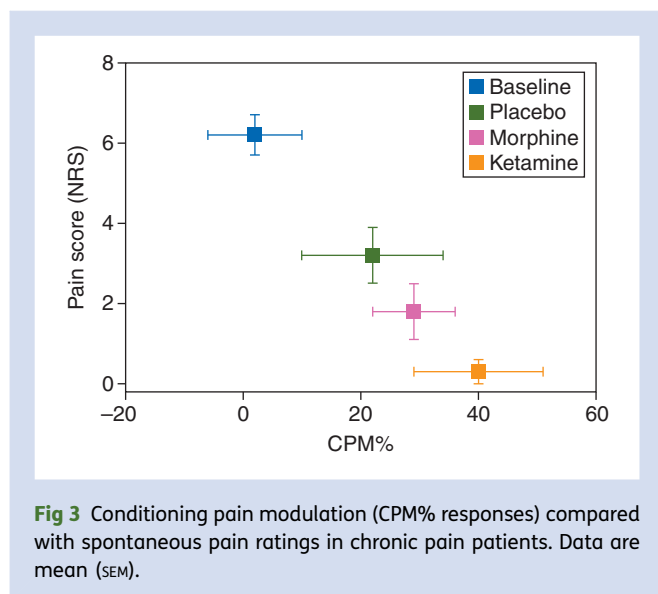


**Fig 2** (A) AUC values of the eVAS-time responses without conditioning stimulus (−) and with conditioning stimulus (+). The conditioning stimulus had no effect on baseline responses, but decreased eVAS responses after treatment with placebo, morphine, and ketamine. *$P<0.001$ *vs* AUC of eVAS-time responses without conditioning stimulus. AUCs of responses without conditioning stimuli were similar for baseline, placebo, morphine, and ketamine. NS, not significant. (B) Magnitude of conditioning pain modulation (CPM%) responses after treatment with placebo (PLCB), morphine (MOR), and ketamine (KET). The magnitude of CPM% responses did not differ among treatments.

**Fig 3** Conditioning pain modulation (CPM% responses) compared with spontaneous pain ratings in chronic pain patients. Data are mean (SEM).

not detectable in this population, but that treatment with ketamine, morphine, and placebo caused activation of CPM responses ($P<0.001$). The magnitude of CPM responses correlated positively with the magnitude and duration of spontaneous pain relief.

Descending inhibitory and facilitatory pathways involved in the modulation of pain originate at higher sites in the central nervous system, including the prefrontal cortex, rostral anterior cingulate cortex (rACC) and insula, which project to the periaquaductal gray and rostral ventromedial medulla (RVM) and modulate nociceptive input at the level of the dorsal horn.[1-4 6] Activation of inhibitory pathways reduces trafficking of nociceptive input to supraspinal sites involved in pain processing and perception. Activation of facilitatory pathways has the reverse effect. A shift in the balance between inhibition and facilitation has been suggested as an underlying mechanism in the development or maintenance of pain.[20] There are various expressions of descending inhibitory pain modulation, including placebo and stress-induced analgesia and CPM.[3 21 22] CPM is considered to be a central mechanism with activation of specific brain regions involved in descending inhibition.[23 24]

Dysfunctional endogenous pain modulation (as tested by CPM or CPM-like paradigms) has been observed in several chronic pain states.[8 11-13 25] In our current study, we included patients with chronic (poly)neuropathic pain (from mixed small and large fibre neuropathy) who all displayed abnormal CPM responses. Previous studies in healthy volunteers showed that females have less efficient CPM responses compared with males and that CPM efficiency decreases with increasing age (starting at middle-age).[26-29] Indeed, in a separate set of healthy people of similar age and sex as our current study population, we did not observe significant CPM responses (M. Niesters, unpublished observation). Since the patient population in this study was predominantly middle-aged and female, CPM responses were *a priori* not expected or were at least assumed to be small. Our data

and those of others indicate that patients of 40 yr and older (especially females) have absent or less activated pain modulation mechanisms (compared with younger patients) and are therefore at a disadvantage in situations where a functional descending inhibitory mechanism is necessary for modulation of pain responses. Consequently, in response to a noxious insult, pain can be more severe and persistence of pain might occur, which possibly is one of the factors involved in the development of chronic pain. There is indeed evidence from animal studies for a link between chronic pain development and efficacy of descending inhibitory pain pathways. Animals with more efficient engagement of descending inhibition show a reduced probability of peripheral nerve injury-induced chronic allodynia compared with animals with less efficient descending inhibition.[14 15]

A novel observation in our study is that CPM responses in neuropathic pain patients could be (re)activated after pharmacological treatment, and that ketamine, morphine, and placebo were equally effective in this respect. The large effect of a 1 h i.v. treatment with placebo was not unexpected. There is ample evidence that activation of descending pain control underlies placebo-analgesia via central opioidergic mechanisms.[22 30] For example, Levine and colleagues[30] showed that placebo analgesia is abolished by the opioid receptor antagonist naloxone. Furthermore, animal research demonstrated that remifentanil and placebo analgesia both activate brain areas involved in descending inhibition including the rACC.[31]

An important finding in our study is that there was a significant correlation between the magnitude of CPM responses and the magnitude (and duration) of spontaneous pain relief (Fig. 3). As stated by De Felice and colleagues,[14] such findings provide a mechanistic explanation for medications that engage descending inhibitory control or mimic its consequences and cause efficient and long-term pain relief, such as we observed after treatment with ketamine. To the best of our knowledge, our study is the first to show that morphine enhances CPM responses in chronic neuropathic pain patients. Recently, Arendt-Nielsen and colleagues[32] tested the effect of two opioid analgesics (fentanyl and buprenorphine transdermal patches) on CPM in healthy volunteers and showed enhanced responses after treatment. In contrast to these and to our data, others observed that morphine reduces rather than increases CPM responses in healthy volunteers (after an i.v. infusion of 0.05 mg kg$^{-1}$) and in non-neuropathic chronic pain patients (after prolonged opioid treatment).[33 34] We have no conclusive explanation for these differences in the effect of opioid treatment on CPM engagement (see below). Involvement of endogenous opioids in CPM engagement is inferred from studies showing that naloxone reduces CPM.[35] Furthermore, opioid receptors are expressed on neurones involved in pathways of descending pain modulation both at spinal and at supraspinal sites.[1-3]

Similar to morphine, ketamine enhanced CPM responses in our patient population. Ketamine has gained a position

in the treatment of chronic pain, especially of therapy-resistant neuropathic pain.[36] Ketamine treatment results in prolonged analgesia, with persistence of effect beyond the treatment period. For example, we showed previously that a 100 h ketamine infusion (20–30 mg h$^{-1}$) results in pain relief for up to 3 months after i.v. treatment in patients with complex regional pain syndrome type 1.[37] The mechanisms through which ketamine exerts these prolonged effects remain unknown. Possibly one of the factors that contribute to ketamine's prolonged analgesic effect is desensitization of up-regulated *N*-methyl-D-aspartate receptors within the spinal cord.[37] Another mechanism might be that ketamine activates endogenous pain modulatory pathways. The observation that ketamine produced greater analgesia than morphine (or placebo) in our patient population correlated with a greater ability to engage descending inhibition as tested by CPM (Fig. 3). Recently, we assessed the effect of ketamine on brain function using the technique of resting-state functional magnetic resonance imaging (RS-fMRI). Ketamine altered connectivity in brain regions responsible for pain sensing and the affective processing of pain, and also in regions involved in activation of descending inhibitory pain pathways, including the rACC, insula, orbitofrontal cortex, and brain stem.[38] These findings corroborate our observation of ketamine's effect on CPM in neuropathic pain patients.

The effects of ketamine on CPM responses in chronic pain patients differ from results in volunteers.[20] In a population of healthy young volunteers, ketamine shifted the balance between pain inhibition and pain facilitation towards pain facilitation. Major differences between study populations (age and underlying disease) could be responsible for the difference in study outcomes. For example, in healthy volunteers, CPM responses might be at maximum strength such that treatment leads to activation of interfering pathways (facilitatory pathways). This might also explain the effect of morphine on CPM in healthy volunteers and possibly also in chronic non-neuropathic pain patients.[33] [34] We also cannot exclude that treatment at maximum CPM activates noise sources resulting in inconsistencies in the data.

## Critique of methods

One might contend that no population of healthy age- and sex-matched controls was included to make a comparison of treatment effects between groups possible. However, as discussed above, healthy volunteers lack underlying disease, that is a primary hit (peripheral nerve damage) and possibly also secondary damage (a defect in the descending inhibitory control system) of their pain pathways. Although we believe that knowledge on the effect of treatment on CPM responses in volunteers is valuable on its own, we argue that a direct comparison between populations is of limited value, as treatment-induced changes in CPM responses in volunteers might differ mechanistically from those in pain patients.

Subjects were allowed to continue their pain medication as long as they had used these drugs for at least 3 months and dosages were constant during the study period. Subjects that used pain medication did not have a larger (or smaller) enhancement of CPM responses compared with those that did not. Therefore, we do not believe that continuation of analgesics during the study period affected our outcome.

Finally, we tested a small group of predominantly middle-aged female pain patients. While this reflects the majority of chronic pain patients in clinical practice, our study needs replication in younger patients (including males) with neuropathic pain. This will further clarify the link between sex, age, defective CPM responses, and chronic pain.

## Conclusions

In chronic neuropathic pain patients with similar QST abnormalities, treatment with placebo, morphine, and ketamine activated previously absent CPM responses, suggesting a role of engagement of descending pain inhibition in their analgesic efficacy. We suggest that in clinical practice, drugs that cause enlargement or re-engagement of CPM should be the first drugs of choice in the treatment of chronic (neuropathic) pain.

## Declaration of interest

None declared.

## Funding

## References

1  Milan MJ. Descending control of pain. *Prog Neurobiol* 2002; **66**: 355–474
2  Vangas H, Schnaible HG. Descending control of persistent pain: inhibitory or facilitatory? *Brain Res Rev* 2004; **46**: 295–309
3  Ossipov MH, Dussor GO, Porreca F. Central modulation of pain. *J Clin Invest* 2010; **120**: 3779–87
4  Dahan A, Niesters M, Sarton E. Endogenous modulation of pain is visible in the brain. *Clin Neurophysiol* 2012; **123**: 642–3
5  Beecher HK. Pain in men wounded in battle. *Ann Surg* 1946; **123**: 96–105
6  Bingel U, Tracey I. Imaging CNS modulation of pain in humans. *Physiology* 2008; **23**: 371–80
7  Pud D, Granovsky Y, Yarnitsky D. The methodology of experimentally induced noxious diffuse inhibitory (DNIC)-like effect in humans. *Pain* 2009; **144**: 16–9
8  King CD, Wong F, Currie T, *et al.* Deficiency in endogenous modulation of prolonged heat pain in patients with irritable bowel syndrome and temporomandibular disorder. *Pain* 2009; **143**: 172–8
9  LeBars D, Dickinson AH, Besson JM. Diffuse noxious inhibitory controls (DNIC). I. Effects on dorsal horn convergent neurons in the rat. *Pain* 1979; **6**: 283–304
10  Yarnitsky D, Arendt-Nielsen L, Bouhassira D, *et al.* Recommendations on terminology and practice of psychophysical DNIC testing. *Eur J Pain* 2010; **14**: 339

11 Lautenbacher S, Rollman GB. Possible deficiencies of pain modulation in fibromyalgia. *Clin J Pain* 1997; **13**: 189–96

12 Seifert F, Kiefer G, DeCol R, *et al.* Differential endogenous pain modulation in complex-regional pain syndrome. *Brain* 2009; **132**: 788–800

13 Olessen SS, Brock C, Karup AL, *et al.* Descending inhibitory pain modulation is impaired in patients with chronic pancreatitis. *Clin Gastroenterol Hepatol* 2010; **8**: 725–30

14 De Felice M, Sanoja R, Wang R, *et al.* Engagement of descending inhibition from the rostral ventromedial medulla protects against chronic neuropathic pain. *Pain* 2011; **152**: 2701–9

15 Wijnvoord N, Albuquerque B, Häussler A, *et al.* Inter-strain differences of serotonergic inhibitory pain control in inbred mice. *Mol Pain* 2010; **6**: 70

16 Yarnitsky D, Granot M, Nahman-Averbuch H, *et al.* Conditioned pain modulation predicts duloxetine efficacy in painful diabetic neuropathy. *Pain* 2012; **153**: 1193–8

17 Maier C, Baron R, Tölle TR, *et al.* Quantitative sensory testing in the German Research Network on Neuropathic Pain (DFNS): somatosensory abnormalities in 1236 patients with different neuropathic pain syndromes. *Pain* 2010; **150**: 439–50

18 Hoitsma E, Drent M, Verstraete E, *et al.* Abnormal warm and cold sensations thresholds suggestive of small-fibre neuropathy in sarcoidosis. *Clin Neurophysiol* 2003; **114**: 2326–33

19 Baron R, Binder A, Wasner G. Neuropathic pain: diagnosis, pathophysiological mechanisms, and treatment. *Lancet Neurol* 2010; **9**: 807–19

20 Niesters M, Dahan A, Swartjes M, *et al.* Effect of ketamine on endogenous pain modulation in healthy volunteers. *Pain* 2011; **152**: 656–63

21 Eippert F, Bingel U, Schoell ED, *et al.* Activation of the opioidergic descending pain control system underlies placebo analgesia. *Neuron* 2009; **63**: 533–43

22 Eippert F, Finsterbusch J, Bingel U, Büchel C. Direct evidence for spinal cord involvement in placebo analgesia. *Science* 2009; **326**: 404

23 De Broucker T, Cesaro P, Iller JC, *et al.* Diffuse noxious inhibitory controls in man: involvement of the spinoreticular tract. *Brain* 1990; **113**: 1223–34

24 Moont R, Crispel Y, Lev R, *et al.* Temporal changes in cortical activation during conditioned pain modulation (CPM), a LORETA study. *Pain* 2011; **152**: 1469–77

25 Arendt-Nielsen L, Nie H, Laursen MB, *et al.* Sensitization in patients with painful knee osteoarthritis. *Pain* 2010; **149**: 573–81

26 Edwards RR, Fillingim RB, Ness TJ. Age-related differences in endogenous pain modulation: a comparison of diffuse noxious inhibitory controls in healthy older and younger adults. *Pain* 2003; **101**: 155–65

27 Larivière M, Goffaux P, Marchand S, Julien N. Changes in pain perception and descending inhibitory controls starts at middle age in healthy adults. *Clin J Pain* 2007; **23**: 506–10

28 Lautenbacher S, Kunz M, Burkhardt S. The effects of DNIC-type inhibition on temporal summation compared to single pulse processing: does sex matter? *Pain* 2008; **140**: 429–35

29 Popescu A, LeResche L, Truelove EL, Drangsholt MT. Gender differences in pain modulation by diffuse noxious inhibitory controls: a systemic review. *Pain* 2010; **150**: 309–18

30 Levine JD, Gordon NC, Fields HL. The mechanism of placebo analgesia. *Lancet* 1978; **23**: 654–7

31 Petrovic P, Ingvar M. Imaging cognitive modulation of pain processing. *Pain* 2002; **95**: 1–5

32 Arendt-Nielsen L, Andresen TR, Malver L, *et al.* A double-blind, placebo controlled study on the effect of buprenorphine and fentanyl on descending pain modulation: a human experimental study. *Clin J Pain* 2012; **28**: 623–7

33 Le Bars D, Willer JC, De Broucker T. Morphine blocks descending pain inhibitory controls in humans. *Pain* 1992; **48**: 13–20

34 Ram KC, Eisenberg E, Haddad M, Pud D. Oral opioid use alters DNIC but not cold pain perception in patients with chronic pain—new perspective of opioid-induced hyperalgesia. *Pain* 2009; **139**: 431–8

35 Willer JC, Le Bars D, De Broucker T. Diffuse noxious inhibitory controls in man: involvement of an opioidergic link. *Eur J Pharmacol* 1990; **182**: 347–55

36 Noppers I, Niesters M, Aarts L, *et al.* Ketamine for treatment of chronic non-cancer pain. *Exp Opin Pharmacother* 2010; **11**: 2417–29

37 Sigtermans M, van Hilten JJ, Bauer MCR, *et al.* Ketamine produces effective and long-term pain relief in patients with complex regional pain syndrome type 1. *Pain* 2009; **145**: 304–11

38 Niesters M, Khalili-Mahani N, Martini C, *et al.* Effect of subanesthetic ketamine on intrinsic functional brain connectivity: a placebo-controlled functional magnetic resonance imaging study in healthy volunteers. *Anesthesiology* 2012; **117**: 868–77

39 Rolke R, Baron R, Maier C, *et al.* Quantitative sensory testing in the German Research Network on Neuropathic Pain (DFNS): standardized protocol and reference values. *Pain* 2006; **123**: 231–43

*Handling editor: H. C. Hemmings*