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EFFECTS OF LOCAL COOLING ON MONOSYNAPTIC REFLEXES IN MAN

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ABSTRACT. Muscle action potentials and isometric contractions induced by tendon taps and electrical stimulation of low-threshold sensory or motor nerves were studied in triceps surae muscles after local application of cold compresses (−12 C) for 20 min. The mean amplitude of the tendon jerks invariably declined, in a few subjects after a short transient increase, the mean decrease at the end of the cooling period being 34% (±20%, S.D., n = 12). The reflex responses to electrical stimulation of sensory nerves usually increased during the first few minutes but were then insignificantly changed (−3% ±15%, mean & S.D., n = 12) as compared to precooling values. Amplitudes of responses to motor nerve stimulation invariably declined although less than the amplitudes of tendon jerks. The results indicate that the effects of the cooling on the stretch reflex are complex, implying both peripheral and central excitability changes.

INTRODUCTION

In a number of different conditions of muscular dystonia, cold has been found to be effective as an adjunct in physical therapy. Thus, brief sprayings of ethyl chloride over hypersensitive regions, so-called trigger areas (24) as well as local cold applications over tense muscles in cases of whiplash injuries (10) have been shown to reduce painful muscle spasm. In cases of spastic pareses, immersion of a spastic limb or a larger portion of the body may also be beneficial (13), not only when the cooling is sufficient to lower the core temperature (1, 2, 26) but also when the period of cooling is too brief to result in any appreciable change in the central body temperature (25). The same favorable effect can also be achieved by local application of cold compresses over spastic muscles (9). This relaxation of spasticity can be assumed to be the result of a depression of the stretch reflexes observed during local cold application both in patients with spastic pareses (5, 18, 19) and in normal subjects (21). Since this effect sets in even before the temperature fall has spread to deeper tissues it has been attributed to changes in the sensory inflow from skin receptors. If the cooling is maintained long enough to lower the intramuscular temperature, the depression is enhanced, presumably by effects on muscle fibers, proprioceptors and nerve fibers involved in the stretch reflex since, as is well known from animal experiments, temperature changes affect muscle spindles (4), nerve fibers and muscle cells. To what extent these effects are operative under the circumstances prevailing when local cooling is applied as a therapeutic procedure is however not known, and it is thus difficult to assess the mode of action and explain the disparate individual effects observed in different patients with spastic disorders (11).

The present investigation was undertaken in an attempt to evaluate effects of local cooling on different parts of the monosynaptic reflex arc in the triceps surae muscles by studying the effects on 1) the stretch reflex as induced by a tendon tap, 2) the stretch reflex as elicited by electric stimulation of sensory fibers originating in the muscle spindles (the H reflex), and 3) the efferent limb of the reflex arc following electric stimulation of the motor fibers (the M response). Since it is difficult to evaluate actual anatomical and physiological changes present in clinical material, the current investigation is based on observations of normal volunteers. As will appear from the results to be reported, the initial effect of local cooling, observed as long as only the skin temperature is lowered, may be a change in alpha motoneuron excitability, but when the temperature fall has spread to underlying tissues the effect is more complex, also the muscle spindle excit-

ability and the efferent limb of the monosynaptic arc being affected. Our assumption is that this complex mode of action may to a large extent explain the disparate effects observed in different spastic conditions, since the predominant factor in a persistent hyperactivity of the stretch reflex may be excitability changes either in the fusimotor system or in the alpha motoneuron pool (23) which should have different susceptibility to changes in the sensory inflow.

METHODS

Two different experimental procedures were used to evaluate effects of local cooling upon the motor functions. With the aid of one of these methods, changes in mechanically and electrically induced monosynaptic reflexes in the triceps surae muscles were measured in a group of fifteen normal volunteers. In the other series of examinations, comprising four normal subjects, measurements were made of changes in the responses of the same muscles to direct stimulation of motor fibers supplying these muscles.

A local temperature fall was achieved by means of packs cooled down to $-12°C$ in a chilling chamber (Hydrocollator Colpac) and placed on the skin over the muscle to be tested. The packs were left in place for about 20 min, care being taken to avoid their coming into contact with recording electrodes or with the skin between and close to these electrodes. The temperature was measured subcutaneously and intramuscularly, usually at a depth of 2 cm, by thermistors placed in thin flexible catheters which were inserted by means of cannulae. The subcutaneous temperature generally dropped to 20–25°C within a few minutes and then remained fairly constant until the cooling packs were removed. The temperature within the muscle fell slowly and nearly linearly, usually by about 5°C in 20 min. The temperature drop was larger near the surface than deeper in the muscle (3) and less pronounced beneath the sides than beneath the middle of the packs. Since temperatures at a depth of 2 cm do not provide a measure of the temperature in the entire muscle, these measurements were undertaken only as a check that a normal temperature fall was taking place, and no attempts were made to compare results obtained at different temperatures.

The subjects were examined either in the prone or in the supine posture. In the former case, the feet were hanging over the edge of the couch, the legs suspended in a fixed, slightly bent position and the footsole kept at an angle of 90° to the legs by a strap supporting the sole and connected to a strain gauge transducer. In the latter case, the legs from the knee down were hanging over the edge of the couch and the foot on the side under study rested on a tension-recording plate.

Ankle jerks were elicited by a hammer operated by an electromagnet and controlled from a Grass stimulator through a relay. This hammer allowed repetition of standardized tendon taps, the foot being kept in position by one of the tension-recording devices, by means of which involuntary tension changes in the Achilles tendon were also recorded for control purposes.

H reflexes were elicited by stimulation of the posterior tibial nerve in the popliteal fossa through surface electrodes. To secure and maintain optimal placement of the cathode over the nerve the electrodes were applied under gentle steady pressure. The effectiveness of the fixation was always controlled by checking that the M response evoked by a stimulus submaximal for the motor fibers remained constant throughout repeated precooling stimulations. Unfortunately, this test could not be used after cooling since the cold proved to cause changes in the M response.

Recordings of the muscle action potentials were made with electrodes of pressed Ag-AgCl powder placed in the bottom of plastic cups filled with electrode paste and fastened to the skin by adhesive tapes 3 cm apart. In this manner it was possible to avoid changes in electrode contacts. After amplification the potentials were displayed on an oscilloscope screen and photographed.

Muscle contractions were recorded by a rigidly mounted strain gauge transducer displaying the pressure exerted by the footsole. The strain gauge constituted one arm of a bridge at the input of a chopper amplifier. As a rule, only the amplitudes of the contractions were recorded on an ink-writer with linear frequency response at frequencies below 100 Hz, but in some experiments also the time course of the contractions was analyzed, the data being stored on a dc tape recorder.

RESULTS

To be able to evaluate concomitant changes in the mechanically and electrically induced monosynaptic reflexes during local muscle cooling, the two types of stimulation employed were delivered alternately, the intervals (2 and 4 sec) being chosen so as to limit the depression of a tendon jerk preceded by an H reflex and of an H reflex preceded by a tendon jerk (16, 20). At these intervals a slight high-frequency depression can be anticipated (8) but since the amplitude of the H wave may be depressed for 20 sec after a monosynaptic reflex (17) such depressions can hardly be definitely excluded unless up to 40 sec are allowed to elapse between each repetition of the electrically and mechanically induced reflexes, and at such long intervals continual changes were found to be difficult to assess.

Tendon jerks and H reflexes of roughly equal amplitudes, indicating that the two types of stimulation activated about the same number of motor units, could be elicited in twelve of the fifteen subjects examined in this series of experiments. Determinations of the reflex variations during repeated stimulations over 10–30 min before cool-

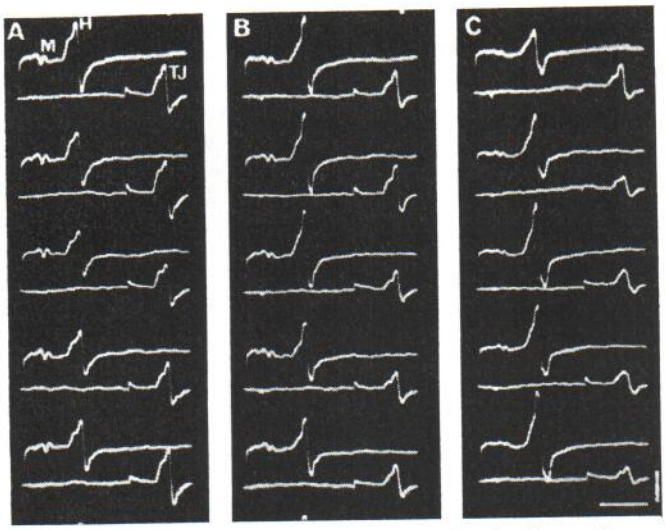

Fig. 1. Effects of local cooling on electrically and mechanically induced monosynaptic reflex responses in normal triceps surae muscle. Responses to electric stimulation (M and H) alternate with responses to tendon taps (TJ) and distances between successive traces from the top downwards correspond to the intervals between stimulations. (*A*) Control recordings before cooling; (*B*) 10 min and (*C*) 20 min after cold application. Horizontal bar in (*C*) 30 msec; vertical bar, 1 mV, also corresponds to 0.8 sec when representing time interval between traces.

ing showed that, in spite of the continual fluctuations in motoneuron excitability and the consequent amplitude variations of the individual responses, the mean amplitude of tendon jerks as well as of H reflexes, as calculated on the ten responses of each type elicited during one minute, remained fairly constant throughout the precooling period.

The three remaining subjects were excluded. In one of them H waves were set up only on weak voluntary contraction of the triceps surae muscles or on Jendrassik's maneuver. In the case of another subject, exceptionally wide variations in H reflexes and tendon jerks, apparently due to insufficient relaxation, did not permit evaluation of the experimental effects. In the third subject, tendon jerks could not invariably be elicited with the hammer used.

Figs. 1, 2 and 3 show some typical recordings of changes in the monosynaptic reflexes elicited in the triceps surae muscles after cold application.

Fig. 1 illustrates the effects as they are reflected by the electromyographically recorded reflex responses. Alternating electric and mechanical stimuli were applied and the upper traces in the records represent responses to electric stimulation of the posterior tibial nerve. The sweep is triggered by the electric stimulus and the first low-amplitude response (the M wave) is the result of stimulation of motor fibers. The second response is the H reflex elicited by activation of low-threshold sensory fibers. The lower traces show the muscle action potential (TJ) set up in response to mechanical stimulation. This potential does not appear until at the right-hand side of the trace since the oscilloscope beam is triggered when the hammer starts to move towards the Achilles tendon.

The records in *A* derive from a precooling period, those in *B* were obtained about 10 min after application of cold and those in *C* after 20 min of cooling, and as appears from the figure the average amplitude of the tendon jerk was markedly reduced after the cold application, whereas there were only insignificant changes in the average amplitude of the H reflexes.

While the electromyographically recorded responses represent activity mainly picked up from superficial muscle fibers, the total activity in the triceps surae muscles should be more truly reflected by the mechanically recorded responses. Fig. 2 shows contraction amplitudes as recorded in series of repeated reflex responses before (*A*) and after application of cold over the calf for 10–12 min (*B*) and 20–22 min (*C*) respectively;

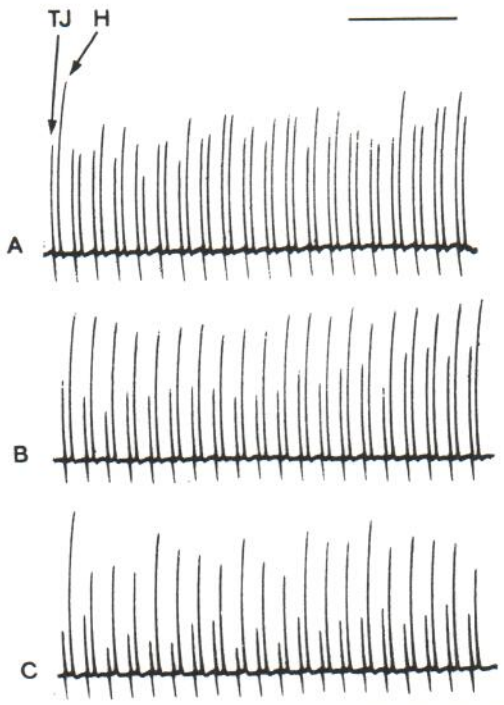

Fig. 2. Effects of local cooling on relative amplitudes of electrically and mechanically induced reflex contractions. Tendon jerks (identified by downward deflection) alternating with H reflexes. (*A*) Control recordings before cooling; (*B*) 10–12 min and (*C*) 20–22 min after cold application. Horizontal bar 30 sec.

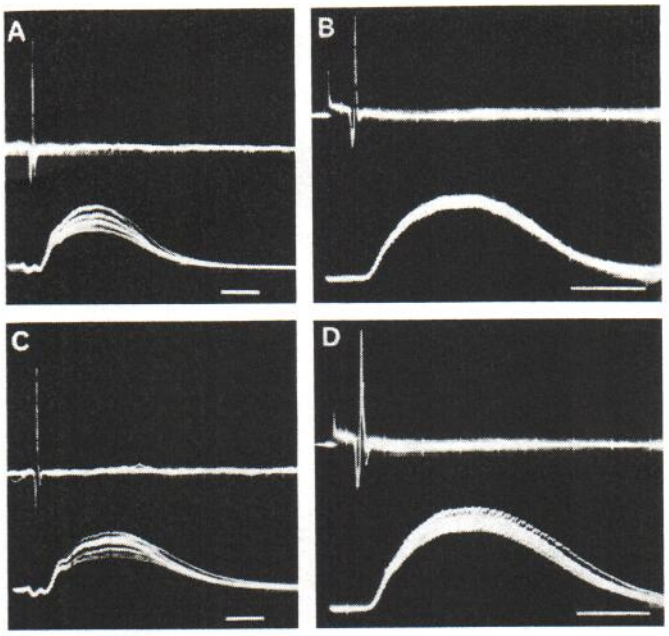

Fig. 3. Effects of local cooling on electrically and mechanically elicited reflex responses. *Lower beams*, ten superimposed contraction curves and *upper beams*, recordings of the corresponding electromyographic activity. Tendon jerks before (*A*) and after 15 min of cold application (*C*); H reflexes before (*B*) and after 16 min of cooling (*D*). Time bars 100 msec.

it is evident that the tendon jerks are markedly reduced after the cooling, whereas the amplitudes of the alternately elicited H reflexes are of fairly equal amplitude.

Fig. 3, from another experiment, illustrates typical changes in contraction curves obtained in one subject after muscle cooling. (*A*) and (*C*) are superimposed records of tendon jerks before and after 15 min of cooling respectively. The initial small deflections in the contraction recordings (lower beams), appearing before onset of the electric activity (upper beams), are caused by passive tension fluctuations following the tap of the hammer against the Achilles tendon, as is also the small deflection seen in the rising phase of the contraction curve. The contraction amplitude varies both before and after the muscle has been cooled, as would be expected in view of the variations in motoneuron excitability, but after the cooling there is a marked reduction in mean amplitude and a concomitant increase in duration, as a consequence of the protracted time course both of the rising and falling phases of the contractions; this is in accord with previous observations of changes in amplitude and in the speed of foot movements in response to tendon taps after cooling (21).

As appears from the superimposed traces of contraction responses obtained in the same subject in response to electric stimulation (Fig. 3 *B* and *D*) the M wave is not accompanied by a contraction large enough to be measurable by the technique used in these experiments. Not until the H wave appears is a contraction recorded, and this can thus be regarded as the secondary response, even though a minimal summation of the muscle twitches elicited by the primary and secondary responses cannot be ruled out since the primary response may cause a minute change in tension. When comparing the responses obtained before (*B*) and after 16 min of cooling (*D*) it is evident that the duration of the contraction increased during the cooling as did the contraction induced by mechanical stimulation, but the mean amplitude did not decrease; instead, it slightly rose as compared to precooling values.

As an illustration of the changes in reflex responses of the muscle during application of cold for 20 min, the mean amplitudes of the mechanically and electrically induced contraction responses obtained in one subject have been plotted in Fig. 4, in which *A* shows mean amplitudes of H reflexes (open circles) and of tendon jerks (filled circles) and *B* the temperatures as measured subcutaneously (open circles) and intramuscularly (filled circles). As appears from the figure, the mean amplitude of the tendon jerks in this case was gradually reduced during the cooling,

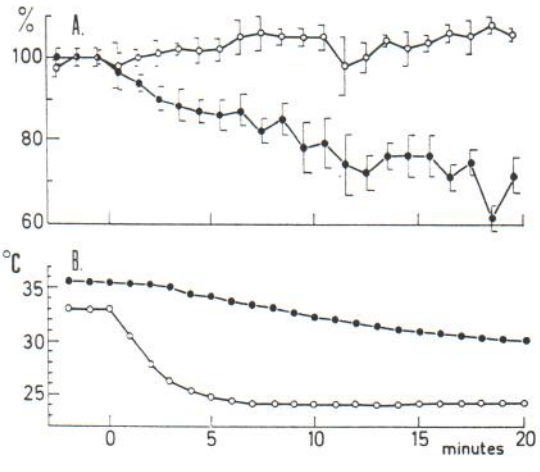

Fig. 4. Mean reflex and temperature changes in normal triceps surae muscle during local cooling applied at time marked zero. (*A*) Relative amplitude of H reflexes (○) and tendon jerks (●); each point represents mean of ten reflexes and vertical bars 2 standard deviations. (*B*) Temperatures as measured subcutaneously (○) and intramuscularly 2 cm beneath the skin surface (●).

whereas the mean amplitude of the H reflexes showed a slight though insignificant increase.

The mean amplitude of the tendon jerks invariably declined during cooling of the triceps surae muscles, and in the case of eight of the twelve subjects examined this decline set in gradually from the onset of cold application; in four cases, however, there was a transient, more or less pronounced increase in mean amplitudes during the first 2–4 min of cold application and then a gradual decline. The amplitude reduction after exposure to cold for 20 min varied considerably between the different subjects, the minimum decrement being 10% and the maximum 70%. The mean decrease observed in the twelve subjects after 20 min of muscle cooling was 34% (±20%, S.D.).

The mean amplitude variations of the H reflexes elicited in the different subjects were fairly wide and as a rule larger than those in the case illustrated in Fig. 4. In most cases the mean amplitude rose during the first 2–4 min of cooling; this increase seemed significant. Such an increment was observed in all cases in which there was an initial increase in amplitude of the tendon jerk but was also found in some cases in the absence of such an initial increase. After the first few minutes the changes in amplitude of the H reflex were fairly varying and of the same order as the precooling spontaneous fluctuations. The mean changes observed in the twelve subjects after 20 min of cooling was a reduction by 3% (±15%, S.D.).

To assess the effects of cooling on the efferent limb of the reflex arc, viz. on the motor nerves running in the cooled calf and on the muscle fibers, action potentials and contractions set up in the muscle in response to electric stimulation of the motor nerves were measured. The motor fibers cannot of course be stimulated selectively, secondary responses (F and H waves) being apt to be elicited, but in three of the four subjects examined in this series of experiments such responses could be virtually eliminated by selecting the point of stimulation in the popliteal fossa and adjusting the stimulus strength very carefully. In the fourth subject, an F wave was set up which however was very small as compared to the primary response. In these experiments reflex responses resulting from stimulation of sensory nerves and recurrent discharges in the motoneurons (22, 14) could thus be regarded as negligible, and for all practical purposes the contraction induced by stimulation of the intact nerve could be taken to be identical with that resulting on single-shock stimulation applied to the peripheral part of a cut muscle nerve.

In these experiments the cooling procedure was the same as applied in the reflex studies and the temperature fall was of the same order. Since the temperature at the site of stimulation is but little (less than one tenth of a degree) affected by the cooling, the number of motor fibers excited can be kept reasonably constant in the course of repeated stimulations provided that shifts in electrode positions and changes in resistance between electrode and skin area are avoided.

Gradual changes in amplitude and duration both of muscle action potentials and contraction curves were invariably observed. These changes were just perceptible 5 to 10 min after the cold application and then steadily increased. The muscle action potential diminished in amplitude but increased in duration and there was a concomitant change in the shape of the potential, the relation between its different phases being altered and notches being more pronounced. In one typical experiment, a reduction in amplitude from 10.1 to 8.2 mV and an increase in duration from 25 to 38 msec had resulted after 20 min of cooling. Similar gradual changes were seen in the contraction curve. In the experiment referred to, the amplitude measured as the power of the plantar flexion at a point 14 cm from the ankle joint axis, diminished from 9.5 to 8.3 kp, and there was a concomitant increase in duration of the contraction from 225 to 300 msec. The relative changes in amplitude and duration of the muscle action potentials and of the contraction curve were of about the same order of magnitude in one and the same subject in three experiments performed on different days, and of the same order also in the different subjects tested.

DISCUSSION

The increase in amplitude of the H wave during the first minutes of cold application observed in most of the subjects under study indicates an enhanced alpha motoneuron excitability, since the H wave is a monosynaptic reflex response elicited by stimulation of Group I a afferent fibers proxi-

mal to the muscle spindles (6, 15). This concept gains support from the fact that in this early phase of cooling no changes were observed in the responses to direct stimulation of the motor nerves. Hence, effects on the peripheral parts of the efferent nerves or on the muscle fibers can be ruled out. The increased excitability at the final common path is most likely due to a change in the sensory inflow from exteroceptors, since at this stage only superficial tissues have been cooled. It is not possible to judge whether spinal mechanisms or a supraspinal influence may be responsible for this increase but it seems likely that an enhanced central excitatory state may be set up in man by spinal mechanisms since cooling invariably produces a transient increase in muscle tone in patients with paraplegia or quadriplegia (5), in whom a supraspinal influence on the spinal neurons should be at least partially blocked.

Also after prolonged cold application the alpha motoneuron excitability may have been enhanced, even though there was no significant change in mean amplitude of the H reflex as compared to precooling values. In favor of this concept is the depression of the responses invariably observed on direct motor nerve stimulation. This depression can be attributed to peripheral effects on motor nerves (21) and on muscle and should result also when the sensory nerves are stimulated and the muscle activated through a monosynaptic reflex. The finding that the amplitude of the H reflex was not diminished after prolonged cold application is thus compatible with the notion of an enhanced alpha motoneuron excitability. After local temperature reduction no excitability changes of this type have previously been described; only after cooling to a degree sufficient to lower the core temperature and induce shivering have effects suggesting an excessive net excitatory drive to the final common path been observed (12).

As a consequence of a heightened excitability in the alpha motoneuron pool the reflex responses to muscle stretch can be expected to increase provided that no concomitant depression of the muscle spindle excitability occurs. Since as a rule no increase of the tendon tap reflex resulted coincidently with the increase in alpha motoneuron activity, the spindle excitability may have been lowered by the cooling. In the early phase of the cooling the temperature was reduced only in superficial tissues, and hence it seems unlikely that the temperature fall should have any direct effect on the spindles at this stage. A depression of the spindle excitability may however result as a consequence of a lowered gamma motoneuron activity. Whether or not this activity is actually reduced cannot with certainty be decided on the basis of comparisons of tendon tap responses and H reflexes, since it has been suggested that tonic small alpha motoneurons should be activated in the H reflex (7), whereas another population of motoneurons may be involved in the phasic stretch reflex elicited by a tendon tap.

After prolonged cooling, when the temperature has been lowered in deeper tissues as well, also the muscle spindle temperature should be reduced. The excitability of isolated cat muscle spindles (4) has been shown to be markedly reduced by temperature changes of the order of magnitude observed in the present study. If similar effects are obtained in man it seems most likely that the muscle spindles are directly affected by the temperature fall. Such a peripheral effect on the muscle spindle excitability may be responsible for the depression of the tendon jerk observed. This depression was invariably seen after prolonged cooling, in the absence of any signs of a reduced alpha motoneuron excitability, and the peripheral effects observed on motor nerve stimulation cannot fully explain the depression of the tendon jerk.

From the results obtained in the present investigation it is evident that the effects of local cold application upon the stretch reflex are complex and that the cooling is likely to affect both peripheral and central nervous mechanisms. The depression of the muscle spindle excitability and the peripheral effects on motor nerves and muscle should tend to reduce the stretch reflex, but on the other hand the effects on the alpha motoneuron excitability should tend to augment them. If similar effects are obtained when cold is applied over spastic muscles, the result of the cooling should be largely dependent on whether the excessive muscle tone is caused by enhanced alpha or gamma motoneuron activity. If the predominant factor in the spasticity present should be an enhanced alpha motoneuron excitability, cooling can hardly be expected to appreciably depress the muscle activity; on the contrary, it would hardly be surprising if it increased the muscle tone. If, on the other hand, the primary cause of the spasticity

should be a heightened fusimotor activity, a depression of the muscle spindle excitability should reduce the muscular hypertonus. The different effects of local cold applications observed among patients with spastic pareses (11) may thus to a large extent have been dependent on whether the exaggerated stretch reflexes were caused by alpha or gamma hyperexcitability.

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