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THE EFFECTS OF MUSCLE COOLING AND STRETCH ON THE AFFERENT ACTIVITY OF MUSCLE SPINDLE SECONDARY ENDINGS IN THE CAT

by

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Submitted in partial fulfillment

of the requirements for the degree of

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Faculty of Graduate Studies

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ABSTRACT

Cooling of the lateral surface of a relaxed hindlimb muscle in the cat caused an afferent discharge, the 'cold response', in previously silent, de-efferented sensory endings of muscle spindles. The origin of this response was studied in the medial gastrocnemius (MG) muscle in 45 cats under nembutal anaesthesia. The mean temperature (measured at the medial muscle surface) initiating sensory discharge in 30 'cold response' spindle endings was 31.7, S.E.M. ± 0.4°C and a mean maximum frequency of 11.8 ± 0.6 imp/sec was reached at 29.5 ± 0.5°C. With further cooling of the muscle the 'cold response' decreased. An analysis of afferent activity from 162 spindle endings showed that the 'cold response' originated in secondary endings, since it was found only in spindle afferents with conduction velocities of 20-70 m/sec, the range for group II secondary afferents. Only two-thirds of the secondary endings possessed the 'cold response' (CR endings). The remaining secondary endings (NCR endings), all primary endings and Golgi tendon organs were activated only by stretch of the muscle. During a maintained stretch the steady sensory discharge of these endings was decreased by muscle cooling. In CR endings a similar effect was seen if the response to maintained stretch was sufficient to mask the 'cold response'. At normal body and muscle temperature the dynamic and static responses (0.5 sec after ramp stretch) of 21 primary, 26 CR and 11 NCR secondary endings were compared using a stretch of 10 mm and

velocities of 5-70 mm/sec. It was found that the dynamic responses and the dynamic indices for the CR endings were significantly less than those of the primary endings but significantly greater than those of the NCR endings studied. The mean static responses of primary (49.3, S.E.M. ± 2.9 imp/sec) and CR endings (49.8 ± 3.9 imp/sec) were the same and both were significantly greater than those of the NCR endings (25.2 ± 2.5 imp/sec). It is suggested that CR secondary endings, like primary endings, measure length plus velocity, whereas the NCR secondary endings measure mainly length.

Cooling of the muscle to 32, 28 and 24°C decreased the static response to stretch (10 mm at velocities of 10-50 mm/sec) more than that of the dynamic response. Because of this muscle cooling did not produce a significant change in the dynamic indices of the three types of ending.

The finding that muscle cooling selectively stimulated secondary endings provided a method of studying the role of these afferents in spinal reflex activity. The effects of cooling the relaxed MG muscle on the monosynaptic reflex (MSR) from the lateral gastrocnemius soleus (LGS) nerve were studied in 12 decerebrate and 4 spinal cats. The main finding was that cooling resulted in an increase in the heteronymous MSR beginning at 32.5 S.E.M. ± 0.6°C, reaching a maximum at 29.3 ± 0.8°C and decreasing with further cooling. Changes in the MSR followed the same pattern

as that from the CR secondary endings during cooling of relaxed MG muscle. It was concluded that the MSR was increased by the asynchronous response of de-efferented CR secondary endings to cooling.

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I. INTRODUCTION

The mammalian muscle spindle has been studied for over a century. In addition to several notable reviews (Granit, 1955; Hunt and Perl, 1960; Matthews, 1964) and symposia (Barker, 1962; Andrew, 1966; Granit, 1966; Banker, Przybylski, van der Meulen and Victor, 1972) comprehensive accounts of the present state of the muscle spindle have been published (Granit, 1970; Matthews, 1972). Such an extensive investigation has greatly extended knowledge of spindle morphology, discharge characteristics and reflex actions.

In general the muscle spindle is regarded as a complex sensory organ, under efferent control, which signals changes in muscle length and contributes to the subconscious control of movement and the sensation of position. The spindle is a partially encapsulated structure with an afferent and efferent nerve supply innervating a variable number of intrafusal muscle fibres. The nuclear bag and nuclear chain intrafusal fibres are distinct anatomical structures with differences in fibre length, diameter and arrangement of nuclei. All intrafusal fibres within a spindle receive a branch of the single primary ending and a variable number of secondary endings, lying predominantly on nuclear chain fibres beside the primary termination. At least two types of motor ending are present, although the

degree of their distribution to the different intrafusal fibres is still controversial.

A comparison of spindle afferents has shown that primary endings are more sensitive than secondary endings to a variety of stimuli, including muscle stretch, vibration and efferent control (Matthews, 1972). Recently spindle sensory endings have been shown to respond to muscle cooling. Lippold, Nicholls and Redfearn (1960) demonstrated in vivo and in vitro that cooling of the relaxed hindlimb muscle of the cat caused an afferent discharge, 'cold response', in previously silent, de-efferented sensory endings of muscle spindles. Muscle cooling initiated afferent activity at 32°C; the frequency of discharge was constant at any one temperature and independent of the cooling rate. The 'cold response' originated in spindle afferent fibres possessing small amplitude spikes, whereas fibres with the largest spikes showed no response to cold. Such results suggested that the sensory endings connected to the smaller diameter spindle group II afferents, from secondary endings, carried the 'cold response'. The 'cold response' is not limited to spindles of the cat muscle but has been demonstrated also in the mouse (Banet and Séguin, 1967) and in the rat (Michalski and Séguin, 1971).

The first aim of the present investigation was to identify conclusively those spindle afferent endings which possess the

'cold response'. Spindle endings were classified as either primary or secondary endings using the generally accepted convention that primary afferents have conduction velocities higher than 72 m/sec, while those of the secondaries are less. The response of both types of afferent ending was studied during moderate cooling in relaxed muscles. The findings showed that the 'cold response' was absent in primary endings and was present only in a portion of the secondary endings. The latter finding led to the second aim of the investigation, namely to study the response to stretch of those secondary endings which responded to muscle cooling (CR secondary endings) and those which did not (NCR secondary endings) and to compare both with primary endings.

Eldred, Lindsley and Buchwald (1960) who identified muscle sensory endings on the basis of their afferent fibre conduction velocity, gave evidence that the afferent activity of both primary and secondary endings of the stretched gastrocnemius muscle of the cat was decreased during muscle cooling. This finding was in a way contradictory to that of Lippold et al. (1960). It was expected that the present investigation would also help to resolve these contradictory findings. In conjunction with the above experiments, therefore, the response to stretch of CR and NCR spindle endings was studied during muscle cooling.

At present the reflex actions of secondary endings are not clear. Initially Lloyd (1946a, b) and Brock, Eccles and Rall

(1951) had shown by monosynaptic testing in the cat that the group II afferents excited flexor and inhibited extensor motoneurones. This finding was confirmed by intracellular motoneurone recordings (Eccles and Lundberg, 1959a). Later group II secondary endings together with group III muscle afferents and high threshold joint and skin afferents were defined as part of a system of flexor reflex afferents (Eccles and Lundberg, 1959a; Holmqvist, Lundberg and Oscarsson, 1960). Thus the secondary endings were thought to function in conjunction with a variety of non-specific afferents to produce facilitation of ipsilateral flexor muscles and inhibition of ipsilateral extensor muscles regardless of the muscles of origin.

On the other hand, excitation of muscle afferent nerves with stimuli of group II strength has been shown to result in excitation of ipsilateral extensor motoneurones (Eccles and Lundberg, 1959a; Wilson and Kato, 1965) and facilitation of the monosynaptic reflex (Holmqvist and Lundberg, 1961). These divergent results may be explained in part by the fact that a selective stimulus for secondary endings is not available. The reflex actions of secondary endings were examined mostly in experiments which depended upon electrical stimulation of nerves for activation of reflex pathways. Because of the overlap in fibre diameter range and the finding that group II fibres do not form a functionally homogeneous group (Paintal, 1960; Barker, Ip and Adal, 1962) electrical stimulation cannot be regarded as particularly selective for any one fibre group.

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Recently Matthews (1969) and McGrath and Matthews (1973) studied the reflex effects of secondary endings in experiments which were based on the use of 'natural stimulation' i.e. muscle stretch, rather than electrical stimulation. They obtained results suggesting that in the decerebrate cat secondary endings from an extensor muscle produced autogenic excitation rather than inhibition and could contribute to the tonic stretch reflex. Thus the role of secondary endings in the stretch reflex is also controversial.

The present finding that muscle cooling could selectively activate secondary endings provided a unique method for testing the effects of secondary activity on spinal reflexes. Therefore the third aim of the study was to investigate the effects of secondary action, elicited by muscle cooling, upon the heteronymous monosynaptic reflex.

From a functional point of view the variability of secondary ending reflex effects indicates that these receptors may not form a homogeneous group. The question as to whether or not secondary endings should be subdivided into functionally distinct groups as previously attempted by Bianconi and van der Meulen (1963) is still unanswered. In this respect, if secondary endings can be clearly shown to be composed of two distinct groups, the conflicting results of their reflex actions may be more readily explained.

II. HISTORICAL REVIEW

1. The Early Investigation of the Muscle Spindle

Mammalian muscle receptors and in particular muscle spindles have been the subject of extensive investigation for over one hundred years. According to Ruffini (1898), the presence of small muscle fibres in adult muscle was first reported by Hassal in 1851. However credit for the earliest description of the muscle spindle belongs to Weisman (1861), who saw the slender bundles of muscle fibres now known to be intrafusal fibres (c.f. Matthews, 1972). Similar bundles of fibres were observed in frog and mammalian muscle by Kölliker (1862) and Kühne (1863) who provided details of spindle structure and special names. Because of their small size and large content of nuclei Kölliker suggested the term muscle bud, "Muskelknospen", and believed spindles to be growth centres persisting in adult muscle. Kühne noted one large nerve fibre in each muscle bundle and thought that the nervous and muscular elements formed small entities whose shape suggested the term muscle spindle, "Muskelspindeln". Based on the above evidence and his own morphological findings Kerschner (1888) concluded that the muscle spindle was a complicated sensory organ serving muscle sense. Onanoff (1890) showed that ventral root section caused atrophy of some spindle nerve fibres, while

destruction of the dorsal root ganglia produced degeneration of nearly all spindle nerve endings. Originally overlooked, Onanoff's evidence for a spindle efferent innervation was later confirmed by Sherrington (1894).

During the 1890's the valuable works of Sherrington and Ruffini provided further details of spindle structure and nerve innervation. Sherrington (1894) described the spindle as fusiform in shape, surrounded by a capsule which enclosed a periaxial space. The individual muscle fibres, termed intrafusal fibres, possessed a central equatorial region filled with spheroidal nuclei and a more distal, non-nucleated polar region. Each intrafusal fibre ran from end to end along the spindle axis and terminated in extrafusal fibres or tendon. Sherrington traced afferent nerves to the spindle and showed that each spindle received one or more large fibres, 7-18 microns (μ) in diameter. The appearance of these nerve terminals within the spindle was outlined by the technique of gold chloride impregnation (Ruffini, 1898). Ruffini described and named three morphologically distinct kinds of nerve ending and these names still apply today. Ruffini's large primary or annulospiral ending, formed from a single medullated afferent fibre, supplied a branch to each spindle intrafusal muscle fibre and terminated in coils or spirals around the midequatorial region. Although the primary

fibre was noted previously (Kühne, 1863; Kerschner, 1888; Sherrington, 1894), Ruffini (1898) was the first to describe the smaller secondary or flower spray ending, which consisted of an irregular termination running along and around the intrafusal fibres to innervate the myotube region adjacent to the primary ending. The primary ending occupied the central 300 μ region of the spindle length, while the secondary covered a 400 μ section, proximal to the equatorial zone but not overlapping the primary ending. Ruffini (1898) distinguished a third discrete nerve ending, (Kerschner's 'plate ending', 1888), smaller than the primary or secondary, confined mostly to the polar regions and similar to the extrafusal fibre motor end plate. Contrary to Kerschner, Ruffini (1898) believed plate endings to be sensory structures.

Despite some indication of motor innervation such as the finding of spindle end plates (Kerschner, 1888; Huber and De Witt, 1897; Weiss and Dutil, 1896) and the degeneration of some spindle fibres after ventral root section (Onanoff, 1890; Sherrington, 1894) the presence of a motor supply to the spindle was not confirmed until many years later. Boeke (1927) sectioned both ventral and dorsal roots proximal to the dorsal root ganglion and found that the plate endings to the intrafusal fibres degenerated. Ruffini's third sensory ending was revealed to be motor because degeneration experiments by Hinsey (1928); Hines

and Tower (1928) showed that plate endings persisted after removal of sympathetic ganglia, but degenerated after ventral root section. The existence of a spindle efferent innervation was further confirmed by Cuajunco (1932) who reported the persistence of polar plate endings after removal of dorsal root ganglia. Thus after almost 70 years of observation and study the mammalian muscle spindle was firmly established as a sensory organ with an efferent innervation.

These early studies provided the anatomical basis for the 'classical picture' of the muscle spindle which served until recent times as the generally accepted description of spindle morphology. The innervation consisted ot two types of afferent fibre and a single type of efferent fibre innervating the intrafusal muscle fibre. The spindle was described as a partially encapsulated structure, fusiform in shape, containing several intrafusal fibres with centrally located nuclei. The individual intrafusals varied in length and diameter and passed through the capsule to attach to extrafusal fibres or tendinous slips.

2. The Present Picture of Muscle Spindle Structure

Little new knowledge was added to the 'classical picture' of the spindle until the 1950's when two different kinds of intrafusal

muscle fibre were recognized. Intrafusal fibres were already known to vary in length and diameter (Sherrington, 1894; Ruffini, 1898), and later Cuajunco (1927) divided intrafusal fibres into large, medium and small groups. In his description of rabbit spindles Barker (1948) applied the term nuclear bag (NB) to the aggregate of 40 or 50 nuclei found in some intrafusal fibres. In addition to Barker's nuclear bag fibre Cooper and Daniel (1956) described an intrafusal fibre in human hand muscle which contained a myotube of central nuclei in the equatorial region. Similar myotube intrafusal fibres were observed in spindles of the cat tenuissimus by Boyd (1956) and later by Barker and Gidumal (1960) who called them nuclear chain fibres (NC). Boyd's beautifully illustrated paper of 1962 provides a comprehensive picture of the two intrafusal fibre types. He found that the nuclear bag fibres are characterized by an enlarged equatorial region containing many tightly packed spheroidal nuclei. At either end of the central portion, the nuclei continue as a single row into the myotube regions. In contrast, the nuclear chain fibre equatorial region contains only a single central row of elongated nuclei. In cat hindlimb muscles the nuclear bag intrafusals are generally longer and thicker than nuclear chain fibres.

There is some controversy as to whether or not each of the two kinds of intrafusal fibre can be traced as a discrete entity from end to end. Earlier the majority of workers held that branching of intrafusal fibres occurs throughout the length of the

spindle (Weismann, 1861; Kühne, 1863; Ruffini, 1898; Haggvist, 1960) while more recently it has been maintained that branching occurs rarely, if at all (Boyd, 1958; Cooper, 1960; Swett and Eldred, 1960).

The longer nuclear bag fibres generally extend beyond the capsule attaching by a tendinous strand at their tapering ends to the perimysium of closely adjacent extrafusal fasciculi (Boyd, 1962). In the rat some nuclear chain fibres also extend beyond capsule poles (Poryako and Smith, 1968), but in the cat they usually end close to the polar ends of the capsule (Cooper and Daniel, 1963) and may insert on bag fibres (Boyd, 1962) or in the capsule wall (Bridgman, Shumpert and Eldred, 1969). The relative number of bag and chain fibres per spindle varies considerably; however in the hindlimb muscles of the cat the mean number of bag fibres per spindle is 2 and of chain fibres, 4 (Boyd, 1962).

Each spindle has only one primary sensory fibre (12 - 20 μ in diameter) consisting of spiral terminations, incomplete rings and a few sprays which innervate a 300 μ central nuclear region on each spindle intrafusal fibre (Barker, 1948; Boyd, 1962; Cooper and Daniel, 1963). In contrast cat spindles may carry up to four or five secondary fibres (Barker and Ip, 1961; Boyd, 1962) and the approximately 400 μ long regions they occupy on either side of the primary termination have been conveniently designated S_1, S_2, S_3 and S_4 by Boyd (1962). Secondary endings

are located predominantly on nuclear chain fibres and assume a spiral form (Boyd, 1962; Barker and Ip, 1963). "Flower-spray" terminations of the secondary ending (Ruffini, 1898) occur and are found mainly on the myotube region of the nuclear bag fibres (Barker and Ip, 1963; Barker, 1967; Mayr, 1971). The afferents from the primary endings have been classified as group I afferent fibres of muscle nerves (Lloyd and Chang, 1948; Rexed and Therman, 1948). They were called Ia fibres by Bradley and Eccles (1953) to distinguish them from Ib afferents from Golgi tendon organs. The secondary endings were classified as group II muscle afferents.

In addition to the polar end plate type of motor innervation (Kerschner, 1888; Huber and De Witt, 1897; Weis and Dutil, 1896) the spindle was found to have diffuse multi-terminal endings along the entire intrafusal fibre length except for the equatorial region. This was first detected in cat and rat spindles by the cholinesterase staining technique which revealed the presence of a motor apparatus near the spindle equatorial region (Cöers and Durand, 1956). Boyd (1962) showed definitely that there were two types of gamma efferent axons to the spindle, the $gamma_1$ terminating in motor end plates, and the $gamma_2$ terminating as a diffuse network. Barker and Ip (1965) introduced the term trail ending rather than network and both types of efferents were called

fusimotor, a term suggested by Hunt and Paintal (1958). Morphological differences between plate and trail endings have been described now in detail (Barker, 1967; Gorvaja, Marinozzi and Pompeiano, 1969; Barker, Stacey and Adal, 1970; Banker and Girvin, 1971). The main difference between them as seen by the light microscope is that plate endings consist of discrete end-plates, whereas trail endings cover a large area of intrafusal fibre surface. Under the electron microscope the main difference in ultrastructural features is that post junctional folding is more prominent beneath plate endings than beneath trail endings.

More recently two types of plate ending (Barker, 1966) termed P_1 and P_2 (Barker, 1967) have been distinguished in cat muscle spindles and are thought to originate from beta and gamma fibres respectively. The P_1 plates, similar in structure to extrafusal motor end plates of alpha fibres, are located at the extreme polar region, while the P_2 plates are in the midpolar region of the intrafusal fibre.

The distribution of these three types of motor terminal have been the subject of some controversy. Boyd (1962) and Boyd and Davey (1966) maintained that the trail ending terminates exclusively on the nuclear chain intrafusal fibres, while motor end plates are always located on the nuclear bag fibres. On the other hand, Barker and Ip (1966) and Barker et al. (1970) believed that the different types of fusimotor endings are now selectively distributed to the

two types of intrafusal muscle fibre. Subsequent histological studies (Corvaja, Marinozzi and Pompeiano, 1969; Barker, Stacey and Adal, 1970; Boyd, 1971b) have shown that plate endings are, in the main, confined to nuclear bag fibres and that nuclear chain fibres are often innervated by trail endings only; however every intrafusal fibre may receive either one or both types. More recently the use of histophysiological techniques has demonstrated that the axons of trail endings innervate both bag and chain intrafusal muscle fibres (Barker, Emonet-Dénand, Laporte, Proske and Stacey, 1970).

In summary, the 'classical picture' of the spindle has now been enhanced by the addition of several significant features. The nuclear bag and nuclear chain intrafusal fibres have been shown to be two distinct anatomical structures with differences in fibre length, diameter and arrangement of nuclei. All intrafusal fibres within a spindle receive a branch of the single primary ending and a variable number of secondary endings lying predominantly on nuclear chain fibres beside the primary termination. Our knowledge of the motor innervation of the intrafusal fibres is still incomplete, but it is clear that at least two types of motor endings are present although the degree of their distribution is still controversial.

3. Characteristics of Spindle Afferent Discharge

Sherrington frequently referred to the sensory role of muscle spindles; however a good understanding of spindle physiology came only with advances in electrophysiological techniques, specifically through that of single nerve fibre recording, introduced by Adrian and Zotterman (1926) and further developed by B. H. C. Matthews (1933). The afferent discharge from single sensory endings in mammalian muscle was first recorded by Matthews (1933) who cut down the muscle nerve until only one afferent fibre from the muscle remained intact. Matthews studied the responses of a large number of single fibres to different mechanical stimuli applied to the muscle and recognized three patterns of discharge A, B and C. The C endings were suggested to come from muscle fascia. However two distinct patterns of response were observed during muscle contraction; the discharge rate of some endings decreased (type A) and that of others increased (type B). Previously Fulton and Pi-Süner (1928) had suggested that muscle contraction would stimulate Golgi tendon organs which lie in series with muscle fibres and would unload spindles which lie in parallel with extrafusal muscle fibres. On this assumption Matthews inferred that A and B responses were characteristic of spindle endings and tendon organs respectively. Matthews divided the A endings into A_1 and A_2 and concluded that secondaries corresponded to the former and primaries to the latter subdivision. Under Matthews' experimental conditions the A_1 and A_2 endings behaved similarly; both were

excited by muscle stretch, possessed low thresholds to extension and a discharge frequency dependent upon velocity and amplitude of stretch. According to B. H. C. Matthews the primary and secondary endings could be distinguished mainly by their response to intrafusal fibre contraction and not to mechanical stimuli.

More recent work has cast doubt on the physiological significance of B. H. C. Matthews' classification of spindles. The identification of an ending as primary or secondary may now be made independently of its subdivision into type A_1 or A_2 by measuring the conduction velocity of its afferent nerve fibre. Merton (1953) observed that impulses could be detected in the dorsal roots at intervals after stimulation of muscle nerves which placed the conduction velocity of the impulses at 30-50 m/sec. Hursh (1939) had shown that the conduction velocity of a medullated fibre in metres per second was equal to approximately 6 times its diameter in microns. The impulses studied by Merton would therefore be travelling in fibres with diameter of about 5-8 μ and so could come from secondary endings which were known to be supplied by afferent fibres of this size in the muscle (Ruffini, 1898; Barker, 1948). Subsequently Hunt (1954) recorded action potentials from single sensory fibres in dorsal roots from the cat's medial gastrocnemius and soleus muscles and systematically classified these afferent fibres (after Lloyd, 1948) into two groups based on fibre size, group I (12-20 μ) and group II (4-12 μ) with

the dividing line at 12 μ. Using Hursh's formula, Hunt's boundary was placed at 72 m/sec. Since that time it has been customary to divide spindle end organs on this basis with primary endings being equated to the larger group I afferents, 72-120 m/sec and secondary endings being equated with the smaller fibres of group II afferents, 24-72 m/sec.

The method, introduced by Hunt and Kuffler (1951) of recording the discharge of single afferents from subdivided dorsal root filaments combined with their classification by conduction velocity greatly enhanced the study of primary and secondary spindle ending responses. Cooper (1959, 1961) compared the behaviour of primary and secondary endings of the cat soleus to a constant amplitude stretch (4 mm) of variable velocity (8-100 mm/sec).

Cooper's findings supported those of Hunt (1954) with respect to the observation of lower threshold to stretch for primary than for secondary endings; however she also found that primary endings possessed a greater sensitivity to dynamic stimuli than secondary endings. During the application of stretch Cooper (1961) noted that the secondary ending discharge frequency hardly exceeded that reached during a maintained stretch, regardless of the stretch velocity. The greater dynamic sensitivity of the primary ending has been confirmed now in a variety of cat preparations and muscles (Lundberg and Winsbury, 1960; Harvey and

Matthews, 1961; Appelberg, 1962; Bessou and Laporte, 1962; Jansen and Matthews, 1962a; Matthews, 1963; Renkin and Vallbo, 1964; Alnaes, Jansen and Rudjord, 1965; Lennerstrand, 1968).

A more detailed analysis of spindle discharge such as measurement of the dynamic index has provided evidence for an overlap in the range of primary and secondary ending responses. The difference between the frequency of discharge just before the end of the dynamic period of stretching and that occurring 0.5 sec later was termed the 'dynamic response' by Jansen and Matthews (1962a) and later called the 'dynamic index' by Crowe and Matthews (1964). Although arbitrary, the 'dynamic index' has proven to be a useful measurement of the velocity responsiveness of a spindle ending. Matthews (1963) found that the dynamic index of both primary and secondary endings in the cat soleus increased with increasing velocities of stretch, but its value was consistently higher for the majority of primary endings at all stretch velocities. Spindle endings cannot be divided completely into two distinct functional groups, since overlap does exist between the sensory responses of some primary and secondary endings. Matthews (1963) found that some spindle endings with afferents in both the high (greater than 80 m/sec) and low (less than 60 m/sec) conduction velocity ranges could not be classified as either primary or secondary endings on the basis of their dynamic index. Alnaes, Jansen and Rudjord (1965) found considerable overlap in the

dynamic indices of primary and secondary endings in the anterior tibial muscle of the cat. Similarly, Cody, Lee and Taylor (1972) reported that they could find no evidence of two distinct populations of afferent fibres in terms of dynamic index for the spindles of the jaw muscles of the cat.

The finding that some overlap in response properties does exist has led many workers to study only fibres with conduction velocities above 80 m/sec and below 60 m/sec (Matthews, 1963; Renkin and Vallbo, 1964; Brown, Engberg and Matthews, 1967). Some spindle endings with conduction velocities near 72 m/sec were reported to have properties intermediate between those of primaries and secondaries (Matthews, 1963). Rack and Westbury (1966) found however, that all such intermediate fibres fitted into the primary or secondary ending groupings after intrafusal fibre contraction was induced by suxamethonium or acetylcholine.

In contrast to the above findings, those dealing with the static sensitivity of the endings are relatively uncomplicated. The static responses of primary and secondary endings to a maintained stretch (measured 0.5 sec after the end of ramp stretch) are not significantly different (Matthews, 1963; Alnaes, Jansen and Rudjord, 1965). Harvey and Matthews (1961) showed also that with passive stretch of the muscle the static discharge of both primary and secondary endings increased linearly at the same rate. The slope of this frequency - extension relationship was

defined as the 'static sensitivity' of the receptor ending (Whitteridge, 1959) and was shown to be the same for primary and secondary endings (Jansen and Matthews, 1962b; Alnaes, Jansen and Rudjord, 1965).

Primary and secondary endings have been further differentiated by their degree of response to vibration. Echlin and Fessard (1938) applied tuning forks to muscle tendons and were able to stimulate unidentified stretch receptors with vibration. Kuffler, Hunt and Quilliam (1951) recorded from single spindle afferents and found that the muscle nerve discharge in the cat followed the rhythm imposed by a tuning fork applied to the tendon. Subsequently Granit and Kenatsch (1956) found that vibratory stimuli applied to the tendon and to the muscle itself was an efficient stimulus of primary endings. In addition they noted that primary endings activated by fusimotor stimulation responded to higher frequencies of vibration than endings vibrated in a defferented muscle.

Bianconi and van der Meulen (1963) compared the responses of primary and secondary endings to vibration. They applied vibration to the localized area of the muscle overlying the spindle and were able to drive all primary endings and nearly one-half of the secondaries studied to discharge one impulse per vibration up to a maximum frequency of 100-300 c.p.s. However, none of the secondary endings could be similarly stimulated, when the vibration was

applied to the tendon of the muscle.

Crowe and Matthews (1964) and Brown, Engberg and Matthews (1967) noted that vibration applied longitudinally to the tendon of the soleus muscle powerfully excited spindle primary endings but had little or no effect on spindle secondary endings. The secondaries ceased to follow the stimulus with longitudinal stretches of low frequency and small amplitude (Brown, Engberg and Matthews, 1967). Thus longitudinal vibration of the muscle tendon has become popular as a selective 'natural' stimulus for primary endings and has been widely employed to study this receptor's role in the central nervous system activity.

4. Efferent Control of Spindle Discharge

Early histological work established the presence of a spindle efferent innervation (Onanoff, 1890; Sherrington, 1894; Boeke, 1927) but the effect of fusimotor stimulation was first demonstrated by B. H. C. Matthews (1933). He showed that stimulation of a motor nerve of a muscle caused excitation of some spindle afferents. Previous to this Eccles and Sherrington (1930) described two sizes of motor fibre in ventral roots and muscle nerves and O'Leary, Heinbecker and Bishop (1935) suggested that the smaller group of efferent fibres might be motor to the muscle spindles. Positive evidence for this was obtained by Leksell (1945). During fairly

selective alpha fibre blockage Leksell observed that gamma stimulation produced little muscle contraction but it increased the afferent discharge. From this he concluded that gamma fibres regulated muscle sensory activity. This conclusion was subsequently confirmed by Kuffler et al. (1951) who found, in addition, that stimulation of a single gamma fibre could increase the discharge of spindle endings.

By 1962 Matthews had shown that gamma fibres could be differentiated into two functionally distinct types; dynamic and static fusimotor fibres. The dynamic fusimotor fibres enhanced the response of the primary endings during the dynamic phase of stretching, while the static fibres failed to do so. On the other hand, stimulation of either dynamic or static fusimotor fibres increased the discharge of the primary endings during maintained stretch. The action of fusimotor fibres on secondary endings was also examined. Static fusimotor fibres had their characteristic effect but the dynamic fusimotor fibres did not influence spindle secondary ending activity (Crowe and Matthews, 1964; Appelberg, Bessou and Laporte, 1966).

It would appear that static and dynamic fusimotor fibres are capable of innervating both nuclear bag and nuclear chain fibres. Combined studies of the histology and physiology of fusimotor fibres (Barker, Emonet-Dénand, Laporte, Proske and Stacey, 1970) have shown that static fusimotor fibres are not

selective in their mode of termination, ending on both nuclear bag and nuclear chain intrafusal fibres. In addition Brown and Butler (1973) employed tetanic stimulation of single fusimotor fibres to deplete intrafusal fibre glycogen and thereby mark the site of termination of the fusimotor fibre. These workers demonstrated that dynamic fusimotor fibres activated mainly nuclear bag intrafusal fibres, while static fusimotor fibres activated mainly nuclear chain intrafusal fibres. However overlap occurs in that dynamic and static fusimotor fibres may occasionally activate nuclear chain and nuclear bag intrafusals respectively.

5. Role of the Muscle Spindles in Spinal Reflex Activity

The role of the muscle spindle in reflex actions began with the study of the tendon jerk. This was first described in 1875 by Erb and Westphal (c.f. Liddell, 1960); however, it was several years before it was conclusively proven to be a reflex response. One of the early attempts to establish the tendon jerk as a reflex phenomenon was carried out by Jolly (1911). He elicited the knee jerk in the quadriceps muscle of the spinal cat, measured its central latency and suggested that the tendon jerk was a reflex mechanism involving one spinal synapse. This observation was supported by Eccles and Pritchard (1937). These workers, using

dorsal root stimulation, were able to record a ventral root discharge with a short delay and concluded that the reflex response was monosynaptic. Similarly after stimulating a dorsal root Renshaw (1940) found that the earliest ventral root spike had a synaptic delay of such short latency (< 1 msec) that it must have been transmitted through only one synapse. Renshaw studied reflex responses with the technique of monosynaptic testing, a method in which the monosynaptic response represents the interaction of volleys delivered to two muscle nerves. Renshaw's method was adapted by Lloyd (1943b) who found that brief short lasting stretches of the gastrocnemius tendon of the cat elicited a monosynaptic reflex response. Thus Lloyd's study firmly established the tendon jerk as reflex in nature and its mode of transmission as monosynaptic.

In addition Lloyd (1943a) demonstrated that group I afferent fibres in both flexor and extensor muscles produced a monosynaptic excitation of motoneurones (homonymous) to the muscle from which the stimulated afferent fibres arose. He concluded further (Lloyd, 1946a, b) that a group I afferent input facilitated motoneurones of muscles synergistic (heteronymous) to those whose afferent fibres had been stimulated and also inhibited the motoneurones of their antagonist.

Initially there was some controversy as to the receptor of origin of the tendon jerk reflex. Fulton and Pi-Suñer (1928)

found that when a tendon jerk was elicited in an extensor muscle of a decerebrate cat the pre-existing electrical activity of the muscle was absent during the jerk but reappeared during muscle relaxation. Previously Hoffman (1920) had demonstrated such a silent period in man during voluntary contraction. Fulton and Pi-Suñer (1928) attributed the tendon jerk and the associated silent period to the decrease in discharge from the stretch afferent end organs during the knee jerk. These workers linked the silent period to the muscle spindles which they argued were arranged in parallel with the extrafusal muscle fibres and would be unresponsive during muscle contraction.

While most workers held that the muscle spindle was the receptor responsible for the tendon jerk, Denny Brown (1928) believed that the tendon jerk was mediated by the Golgi tendon organs. However, the first single fibre recordings from mammalian spindle afferents by B. H. C. Matthews (1933) confirmed Fulton and Pi-Suñer's explanation of the silent period. Matthews (1933) showed that spindle discharge decreased during muscle contraction, as Fulton and Pi-Suñer had suggested in their explanation for the silent period following the tendon jerk.

Originally the role of primary and secondary spindle endings in the tendon jerk and the tonic stretch reflex was confused. The Golgi tendon organ's high threshold to stretch (Matthews, 1933) eliminated that receptor as being responsible for the tendon jerk

which could be elicited by brief short stretches (Liddell and Sherrington, 1924; Lloyd, 1943b). However, Matthews' (1933) incorrect conclusion that spindle primary endings had a relatively higher threshold to passive stretch than the secondary endings favoured the latter receptor as the mediator of the tendon jerk. This conclusion was reversed following Lloyd's monosynaptic transmission experiments in which he calculated the conduction velocity of afferent fibres eliciting the tendon jerk to be approximately 116 m/sec. This finding made the large diameter afferents of primary endings responsible for the tendon jerk. Finally Lundberg and Winsbury (1960) found that primary afferents were selectively excited by a brief muscle stretch (< 100 μ) and that such stretches reflexly evoked intracellularly recorded monosynaptic excitatory postsynaptic potentials.

Liddell and Sherrington (1924) introduced the term 'stretch reflex' to describe the reflex response of a muscle to a prolonged stretch. The tendon jerk could be equated with the phasic component of the stretch reflex, while the tonic component was described as a response to maintained muscle extension. In the decerebrate cat both the phasic and tonic components of the stretch reflex are thought to depend upon the excitation of the primary endings of the spindle by stretching. This conclusion has been supported recently by the use of high frequency vibration as a selective stimulus of primary endings (Matthews, 1966; Gilles, Burke and

Lance, 1971). These workers have shown that prolonged vibration, by selectively stimulating primary endings, can cause a sustained reflex contraction.

The central effects produced by group II afferents were initially studied by Lloyd (1946a, b). He showed that group II strength stimulation of any muscle nerve produced autogenetic excitation of flexor motoneurones but exerted a weak or barely detectable autogenetic inhibition of extensor motoneurones. Lloyd's observations were subsequently confirmed by Brock, Eccles and Rall (1951) using monosynaptic testing. Hunt (1954) then showed that practically all group II afferents, at least in the cat triceps surae, originated in the spindle, presumably from secondary endings. The extensor inhibitory role of secondary afferents was supported further by Laporte and Bessou (1959) who showed that group II fibres, excited by stretching the muscle inhibited extensor and excited flexor motoneurones following block of group I fibres from the muscle. Intracellular motoneurone recording techniques also established an autogenetic inhibitory role for group II fibres from secondary endings (Eccles and Lundberg, 1959a). These workers recorded inhibitory postsynaptic potentials from extensor motoneurones in the cat when muscle nerves were stimulated with group II strength. More recently Cangiano and Lutzemberger (1972) found that selective activation of secondary afferents during block of impulses in group I fibres gave rise to an

hyperpolarization of extensor motoneurones.

The secondary endings together with group III endings and high threshold joint and skin afferents were defined as part of a system of flexor reflex afferents, the FRA system (Eccles and Lundberg, 1959a; Holmqvist, Lundberg and Oscarsson, 1960). Thus the secondary spindle afferents were thought to produce facilitation of ipsilateral flexor muscles and inhibition of ipsilateral extensor muscles regardless of the muscle of origin.

In some studies however, excitation of muscle afferents with stimuli of group II strength has been shown to cause excitation of ipsilateral extensor motoneurones (Eccles and Lundberg, 1959a; Wilson and Kato, 1965) and facilitation of the monosynaptic reflex (Holmqvist and Lundberg, 1961). Additional evidence for extensor excitatory effects of group II fibres was provided by Pacheco and Guzmán (1969) who demonstrated that group II afferents excited ipsilateral extensor motoneurones through a polysynaptic pathway.

Matthews (1969) and McGrath and Matthews (1973) aroused further controversy concerning the reflex role of spindle secondary endings with the suggestion that primary endings do not provide the sole source of autogenetic excitation elicited by muscle stretch. These workers performed experiments on the cat soleus muscle which were based on the use of 'natural' stimulation i.e., muscle ramp stretch, and vibration rather than electrical

stimulation. They obtained results suggesting that in the decerebrate preparation, spindle secondary endings from an extensor muscle contribute excitation to the extensor motoneurones. Such findings led these workers to conclude that the spindle secondary endings were responsible, at least in part, for the tonic stretch reflex of the decerebrate cat.

While the conclusions of Matthews and McGrath formed the basis of some controversy (Grillner, 1970, 1972) the results of their experiments in no way invalidated the previous inhibitory role assigned to spindle secondaries, for such endings may have several pathways to extensor motoneurones, although their precise course through the central nervous system remains unknown.

6. The Response of Muscle Spindles to Temperature Changes

The ability of mammalian muscle spindles to respond to temperature changes has been known since 1960, when Lippold, Nicholls and Redfearn demonstrated the 'cold response'. These workers found that cooling of the relaxed tenuissimus muscle of the cat *in vivo* and *in vitro* caused an afferent discharge, 'cold response' in previously silent, de-efferented sensory endings of muscle spindles. The cold evoked activity had a characteristic frequency response curve similar to that of a cold receptor (Hensel and Zotterman,

1951). Afferent activity was generally initiated at 32°C, reached a maximum frequency and then declined with further cooling. The frequency was constant at any one temperature and independent of the cooling rate. Lippold and his colleagues attributed the 'cold response' to a direct effect of temperature upon the spindle ending membrane.

More recently the 'cold response' was described and confirmed in spindle sensory endings of the soleus muscle of the mouse (Banet and Séguin, 1967) and the anterior tibial muscle of the rat (Michalski and Séguin, 1971). Despite these studies little information is available concerning the identification of those sensory fibres which possessed the 'cold response'. Lippold et al. (1960) obtained the 'cold response' from spindle afferent fibres giving small amplitude spikes, whereas fibres with the largest spikes showed no response to cold. On this basis Lippold et al. (1960) and later Matthews (1964) suggested that only sensory endings connected to the group II fibres carried the 'cold response'. An exception to this conclusion was the observation by Lippold and his co-workers that other than spike height no further differences existed between cold response and non cold response afferent fibres.

In contrast Eldred, Lindsley and Buchwald (1960) who identified muscle sensory endings on the basis of their afferent fibre conduction velocity, gave evidence that the afferent activity of both primary and secondary endings of the stretched gastrocnemius

muscle of the cat was decreased during muscle cooling. These findings may not be contradictory since Eldred et al. (1960) might have masked the 'cold response' by their use of a stretched muscle. Nevertheless it would be of interest to have both facets of spindle response studied simultaneously. In addition the 'cold response' is an example of dual sensitivity to two different forms of stimuli and raises the problem of receptor specificity. Whether the 'cold response' contributes in any way to thermal reflexes, sensation or perception awaits a study of the distribution of the 'cold response' to spindle endings and an investigation of its central effects.

III. METHODS

1. Preparation: Recording from Single Sensory Afferents

Experiments were performed in 45 cats (weight range 1800 - 3700 gm) under pentobarbital sodium (Nembutal, Abbott Laboratories) anaesthesia (40 mg/Kgm injected intraperitoneally). Spinal segments L_3 to S_2 were exposed by laminectomy and dorsal and ventral roots L_6 to S_1 on the left side were cut near their entry into the cord. The left hip and hindlimb were completely denervated except for the muscle under study, the medial gastrocnemius. The medial gastrocnemius nerve was exposed and freed proximally for 2 to 3 cm and the muscle was separated as far as possible from surrounding structures leaving it attached mainly by its origin, blood supply and nerve supply. The medial gastrocnemius tendon was dissected free from the remainder of the triceps surae but was left attached to the calcaneum until the initial muscle length had been determined (as described later). The skin was then closed over the muscles leaving the tendon exposed.

The animal was fixed to a rigid metal frame (SE-4 Canberra-type spinal investigation unit) by heavy metal pins inserted in the pelvis. The left leg was held by steel pins placed in the tibia at the knee and ankle. The steel pins were then clamped to the frame. The spinal cord and limb muscles surrounding the

popliteal fossa were covered with warm paraffin oil in pools made from skin flaps. Spinal and muscle oil pool temperatures were maintained at 37°C by a heating lamp and a heating coil respectively and were monitored throughout the experiments with thermistors (Yellow Springs Instrument Co. [YSI, type 421]) connected to a telethermometer (YSI, model 46). The animal's body temperature was maintained at 37°C by means of an electric heating pad placed under the abdomen and controlled by a telethermometer (YSI, model 73A) connected to a rectal thermistor (YSI, type 402).

2. Initial Muscle Length

The initial length of the muscle was set at the beginning of the experiment. In order to ensure that the relationship of this initial muscle length to its normal range of extension was similar in different preparations the following procedure was employed. Before detaching the medial gastrocnemius tendon from the calcaneum, the foot was fixed so that the angle between the plantar surface of the foot and the anterior border of the tibia was 90°. The length of the muscle with the leg in this position was taken as the initial length of the muscle. When the angle was reduced to between 30 and 40° the muscle was at its maximal physiological length and this represented a stretch of 12-14 mm beyond that at the initial 90°

position. With the ankle held in the initial position the leg pins were fixed to the frame and the tendon connected by a rigid aluminum rod to the mechanical stretcher. The tendon was then detached from the calcaneum along with a chip of that bone. When a spindle afferent was tested for the 'cold response', the muscle was released from the initial position and completely relaxed so that the tendon became slack.

3. Application of Stretch

In 23 cats the medial gastrocnemius muscle was subjected to passive length changes (extension and relaxation) of constant amplitude. Muscle extension was accomplished by means of a mechanical stretcher designed and constructed by the Department of Engineering, University of Western Ontario. The stretcher was capable of producing a linear ramp stretch of 2 to 20 mm at velocities as high as 140 mm/sec. Transducers were incorporated in the stretcher and length and tension could be recorded simultaneously with the sensory discharge. Except where otherwise indicated the muscle was stretched 10 mm from its initial length at velocities of 5 to 70 mm/sec.

4. Muscle Cooling

The muscle was cooled by means of a frigistor placed against the skin under the medial gastrocnemius muscle. The frigistor thermoelectric cooling module, .2" x 3", (Dynatech Frigistor Co.) was operated from a DC power supply (Dynatech Frigistor Co.). Thermoelectric cooling makes use of the Peltier effect, thus heat absorption occurs on one surface of the frigistor, while heat is generated at the other surface. Heat produced on the latter frigistor surface flowed into a brass heat sink, 6" x 3 1/2" x 1/4", through which ice water (approximately 5°C) was circulated. In this way a temperature gradient was established in the muscle such that the muscle surface directly over the frigistor was always colder, but never less than 15°C, than the opposite medial surface of the muscle. The muscle temperature was monitored by means of a telethermometer (YSI, model 421) and a 24 gauge needle thermistor (YSI, 524). The needle was placed between the fascia separating the medial and lateral gastrocnemius muscles at a position where the muscle was thickest, (approximately 3 to 4 cm from its origin).

Muscle cooling curves were constructed in order to study the intramuscular temperature changes taking place at different muscle positions and depths with respect to time (Appendix A). Although the rate of cooling varied with muscle depth, it was found that muscle cooling was sufficient to allow cooling of all parts of the muscle to

temperatures less than 24°C. It was concluded that the method of cooling employed in the present study was sufficient to reach all spindles in the medial gastrocnemius muscle.

5. Electrical Recording

Muscle spindle sensory activity was recorded in vivo using the arrangement illustrated in Figure 1. Afferent recordings were made from dorsal roots L_7 to S_1 from which fine filaments containing the activity of a single muscle receptor were dissected out and placed on bipolar silver - silver chloride electrodes. Muscle spindle afferents were identified by the usual criteria: 1. response of the receptor to muscle stretch, 2. the presence of a pause (muscle spindle) or acceleration (tendon organ) of discharge during muscle contraction induced by a single shock to the appropriate ventral root, 3. the conduction velocity in the afferent nerve fibre.

In measurements of conduction velocity 0.1 msec stimuli ranging from 0.05 - 0.2 volts were applied to the whole medial gastrocnemius nerve near its insertion into the muscle and the latency of the conducted potential in the dorsal root filament was measured. At the end of the experiment the length of nerve from recording electrode to stimulating electrode was exposed

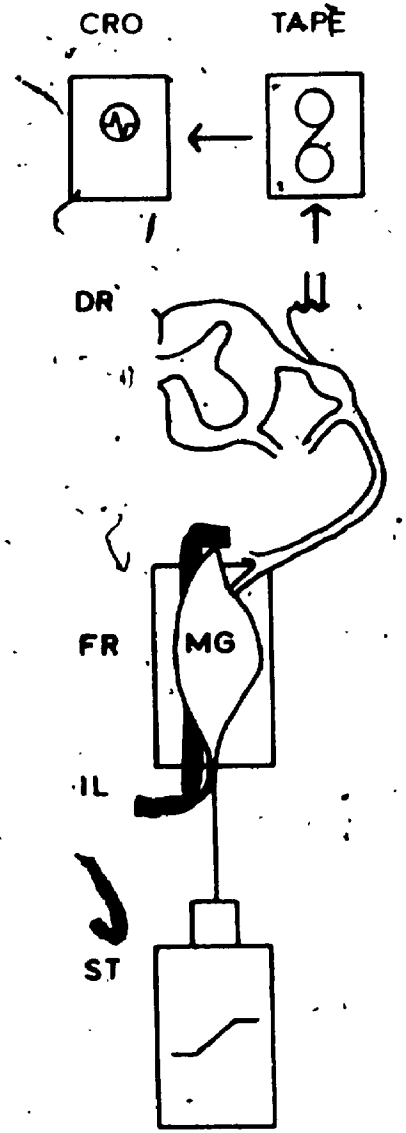
FIGURE 1

Illustrates the experimental arrangement and procedure used to study the sensory discharge of spindle endings.

A. Experimental arrangement. Following laminectomy and hip denervation the frigistor FR, was placed under the area of the hindlimb occupied by the medial gastrocnemius muscle (MG). The initial muscle length (IL) was fixed by setting the angle between the plantar surface of the foot and the anterior border of the tibia at 90°. The MG tendon was detached from the calcaneum along with a chip of that bone and attached to a mechanical stretcher (ST) by means of a rigid aluminum connecting link. The afferent discharge of single spindle endings was recorded from dorsal root filaments (DR) on bipolar electrodes. The activity was amplified by means of a preamplifier, stored on magnetic tape (TP) and monitored on an oscilloscope (CRO).

B. Experimental procedure. The sensory characteristics of each isolated spindle afferent were studied as follows: 1. identification of the afferent at 37°C by the usual criteria: a) conduction velocity; b) stretch responsiveness; c) pause during muscle contraction; 2. test for the presence of the 'cold response' by cooling the relaxed muscle from 37 - 20°C; 3. the response to static stretch was measured at 0.5 sec after a ramp stretch of 10 mm from the initial length; 4. the velocity responsiveness was obtained by stretching the muscle 10 mm from the initial length at velocities ranging from 5-70 mm/sec; 5. the instantaneous frequency of discharge was computed; 6. the dynamic index as illustrated in the inset was calculated from the display of instantaneous frequency. Dynamic index = dynamic response - static response measured 0.5 sec after the end of ramp stretch.

A



B

1 IDENTIFICATION OF MUSCLE RECEPTOR AFFERENTS

A) CONDUCTION VELOCITY

B) STRETCH RESPONSIVENESS

C) PAUSE DURING MUSCLE CONTRACTION

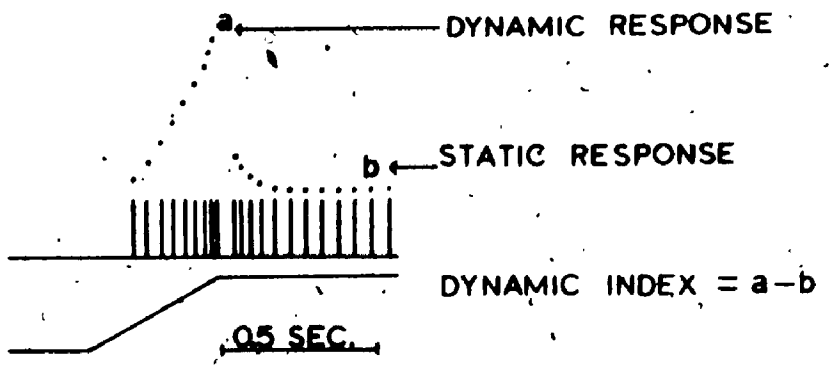
2 RESPONSE TO COOLING OF RELAXED MUSCLE

3 RESPONSE TO STATIC STRETCH

4 RESPONSE TO VELOCITY OF STRETCH

5 INSTANTANEOUS FREQUENCY ANALYSIS

6 DYNAMIC INDEX



and measured *in situ* using a piece of no. 1 surgical suture placed along the entire nerve length.

Identification of each muscle spindle afferent was carried out while the medial gastrocnemius muscle was maintained at 37°C. Following this, the spindle ending was tested for the presence of a 'cold response' by cooling the relaxed medial gastrocnemius muscle from 37 to 24°C. Sensory activity, amplified by means of a Grass P5l1 preamplifier, was displayed on a Tektronix 502 or 565 oscilloscope and recorded on linagraph paper using a Grass C4 camera or stored on magnetic tape (Phillips Analog - 7). A Grass S4 stimulator was used for nerve stimulation.

6. Analysis of Sensory Discharge

The frequency of discharge of those spindle endings studied during muscle stretch was determined from a direct display of their instantaneous frequency. To accomplish this the sequence below was followed. The stored action potentials were amplified, gated and then used to trigger a PDP - 12 Digital Computer. A computer program of instantaneous frequency analysis (Appendix B) encompassed a frequency range of 10 to 450 imp/sec and was accurate to within ± 5%. The computer output could be displayed as the instantaneous frequency of discharge of the sensory endings. The voltage of the

computer output signal varied with the reciprocal of the time interval between spikes. The output was displayed DC on one channel of a 565 Tektronix oscilloscope, the varying signal causing a shift in the DC baseline. The gated spikes were simultaneously amplified by a Grass 511 amplifier and the amplified output used to drive a Tektronix wave form generator (type 162). The wave form triggered a Tektronix pulse generator (type 161) from which a 200 microsecond pulse was fed into the upper beam CRT grid (Z axis modulation). Thus each action potential caused a momentary brightening of a cathode ray tube spot. The vertical deflection of the spot at this instant was proportional to the reciprocal of the time interval since the preceding action potential, thus giving a direct record of the frequency of discharge. A direct oscilloscope display of the reciprocal of the time interval between successive action potentials (i.e. instantaneous frequency) is shown in Appendix B.

The instantaneous frequency measurements were made by photographing the "dot" display on Grass Kymograph film no. 1 with a Grass C4 camera. The film image was then enlarged by means of a projector and the amplitude of the individual dots measured against a superimposed scale which represented the calibration of the computer output from 10 to 450 imp/sec. The computer program was calibrated by a wave form generator (Tektronix, Model 116).

7. Dynamic Index

The dynamic index (Crowe and Matthews, 1964) of 58 single sensory endings was calculated by subtracting the static frequency after ramp stretch from the peak frequency which occurs during ramp stretch. Crowe and Matthews (1964) called the difference between the frequency of discharge just before the end of the dynamic period of stretching and that occurring 0.5 sec later, the dynamic index. The choice of 0.5 sec as a period of measurement has no particular significance and different times would give somewhat different results depending upon how rapidly the sensory discharge adapts with time. In the present experiments the difference between the peak frequency during ramp stretch and that occurring at the final maintained length 0.5 sec after completion of the dynamic phase of stretching was used as a measure of the dynamic index of an ending (see Figure 1). The sensory discharge occurring during the application of the ramp stretch was termed the dynamic response, while the frequency of discharge 0.5 sec later was termed the static response.

8. Monosynaptic Testing

The effects of cooling the medial gastrocnemius muscle on the heteronymous monosynaptic reflex (MSR) from the lateral

gastrocnemius-soleus (LGS) nerve were studied in 12 decerebrate and 4 spinal cats. The animals were decerebrated by inter-collicular section under ether anaesthesia. Following decerebration four cats were made spinal by transverse sectioning of the spinal cord at the T_{10} level. The method of cord exposure and temperature maintenance was similar to that outlined above except that ventral roots L_6 - S_1 were cut immediately at the dura together with all dorsal roots below the level of S_1. Denervation of the left leg and hip included section of the following nerves: femoral, obturator, caudal femoral cutaneous, caudal cutaneous sural, lateral cutaneous of the thigh, superior and inferior gluteal, hamstring, lateral popliteal and medial popliteal except for its branches to MG muscle. The contralateral hindlimb was denervated by cutting the femoral, obturator, sciatic, hip and hamstring nerves.

Monosynaptic recordings were begun 3 to 4 hours after the cessation of ether anaesthesia. A single test shock was delivered to the central end of the cut LGS nerve through bipolar silver - silver chloride electrodes. Stimulus intensity ranged from 0.08 - 0.3 volts with 0.1 msec duration and a frequency of 0.5 Hz. The test shock was just sufficient to elicit a maximal MSR. Since the amplitude of the reflex response varied to some extent with each test shock the mean of 20 MSR's was used to plot changes in the MSR during muscle cooling. The MSR was recorded from either L_7 or S_1 ventral root, amplified with a P511 Grass amplifier, displayed on a Tektronix 502 oscilloscope and photographed with a

Grass C4 camera.

In experiments involving blocking of the MG nerve during muscle cooling the nerve was anaesthetized using an 0.3% procaine solution.. The solution was prepared by mixing procaine (20 mg/ml) with Ringer's solution. The solution was maintained at 37°C and applied to the nerve by means of a piece of filter paper one cm square. The filter paper was soaked in procaine solution, folded double and the MG nerve placed in the notch. MG nerve activity was monitored by recording the compound potential (elicited by stimulation of the MG nerve between the filter paper and the muscle) at a position 1.5 - 2.0 cm proximal to the filter paper. Recovery of the nerve was accomplished by bathing the MG nerve in Ringer soaked filter paper.

9. Statistical Analysis of Data

Values presented in the text show the mean ± standard error of the mean, unless it is otherwise stated. In the statistical analyses, the Fisher "t" Test was used to test for differences between means. A probability of less than 5% due to chance ($P < 0.05$) was chosen as the level of statistical significance.

IV. RESULTS

The experiments have confirmed that cooling of the relaxed hindlimb muscle in the cat initiated an afferent discharge, the 'cold response'* in previously silent sensory endings of de-efferented muscle spindles. The main finding was that this 'cold response' originated in fibres with conduction velocities of 20-65 m/sec, (Group II secondary ending range, Hunt, 1954). Two-thirds of the secondary endings studied became active when cooled (cold response secondary endings). All of the primary endings and the remaining secondary endings (non cold response secondary endings) were activated only by stretch of the muscle. Investigation of the sensory discharge of primary, 'cold response' and 'non cold response' secondary endings was performed by stretching the muscle a constant amplitude with a variety of velocities of muscle stretch. The results showed that the three types of sensory ending differed in their response to rate and amplitude of muscle stretch and their rate of adaptation. The group II endings which did not possess the 'cold response' had stretch responses similar to those classically

*Lippold et al., 1960 introduced the term 'cold response' to describe the spindle afferent discharge evoked by cooling the relaxed tenuissimus muscle.

ascribed to secondary endings, first described by Cooper (1959, 1961). The 'cold response' endings displayed properties intermediate between those of the primary and the 'non cold response' secondary endings. Selective stimulation of secondary endings by cooling of the de-efferented muscle combined with monosynaptic testing (Lloyd, 1946a, b) provided a method for studying the role of secondary endings in spinal reflex activity. The main finding was that in decerebrate and spinal preparations, cooling of the medial gastrocnemius muscle resulted in facilitation of the heteronymous monosynaptic reflex of its synergist, the lateral gastrocnemius.

A. In Vivo Response of Spindle Sensory Endings to Cooling in Relaxed and Stretched Medial Gastrocnemius Muscle in the Cat.

1. Relaxed Muscle

The response to muscle cooling was studied in single afferent fibres of muscle spindles. Figure 2 shows the type of recording obtained from a single afferent and illustrates the 'cold response'. Each spindle afferent was identified by the response of the muscle receptor to stretch (A), the presence of a pause of

FIGURE 2

Illustrates the criteria employed for identification of a muscle spindle receptor (response to stretch, pause during muscle contraction), and the 'cold response'. The records show the activity in a single afferent fibre (conduction velocity 48 m/sec) from a muscle spindle secondary ending in the de-efferented medial gastrocnemius muscle of an anaesthetized cat.

The top line of each record represents afferent activity. The bottom line in A and B shows stretch of the muscle. Temperature of the muscle as indicated:

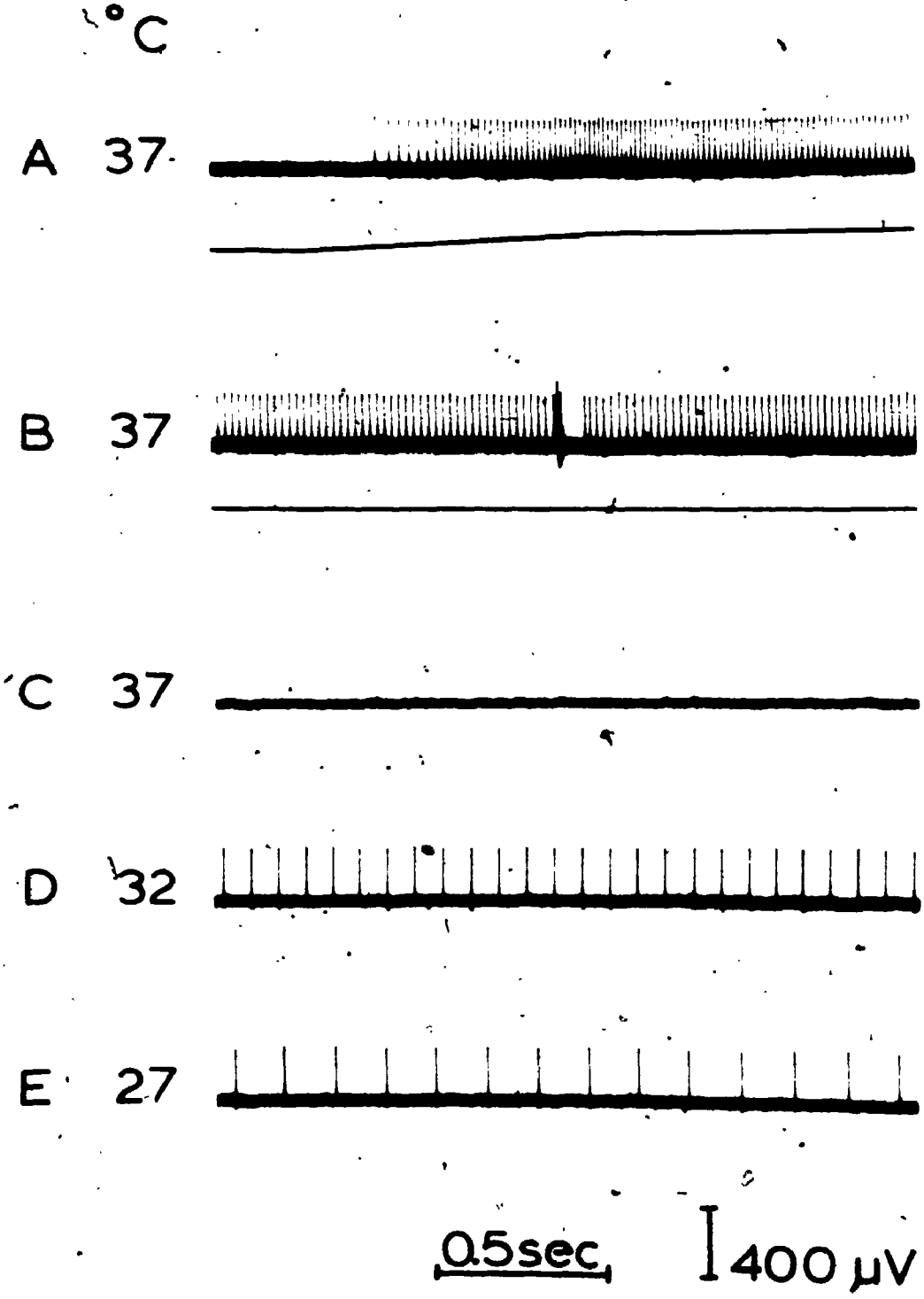
A. Response of the ending during ramp extension (10 mm/sec) and during maintained stretch (10 mm).

B. After a minute of constant stretch, a twitch of the muscle was elicited by electrical stimulation of the ventral root; this caused a pause in afferent activity, characteristic of muscle spindles.

C. In the relaxed muscle maintained at 37°C the receptor was silent.

D. Selective cooling of the muscle initiated a spontaneous discharge ('cold response') of the reteptor beginning at 32.5°C and reaching a maximum of 12 imp/sec at 32°C.

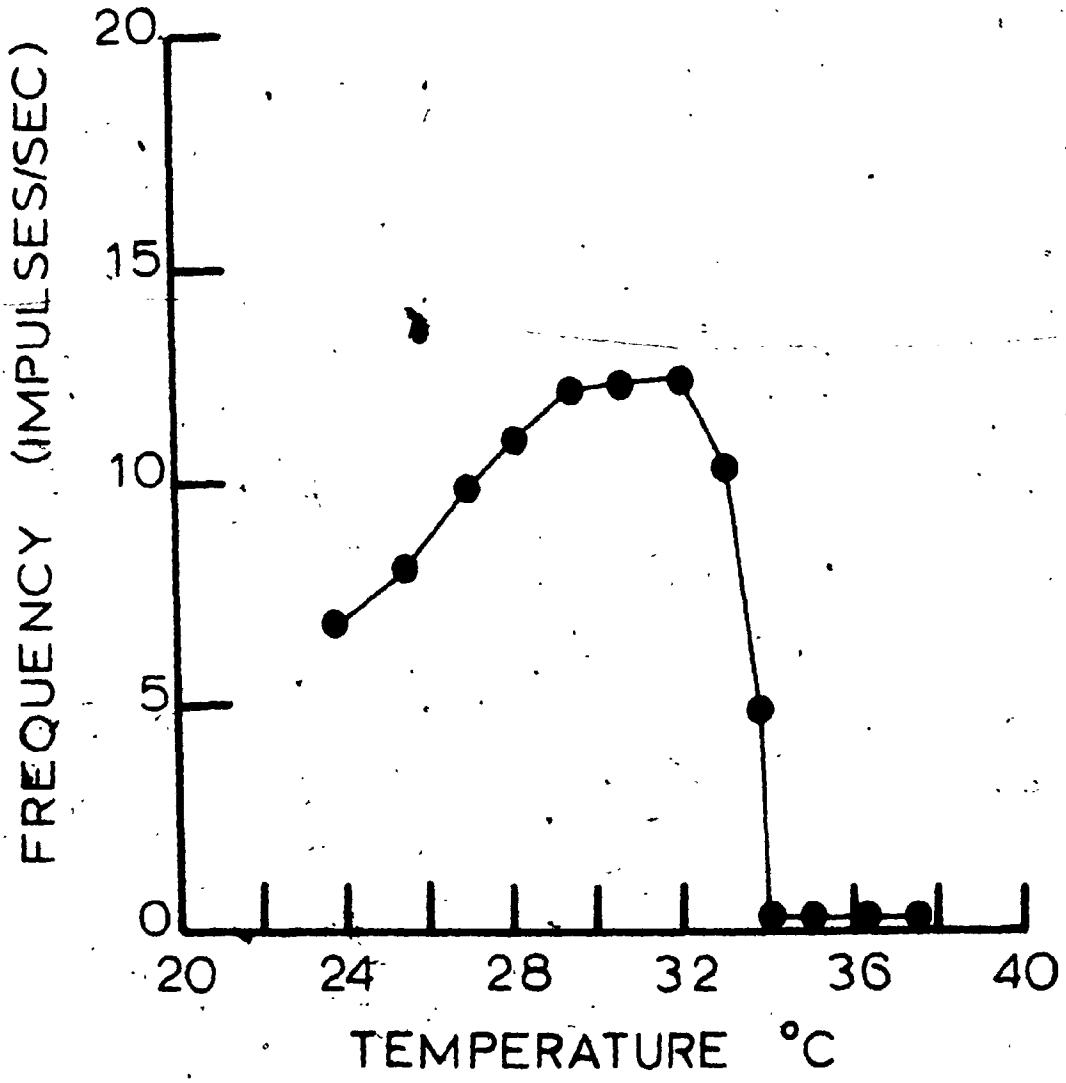
E. Further cooling of the muscle resulted in a gradual decrease in the afferent discharge until at 27°C the frequency was 7 imp/sec.


°C
A 37
B 37
C 37
D 32
E 27
0.5sec
400 µV

discharge during muscle contraction (B) and the conduction velocity of the afferent fibre. There was no activity from the spindle ending in the relaxed muscle maintained at 37°C (C). When it was gradually cooled, an afferent discharge, the 'cold response', began at 32.5°C, reached a maximum activity at 32°C (D) and decreased with further cooling (E). Figure 3 illustrates the characteristic changes in the 'cold response' during cooling of the relaxed muscle in the temperature range used throughout the experiments (37° - 24°C). At 33.8°C the sensory ending began to fire abruptly with a regular discharge. The frequency, initially 5 imp/sec, increased to a maximum of 12 imp/sec at 31.5°C and declined with further cooling. At any one temperature the frequency of impulses was constant and non adapting. The threshold temperature and cooling curves were reproducible even with repeated cooling and rewarming of the muscle. The cooling curves of different sensory endings however, differed with respect to the threshold temperature and the maximum activity obtained as well as the temperature at which maximum activity occurred. The mean temperature of initiation of sensory discharge for 30 'cold response' spindle endings was 31.7, S.E.M. ± 0.4°C (range 27.6 - 35.0°C) and the maximum frequency reached 11.8, S.E.M. ± 0.6 imp/sec (range 6.3 - 18.0 imp/sec) at 29.5, S.E.M. ± 0.5°C (range 23.2 - 32.6°C). These values represent the temperature recorded at the medial surface of the muscle but are relative to the actual temperatures of the endings within the muscle.

FIGURE 3

Example of the relationship between frequency of discharge of a spindle ending and temperature during cooling of the relaxed de-efferented medial gastrocnemius muscle. Initially silent, this unit (conduction velocity 47 m/sec) became active at 33.8°C and decreased its activity with further cooling.


FREQUENCY (IMPULSES/SEC)
20
15
10
5
0
20
24
28
32
36
40
TEMPERATURE °C

than the dynamic response of the primary endings.

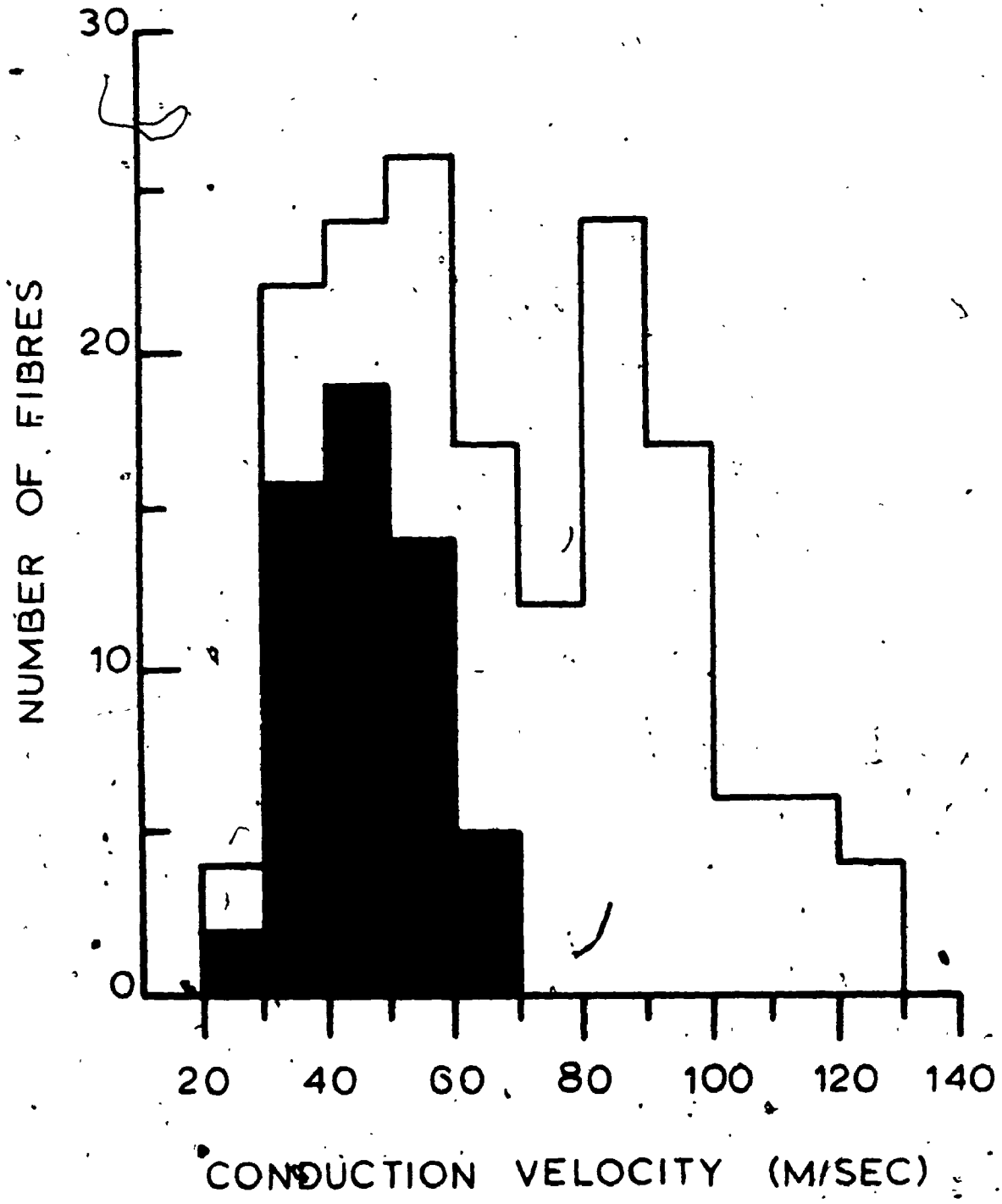
In marked contrast to the primary and CR type endings the NCR sensory endings showed only a slight increase in discharge frequency during the dynamic period of stretching. Figure 11 illustrates this point. The dynamic response of the NCR ending became appreciable only at velocities of stretching so high that there was time for only a few impulses to be discharged during the actual stretch. Also higher velocities of stretching did not progressively increase the maximum frequency of discharge. In fact the sensory discharge rate during the application of stretch hardly exceeded that reached during a maintained stretch. Thus the response characteristics of the NCR ending are similar to those described by Cooper (1959, 1961) for secondary endings as opposed to primary endings.

2. Comparison of the Dynamic Indices of Primary, CR and NCR Secondary Endings

According to Jansen and Matthews (1962a) and Crowe and Matthews (1964) the dynamic component of the response of an ending to stretching may be assessed by measuring the decrease in frequency of its discharge that occurs on completion of the dynamic phase of stretching as described in the methods. The

FIGURE 4

Distribution of conduction velocities of afferents from 162 muscle spindle sensory endings of the medial gastrocnemius muscle in 40 cats. Only fibres in the conduction velocity range of 20-65 m/sec responded to muscle cooling (shaded area). These endings, classified as secondary endings, (Hunt, 1954) represented 35% of all the endings studied and 65% of the secondaries.


30
20
10
0
NUMBER OF FIBRES
20
40
60
80
100
120
140
CONDUCTION VELOCITY (M/SEC)

(hereafter referred to as NCR endings). The mean conduction velocities of the 76 primary, 56 CR and 30 NCR endings of Figure 4 were 82.8, S.E.M. ± 2.9; 45.2, S.E.M. ± 1.3; and 48.8, S.E.M. ± 2.3 m/sec respectively. The mean conduction velocity of the 56 CR secondary endings was not significantly different from that of the 30 NCR secondary endings; however, further differences between these two types of ending were found in the subsequent analysis of their response to stretch.

3. Response of Muscle Sensory Endings to Cooling in Stretched Muscle

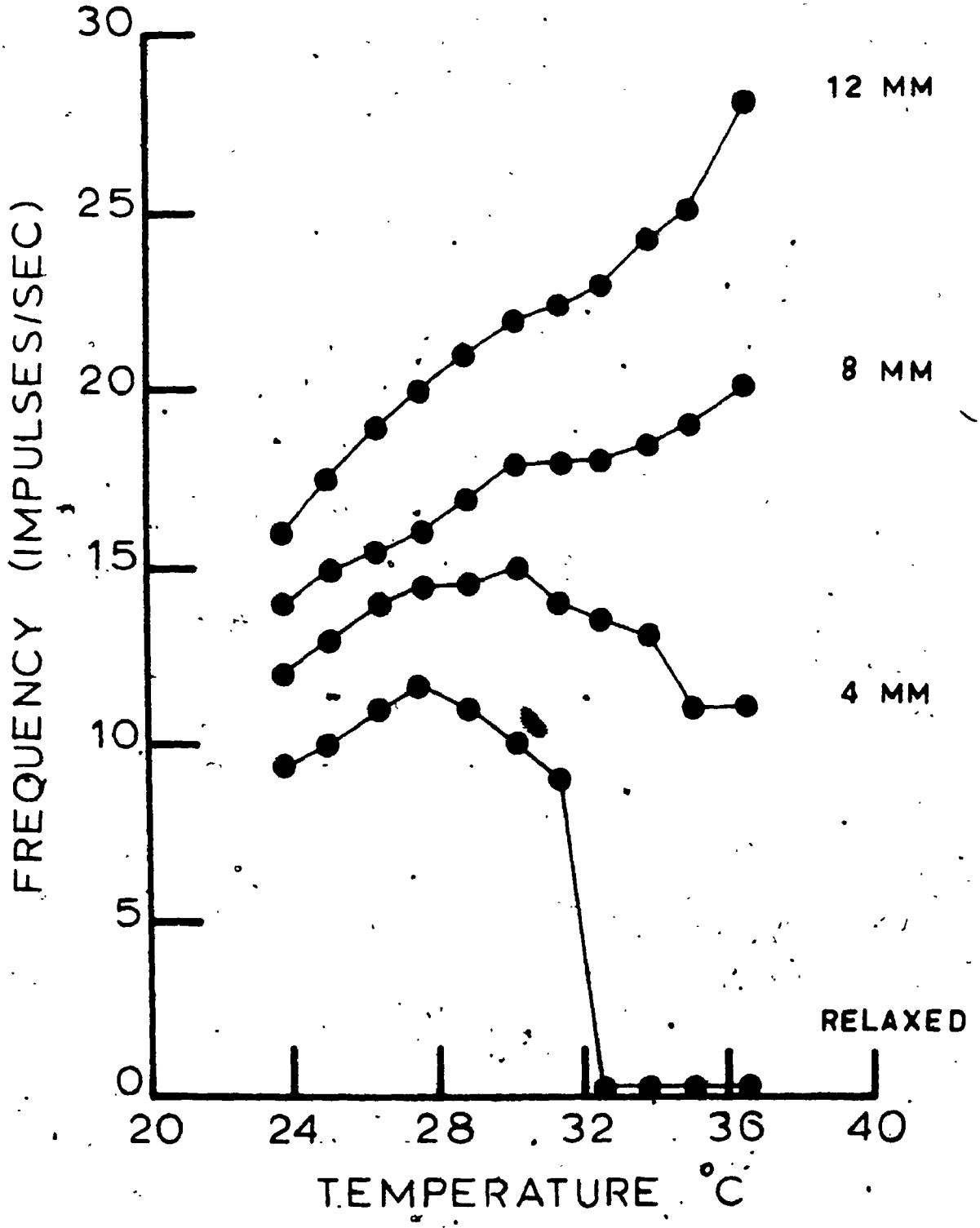
Eldred et al., (1960) found that the afferent activity of both primary and secondary endings of the stretched gastrocnemius muscle of the cat was decreased during muscle cooling. This finding seems contradictory to the above finding (and that of Lippold et al., 1960) of the response of secondary endings to muscle cooling. An explanation for this apparently conflicting view was found in the present investigation, when the effect of muscle cooling on muscle receptors was investigated in relaxed and stretched muscle. Generally in muscle stretched 8-12 mm, cooling caused a decrease in discharge of all the muscle receptor endings; primary, CR and NCR secondary and Golgi tendon organs.

a. CR Secondary Endings

During moderate stretch of the muscle, 4 mm, a steady discharge of the 'cold response' endings occurred which increased with cooling in a manner similar to the response seen in the relaxed muscle. With stretches of 8 to 12 mm however, cooling produced an almost consistent decrease in discharge. Because of variations in the threshold temperature for the 'cold response' it was not possible to construct curves showing the mean response of several endings but Figure 5 illustrates the relationship between the discharge and muscle temperature for a typical single CR ending with the muscle relaxed and then maintained at 4, 8 and 12 mm from the initial length. During muscle stretch the sensory activity was monitored for four minutes prior to muscle cooling to ensure that the receptor ending had attained a steady rate of discharge. The 'cold response' began in the relaxed muscle at 31.5°C with an initial frequency of 9 imp/sec, reached a maximum of 11.5 imp/sec at 27.6°C and then decreased to 9 imp/sec at 24°C. A maintained 4 mm stretch of the muscle produced a steady discharge of 11 imp/sec at 36.5°C. Subsequent cooling caused a gradual increase in frequency to a maximum of 15 imp/sec at 31°C. Although the temperature response curve was similar to the previous one, the frequency for any given temperature was higher. With an 8 mm stretch the sensory discharge

FIGURE 5

Shows changes in the response of a single 'cold response' secondary ending (afferent conduction velocity 38 m/sec) to cooling during maintained stretch at the lengths indicated. During a slight stretch of the muscle (4 mm) the 'cold response' was still readily apparent, but now began at a higher temperature and had a higher maximum frequency of discharge. With further stretch, up to 12 mm, the characteristic 'cold response' was no longer apparent and the sensory discharge simply declined with decrease in temperature.


30
25
20
15
10
5
0
FREQUENCY (IMPULSES/SEC)
12 MM
8 MM
4 MM
RELAXED
20
24
28
32
36
40
TEMPERATURE °C

was 20 imp/sec at 36°C. Initially the rate gradually decreased during muscle cooling, remained constant between 33 - 30°C but decreased with further cooling, so that at 24°C it had fallen to 30% of the initial discharge rate. Stretching the muscle 12 mm evoked a steady discharge of 28 imp/sec (36.5°C) which declined to 16 imp/sec at 24°C (43%).

Thus slightly stretching the muscle 4 mm resulted in an increase in frequency and decrease in threshold of the 'cold response' discharge. However cooling with the muscle under further stretch (8 mm, 12 mm) 'masked' the 'cold response' (see also Figure 16) and a depressant effect such as that reported by Eldred et al., (1960) became evident. Presumably the 'cold response' from secondary endings could have been masked in the experiments of Eldred and his co-workers, as the spindles, under stretch, were already firing at normal body temperature.

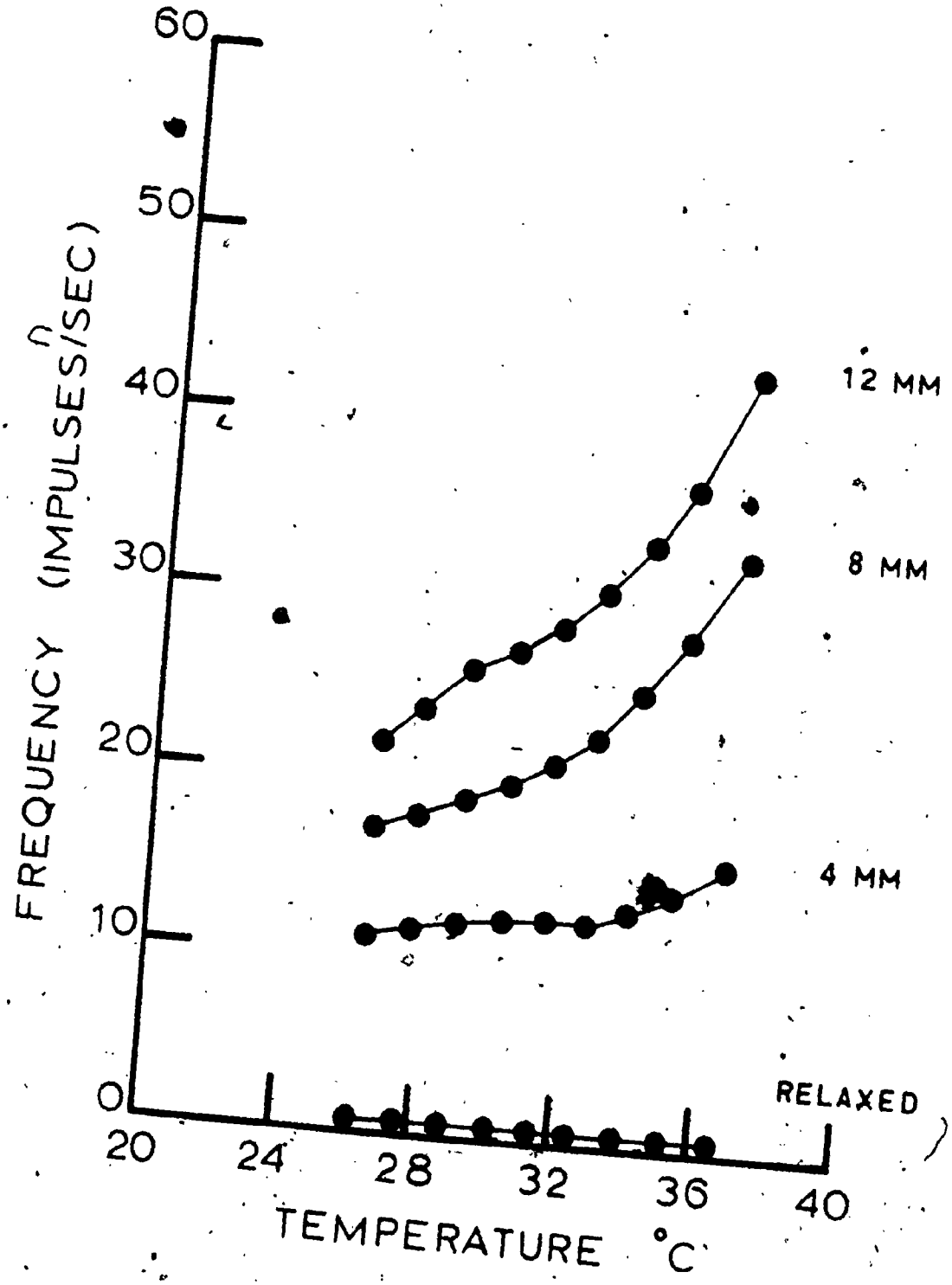
b. NCR Secondary Endings

Muscle receptors which did not have a 'cold response' responded to stretch and during a maintained stretch gave a steady discharge which decreased during muscle cooling. The sensory discharge for all receptors was monitored for four minutes before muscle cooling was initiated in order to ensure a constant

control frequency. Figure 6 shows the effect of muscle cooling on the mean discharge of three NCR secondary endings. The endings remained silent during cooling of the relaxed muscle; however the steady sensory discharge elicited by maintained muscle stretch of 4, 8 or 12 mm was decreased during muscle cooling. The discharge slowing ranged from a few impulses per second at 4 mm stretch for a temperature decrease of 10°C to a mean of 22 imp/sec at 12 mm stretch for a similar temperature change. The curves relating frequency to temperature show a more prominent decrease in discharge, when the muscle is stretched to greater lengths from the resting position. At 4 mm of stretch the mean rate of discharge dropped by 37% from the pre-cooling level over the temperature range of 36.5 - 26°C. At the greater lengths of stretch (8 and 12 mm) the mean frequency decreased to 49% and 50% of the initial value respectively over the 10°C change. In addition the depressant effect of muscle cooling on the stretch evoked sensory discharge was not linear. At each length of stretch the frequency declined more rapidly during cooling from 36.5 - 32°C than during cooling from 32 - 26°C. The sensory discharge at 32°C with 4, 8 and 12 mm stretch had fallen to 80, 70 and 64% of its total decrease from 36.5 to 26°C.

FIGURE 6

The effect of muscle cooling on the stretch evoked mean sensory discharge of three NCR secondary endings. The NCR endings remained silent during cooling of the relaxed muscle; however, the steady sensory discharge elicited by maintained stretch of the muscle at 4, 8, 12 mm decreased during muscle cooling. Conduction velocities of the endings were 28, 33, 41 m/sec.


60
50
40
30
20
10
0
FREQUENCY (IMPULSES/SEC)
12 MM
8 MM
4 MM
RELAXED
20
24
28
32
36
40
TEMPERATURE °C

c. Primary Endings

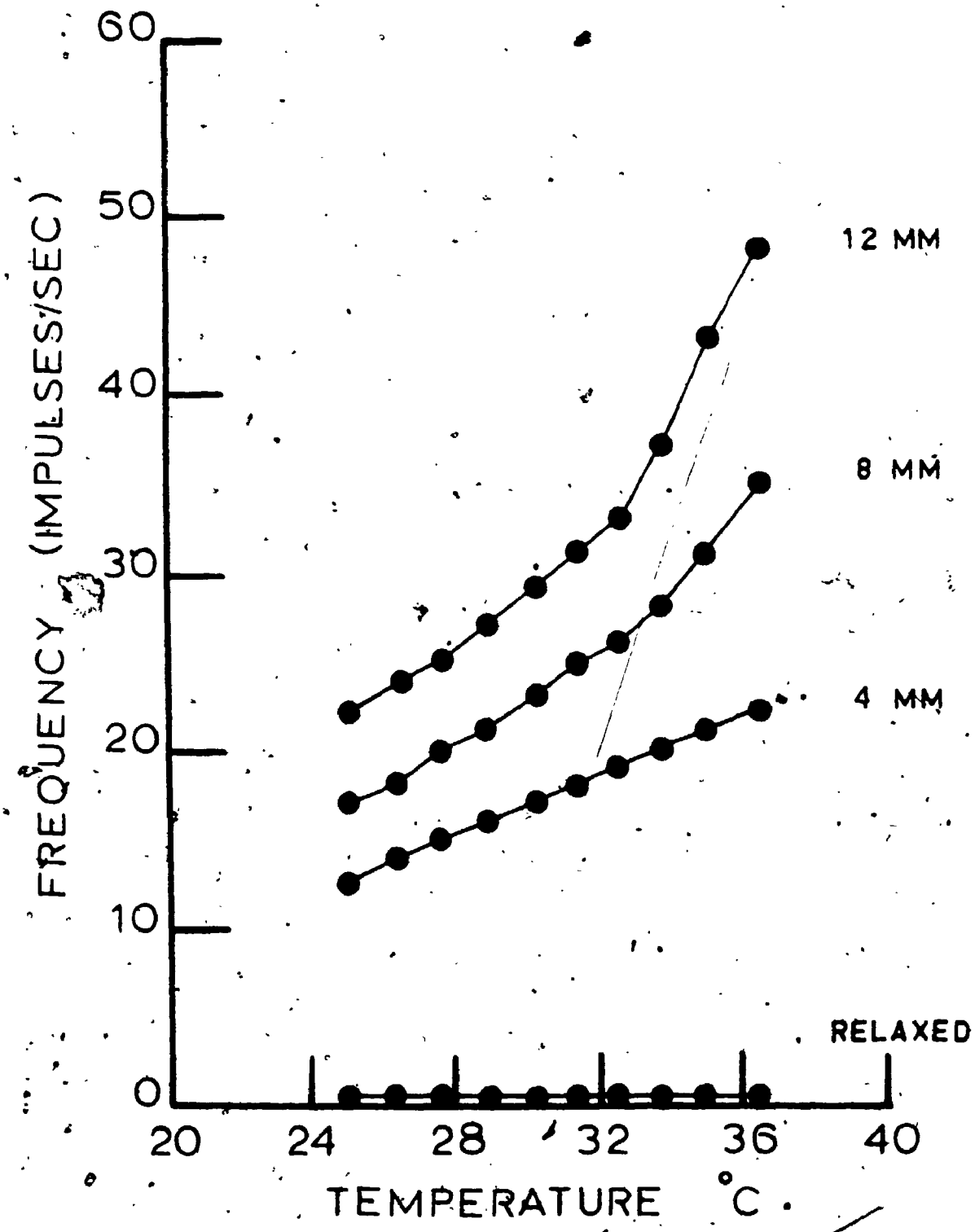
Figure 7 illustrates mean changes in the frequency of five primary endings during cooling of the medial gastrocnemius muscle maintained at different increments of stretch from the resting length. Cooling of the relaxed muscle did not initiate a sensory discharge; however, the steady firing evoked by maintained muscle stretch was slowed with cooling. The decrease in discharge of each primary ending was more prominent during cooling with the muscle maintained at greater lengths. The mean discharge of the five endings under 4 mm stretch fell 41% from the mean initial frequency at 36.5°C over the 36,5°C to 25°C cooling range and 49 and 52% with the muscle stretched 8 and 12 mm respectively. With moderate stretch, 4 mm, the decrease in mean frequency was linear during muscle cooling. At greater lengths, 8 and 12 mm, the frequency declined rapidly with cooling to 32°C and more gradually with further cooling. The mean sensory discharge had fallen to 58 and 50% at 32°C of its total decrease from 36.5 to 25°C for 8 and 12 mm respectively.

d. Golgi Tendon Organs

The effect of temperature on the sensory discharge of Golgi

FIGURE 7

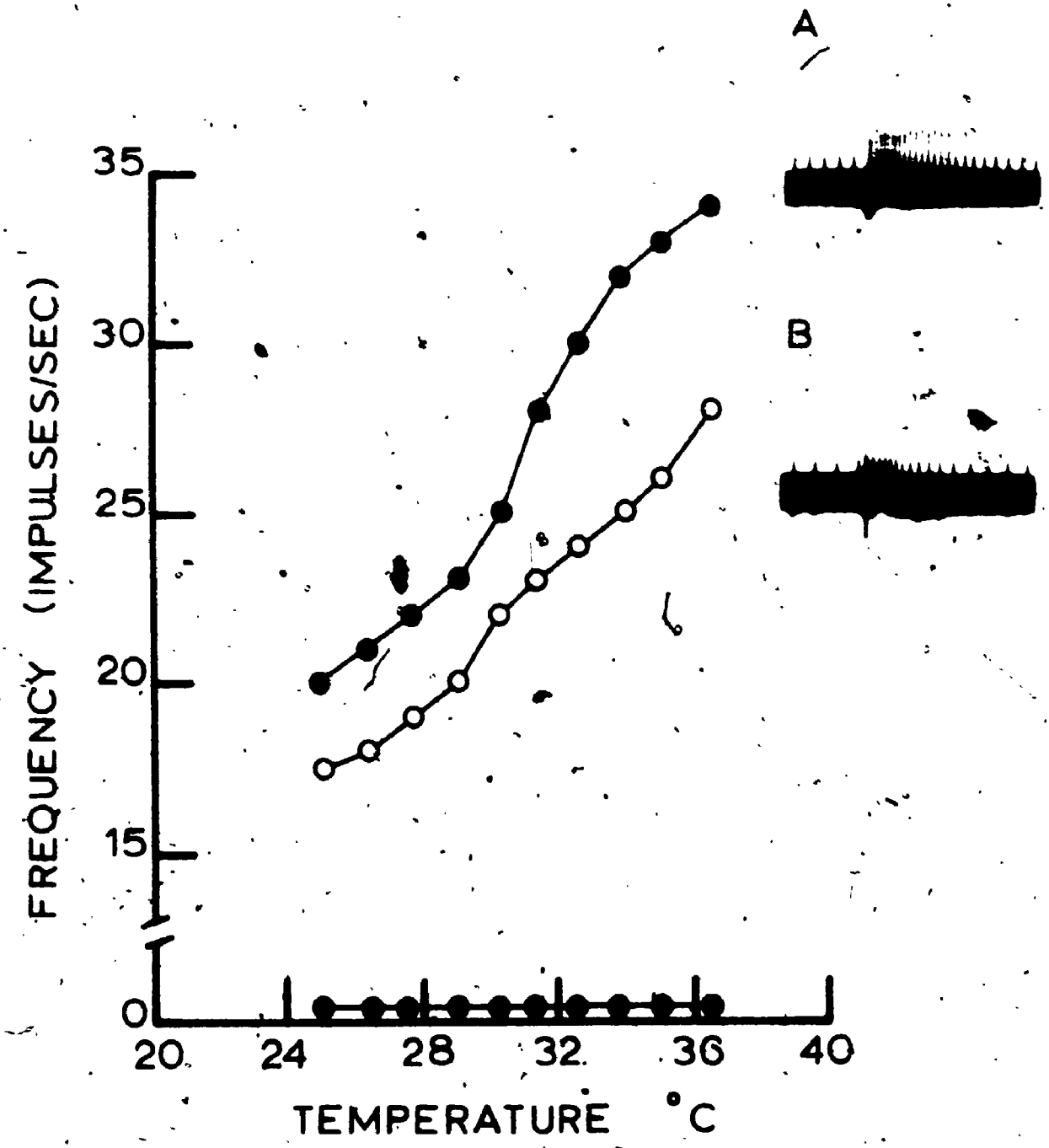
The effect of muscle cooling on the stretch evoked sensory discharge of primary endings. The mean values of 5 primary endings are plotted over the cooling temperature range 36.5 - 25°C. The primary endings remained silent during cooling of the relaxed muscle; however, the steady sensory discharge elicited by maintained stretch (4, 8, 12 mm) was decreased during muscle cooling. Conduction velocities of the receptor afferents were 82, 90, 93, 98 and 104 m/sec.


60
50
40
30
20
10
0
FREQUENCY (IMPULSES/SEC)
12 MM
8 MM
4 MM
RELAXED
20
24
28
32
36
40
TEMPERATURE °C

tendon organs was also examined. This was thought to be of some importance, since the tendon organ also responds to muscle stretch. Presumably cooling would act directly on the Golgi tendon receptor ending or indirectly on the muscle. It was hoped that these results would provide some idea of how much of the change in spindle response during cooling alone or cooling with stretch could be attributed to a direct effect of low temperature on the sensory ending itself and how much could be attributed to other factors. Golgi tendon organs remained silent during cooling of the relaxed muscle; however, the steady sensory discharge elicited by muscle stretch was decreased during muscle cooling. Figure 8 illustrates the behaviour of two afferent units, identified as Golgi tendon organs, when the muscle was gradually cooled. Since tendon organs have a higher threshold to stretch than muscle spindles, (Matthews, 1933; Hunt and Kuffler, 1951; Jansen and Rudjord, 1964) it was necessary to stretch the muscle to greater lengths from its initial length to elicit a steady discharge. The rate of discharge of receptor A dropped 59% from the initial frequency at 36.5°C, during cooling of the muscle to 25°C. The second tendon receptor (B) slowed in discharge during cooling from 28 imp/sec at 36.5 to 17.5 imp/sec at 25°C, a decline to 63% from the pre-cooling rate. These rates of decrease are similar to those described for primary and secondary endings and suggest that muscle cooling has similar effects upon the stretch evoked sensory response of both spindles

FIGURE 8

The effect of muscle cooling on the stretch evoked sensory discharge of two different Golgi tendon organs, with afferent conduction velocities of A_1 - 91 m/sec; B_1 - 87 m/sec. They remained silent during cooling of the relaxed muscle but the steady frequency elicited by muscle stretch of 12 mm was decreased by cooling. Inserts show the acceleration in response of each unit during muscle twitch confirming that they were tendon organs.


A
B
35
30
25
20
15
0
FREQUENCY (IMPULSES/SEC)
20
24
28
32
36
40
TEMPERATURE °C

and tendon organs.

It is obvious from the examples of Figures 5, 6, 7 and 8 that temperature has a similar effect upon the stretch evoked sensory discharge of primary, CR, NCR endings and Golgi tendon organs. The findings imply that muscle cooling has the same depressant effect upon the stretch evoked sensory discharge of both primary and NCR endings. It may further be seen that CR endings behave in a similar manner, if the muscle is sufficiently stretched (> 8 mm) during muscle cooling.

B. Comparison of Discharge Characteristics of the Primary, CR Secondary and NCR Secondary Endings at Normal Body Temperature.

1. Effects of Linear Stretch on Spindle Ending Discharge

The above results have shown that cooling the relaxed medial gastrocnemius muscle caused a 'cold response' only in some secondary endings of muscle spindles. Further differences between these CR secondary endings and the primary and NCR endings were found in an investigation of the responses of the three types of spindle ending to muscle stretch.

It is well known that the afferent discharge from a muscle

spindle, evoked by stretching the muscle containing it, consists of two parts, a 'static response', related to the amount of extension and a 'dynamic response', related to the rate of extension (Matthews, 1933). These responses to muscle stretch were studied in 58 afferent fibres (21 from primary, 26 from CR, 11 from NCR endings). The muscle was stretched a distance of 10 mm from the initial length with velocities of 5 mm/sec to 70 mm/sec. It was found that the primary and CR endings were sensitive to the dynamic and static stimulus of muscle stretch, while the NCR endings were mainly sensitive to the static component of muscle stretch.

An example of the instantaneous response patterns of two primary endings is shown in Figure 9. The primary ending in A had a large dynamic response at all rates of stretch. The frequency of discharge of the dynamic component increased progressively with increases in stretch velocities up to 60 mm/sec. There was an abrupt fall in the frequency on completion of the dynamic period of stretching, the decay in discharge frequency being more prominent at the higher velocities of stretching. The static discharge of the ending was independent of the velocity of stretch. Although the majority of the primary endings studied behaved in this way, three of the primary endings in the present study resembled unit B of Figure 9 in their response pattern. As illustrated the discharge of the ending increased slowly during stretch and fell gradually to a static level at all

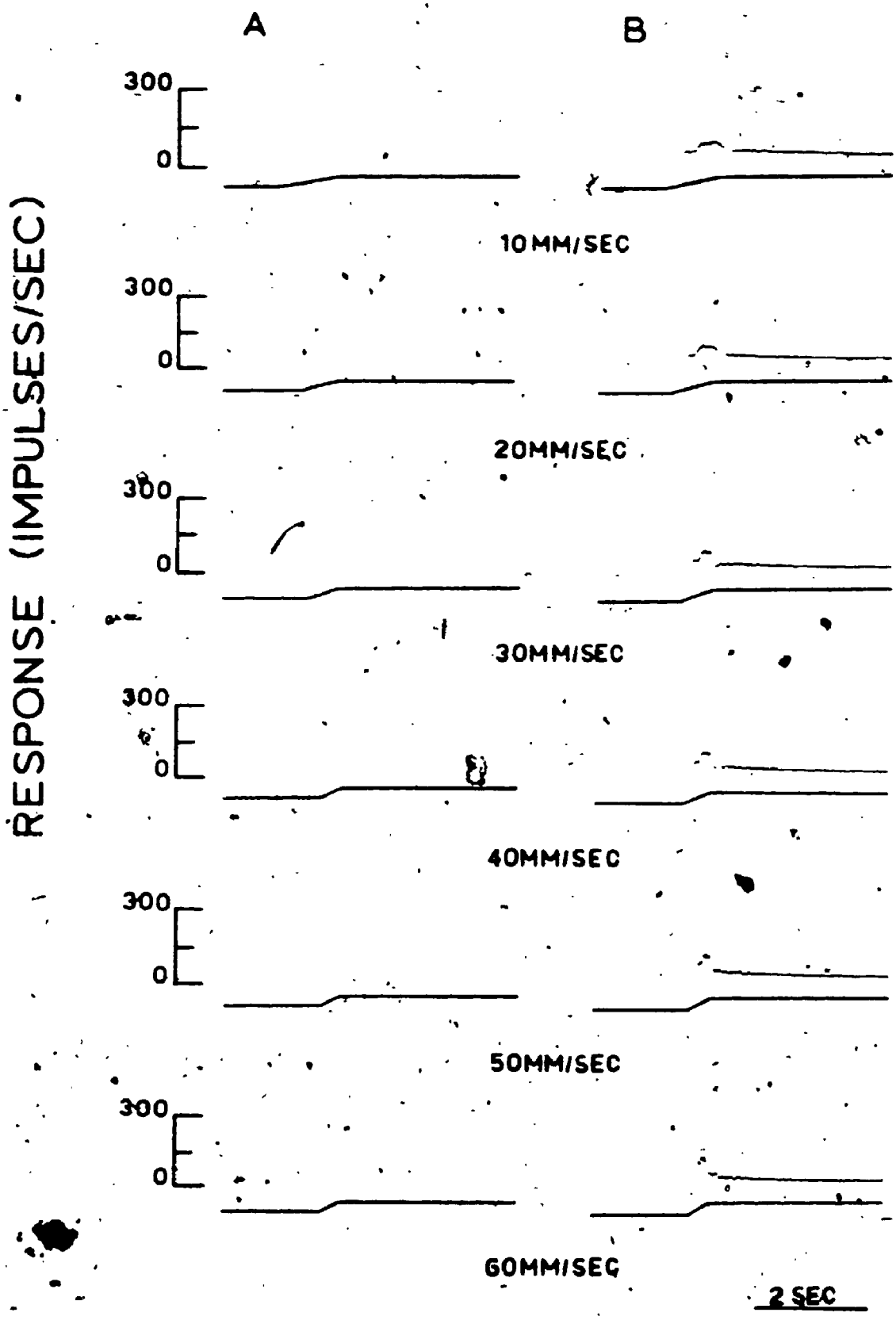
FIGURE 9

Records illustrating the afferent response of two primary endings to a 10 mm stretch of the medial gastrocnemius muscle from its initial length at velocities of 10 to 60 mm/sec. Each spot represents an action potential, and its height above zero is the reciprocal of the time interval since the preceding action potential, i.e. the instantaneous frequency of discharge. The bottom line indicates changes in the length of the muscle.

The majority of primary endings showed responses similar to those shown in A; that is, a rapidly rising dynamic component and rapid adaptation during maintained stretch.

Three primary endings (14%) showed responses similar to B; that is, a comparatively slow rising dynamic phase and slow adaptation during maintained stretch.

Conduction velocity of the afferents: A - 90 m/sec; B - 104 m/sec; muscle temperature 37°C.


A
B
300
0
10MM/SEC
20MM/SEC
30MM/SEC
40MM/SEC
50MM/SEC
60MM/SEC
2 SEC
RESPONSE (IMPULSES/SEC)

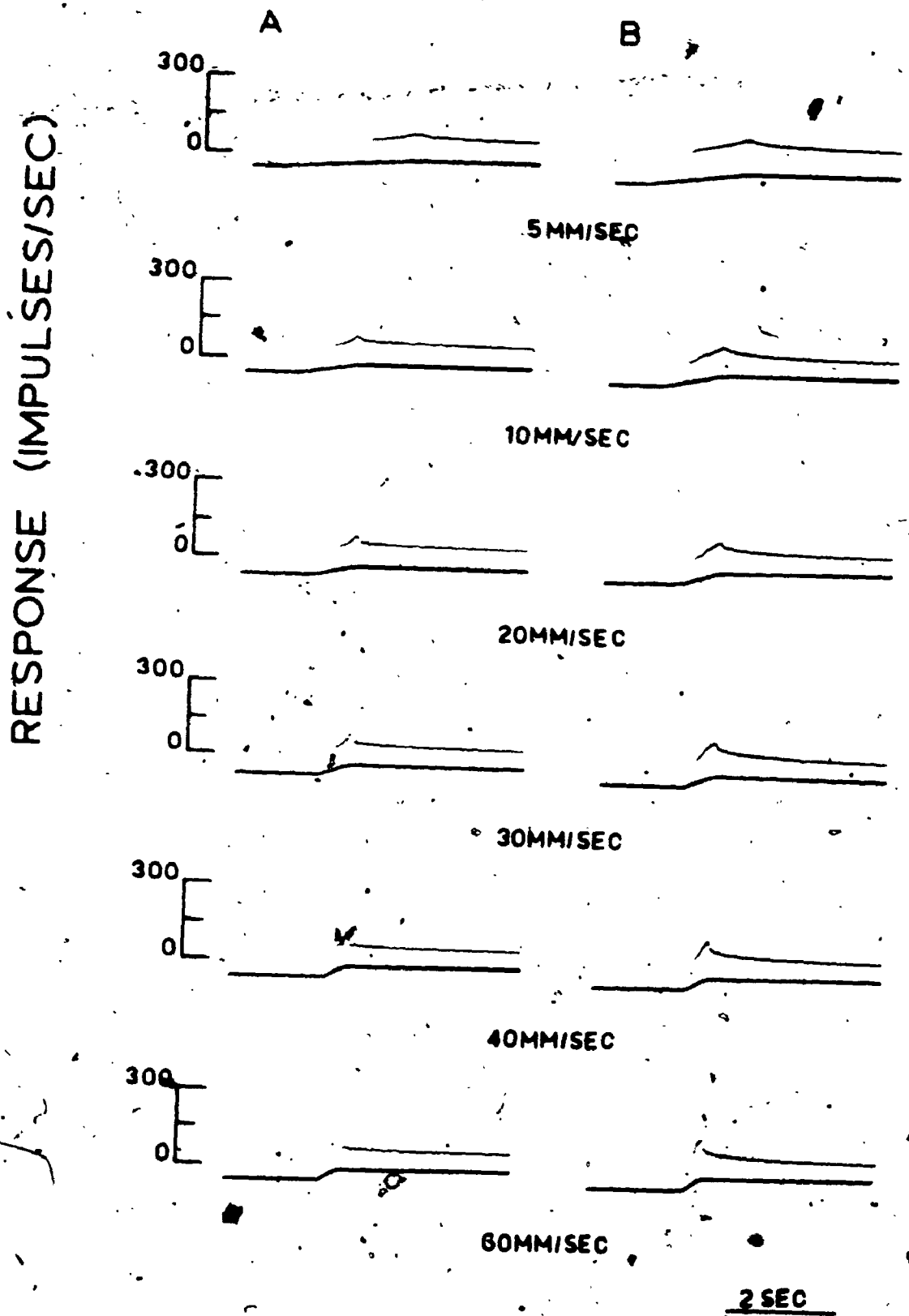
velocities of stretch.

The CR secondary endings were also sensitive to the dynamic stimulus of muscle stretch. This is illustrated in Figure 10 which shows the behaviour of two CR secondary endings tested in the same way as the primary endings. Part B of Figure 10 demonstrates the response of a typical CR secondary ending. The response was similar to that of the primary endings; the frequency of discharge of the CR ending increased progressively as the rate of stretch increased and its static response was independent of the velocity of stretch. At the end of the dynamic phase of stretching a gradual decline in discharge frequency was evident, whereas a more abrupt decline occurred in the frequency of the primary ending. The majority of CR secondaries possessed the typical pattern of Figure 10B; however an occasional CR secondary discharge pattern was found to resemble that of the primary afferents. Examination of this afferent discharge pattern during muscle stretch showed that the fall in frequency occurred abruptly at the end of the dynamic phase of stretching. This atypical pattern is illustrated in Figure 10A. Such responses were seen in only two CR secondaries (8%) but they are of some interest, because of their similarity to the typical primary discharge. Thus the CR secondary ending is appreciably sensitive to the velocity component of muscle stretch; however the dynamic response evoked during the application of stretch is less

FIGURE 10

Response of two CR secondary endings to stretch. Parameters of stretch and method of recording as in Figure 9. The dynamic phase of the response in both A and B was qualitatively similar, but slightly less (quantitatively) than that of the primary endings. There was a dynamic response which increased in amplitude with increase in velocity of stretch. As illustrated in B, usually the response fell gradually at the end of ramp stretch. In some endings (A) the response was similar to that of the primary ending, in that, at the end of ramp stretch, the frequency fell abruptly.

Conduction velocity of the afferents: A - 40 m/sec; B - 48 m/sec; muscle temperature 37°C.


A
B
300
0
RESPONSE (IMPULSES/SEC)
5MM/SEC
10MM/SEC
20MM/SEC
30MM/SEC
40MM/SEC
60MM/SEC
2 SEC

than the dynamic response of the primary endings.

In marked contrast to the primary and CR type endings the NCR sensory endings showed only a slight increase in discharge frequency during the dynamic period of stretching. Figure 11 illustrates this point. The dynamic response of the NCR ending became appreciable only at velocities of stretching so high that there was time for only a few impulses to be discharged during the actual stretch. Also higher velocities of stretching did not progressively increase the maximum frequency of discharge. In fact the sensory discharge rate during the application of stretch hardly exceeded that reached during a maintained stretch. Thus the response characteristics of the NCR ending are similar to those described by Cooper (1959, 1961) for secondary endings as opposed to primary endings.

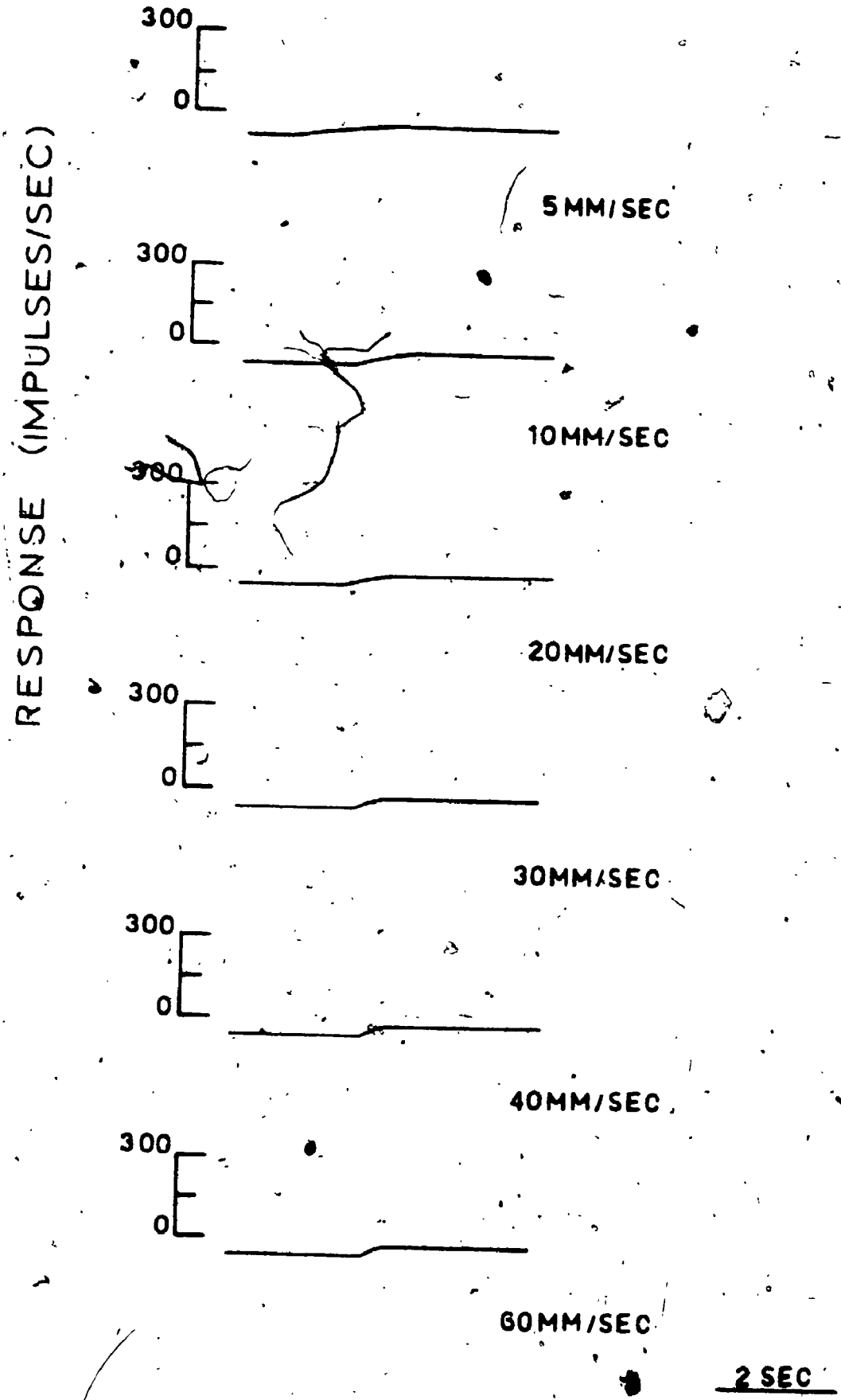
2. Comparison of the Dynamic Indices of Primary, CR and NCR Secondary Endings

According to Jansen and Matthews (1962a) and Crowe and Matthews (1964) the dynamic component of the response of an ending to stretching may be assessed by measuring the decrease in frequency of its discharge that occurs on completion of the dynamic phase of stretching as described in the methods. The

FIGURE 11

Illustrates the response of an NCR secondary ending to stretch. Parameters of stretch and recording method as in Figure 9. The discharge during the stretch was much smaller than that of the primary and CR endings even at high stretch velocities and hardly exceeded that occurring during maintained stretch (static component).

Conduction velocity: 55 m/sec; muscle temperature 37°C.


RESPONSE (IMPULSES/SEC)
300
0
5MM/SEC
300
0
10MM/SEC
300
0
20MM/SEC
300
0
30MM/SEC
300
0
40MM/SEC
300
0
60MM/SEC
2 SEC

dynamic index provides a convenient measure of the velocity responsiveness of an ending over and above its responsiveness to a maintained stretch of the muscle. In the present experiments, the difference between the peak frequency during ramp stretch and that occurring at the final length 0.5 sec after completion of the dynamic phase of stretching was used as a measure of the dynamic index of an ending.

The main finding from 26 experiments was that the dynamic indices of primary endings (afferent with conduction velocities > 72 m/sec) were generally greater at all velocities of stretch than those with endings with lower afferent conduction velocities (< 72 m/sec). This is illustrated in figure 12 which shows the mean dynamic index of 21 primary, 26 CR secondary and 11 NCR secondary endings at successively increasing velocities of stretch. For the primary and CR secondary endings, increasing the velocity of stretch increased the mean dynamic indices, but at any given velocity the mean dynamic index was always consistently greater for the primary endings than for the CR secondary endings. In contrast, the mean dynamic index of the NCR secondary endings was only slightly increased with increasing velocities of stretch. For each stretch velocity there was a significant difference (t test) between the dynamic indices of the primary and CR secondary endings ($P < 0.01$) and between the primary and NCR secondary endings ($P < 0.01$). Similarly the dynamic indices of the CR

2 3

OF/DE

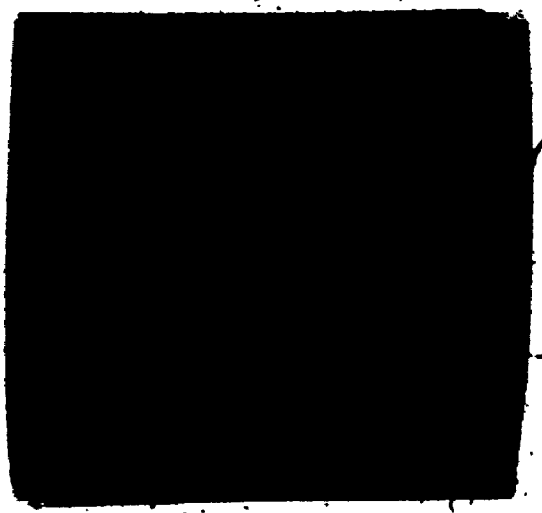
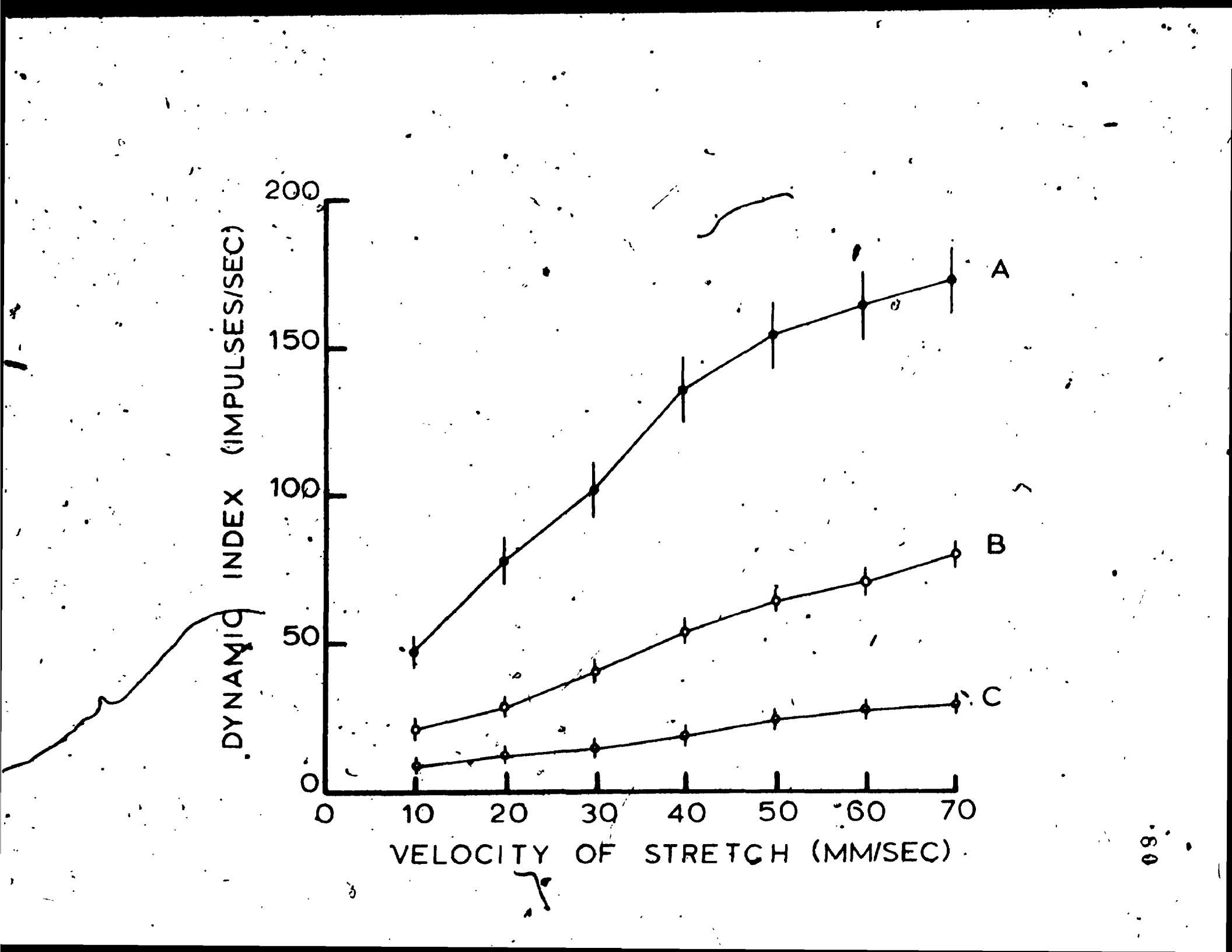


FIGURE 12

Comparison of the mean dynamic index of 21 primary (A), 26 CR secondary (B) and 11 NCR secondary (C) endings subjected to various velocities of stretch (10-70 mm/sec) and a constant amplitude (10 mm). The mean dynamic indices of the CR secondary endings occupied a range of values intermediate between those of the primary and NCR endings. The dynamic indices for the CR secondary endings were significantly less ($P < 0.01$) than the primary and greater ($P < 0.01$) than the NCR endings for any velocity of stretch. Muscle temperature 36 - 37°C.

Vertical lines represent the standard error of the mean.


200
150
100
50
0
DYNAMIC INDEX (IMPULSES/SEC)
A
B
C
0
10
20
30
40
50
60
70
VELOCITY OF STRETCH (MM/SEC)

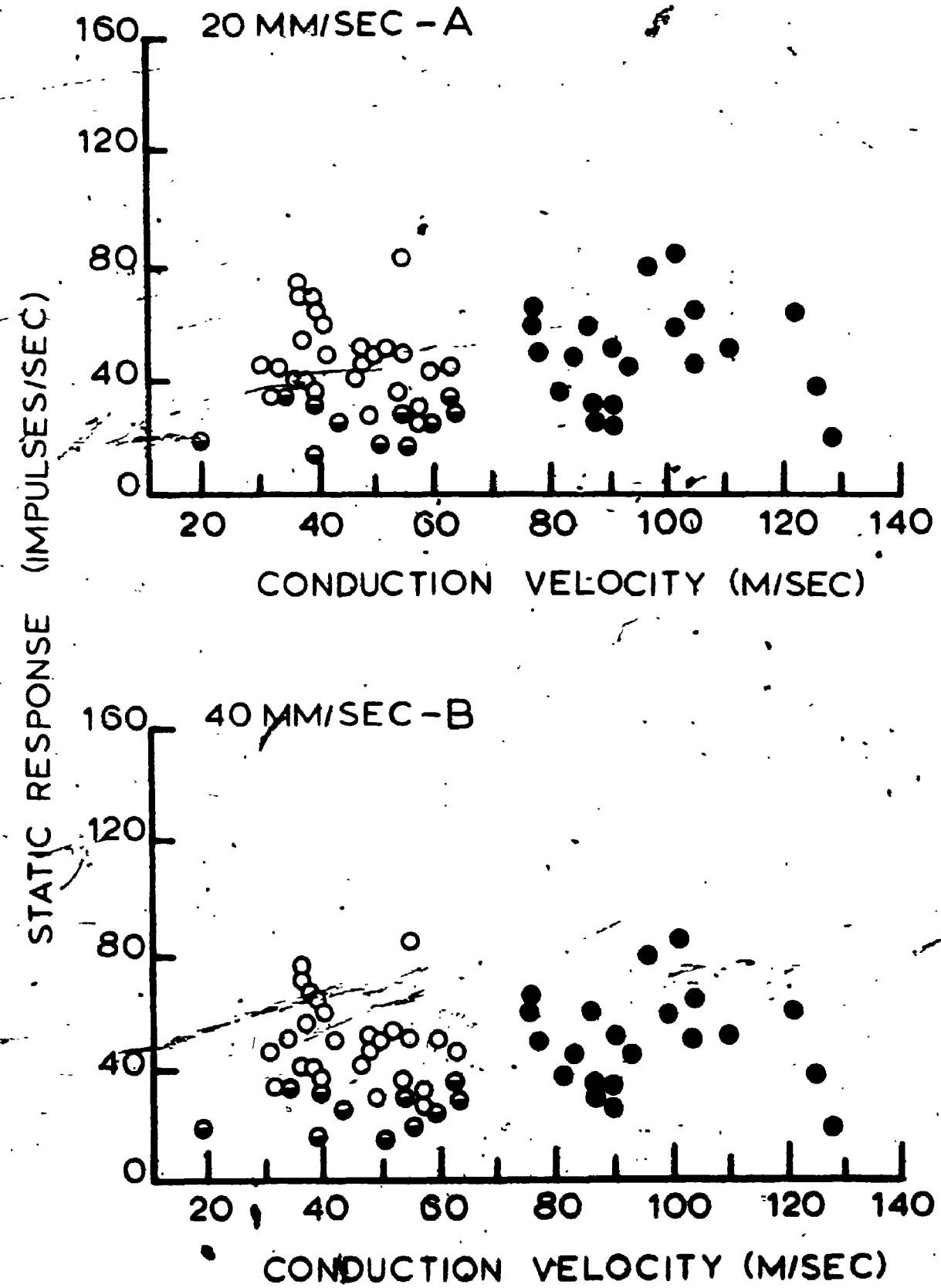
secondaries were significantly different ($P < 0.01$) from those of the NCR.secondaries at all velocities of stretch.

3. Static Responses of Muscle Spindle Endings

It has been shown above that the dynamic index of a spindle ending (measured by subtracting the response 0.5 sec after the end of ramp stretch, static response, from the dynamic response) increased progressively as the velocity of stretch was increased. It might be suggested that the increase in dynamic index, assessed by this means, resulted from differences in magnitude of the static response rather than an increase in the dynamic response. It was found however, that the static response of an ending remained constant for different velocities of stretch and was therefore independent of the velocity of stretch. This is illustrated in Figure 13 which shows scatter diagrams of the static response at two different velocities of stretch of the 58 sensory endings illustrated previously in Figure 12. Each point represents the static frequency of an ending measured 0.5 sec after the completion of stretch and plotted against its afferent fibre conduction velocity. There is no difference between the corresponding points in the scatter diagram of 13A - 20 mm/sec and 13B - 40 mm/sec. Similar results were obtained for the other velocities of stretch employed

FIGURE 13

Scatter diagrams relating the static response of the 58 sensory endings of Figure 12 to the conduction velocities of their afferent fibres and the velocity of stretch. The static response was the frequency of discharge at the final extension and measured 0.5 sec after completion of stretch as used in calculation of the dynamic index. The velocities of stretching are as indicated. These diagrams show that the static response is independent of the velocity of stretch for all endings and the conduction velocity of the afferents of primaries and CR secondaries. It also shows that the mean static response of these two types of ending were significantly greater ($P < 0.01$) than those of the NCR secondaries. 21 primary ●; 26 CR secondary ○; 11 NCR secondary ⊖.


20 MM/SEC - A
160
120
80
40
0
20
40
60
80
100
120
140
STATIC RESPONSE (IMPULSES/SEC)
CONDUCTION VELOCITY (M/SEC)
40 MM/SEC - B
160
120
80
40
0
20
40
60
80
100
120
140
CONDUCTION VELOCITY (M/SEC)

in the present study. Thus the increase in dynamic index (as shown in Figure 12) with increasing velocities of stretch resulted from an increase in the dynamic response rather than a change in the static response of the spindle ending.

As shown in Figure 13, the static responses of the primary and CR secondary endings overlapped considerably, while those of NCR secondary endings were in the lower part of the response range. The 21 primary and 26 CR secondary endings had mean static responses of 49.3, S.E.M. ± 2.9 imp/sec and 49.8, S.E.M. ± 3.9 imp/sec respectively. The 11 NCR endings had a mean static response of 25.2, S.E.M. ± 2.5 imp/sec. The mean static responses of the primary and CR secondary endings were the same and both were significantly greater ($P < 0.01$) than the mean static responses of the NCR endings.

If the CR and NCR secondary endings are considered as a single group, the mean static response of the 37 secondary endings was 42.3 ± 2.8 imp/sec. In this case the mean static response of all secondary endings was less than that of the primary endings but the difference was not statistically significant ($P > 0.05$). These findings imply that secondary endings as a single population measure muscle length (0.5 sec after end of ramp stretch) as well as primary endings measure muscle length.

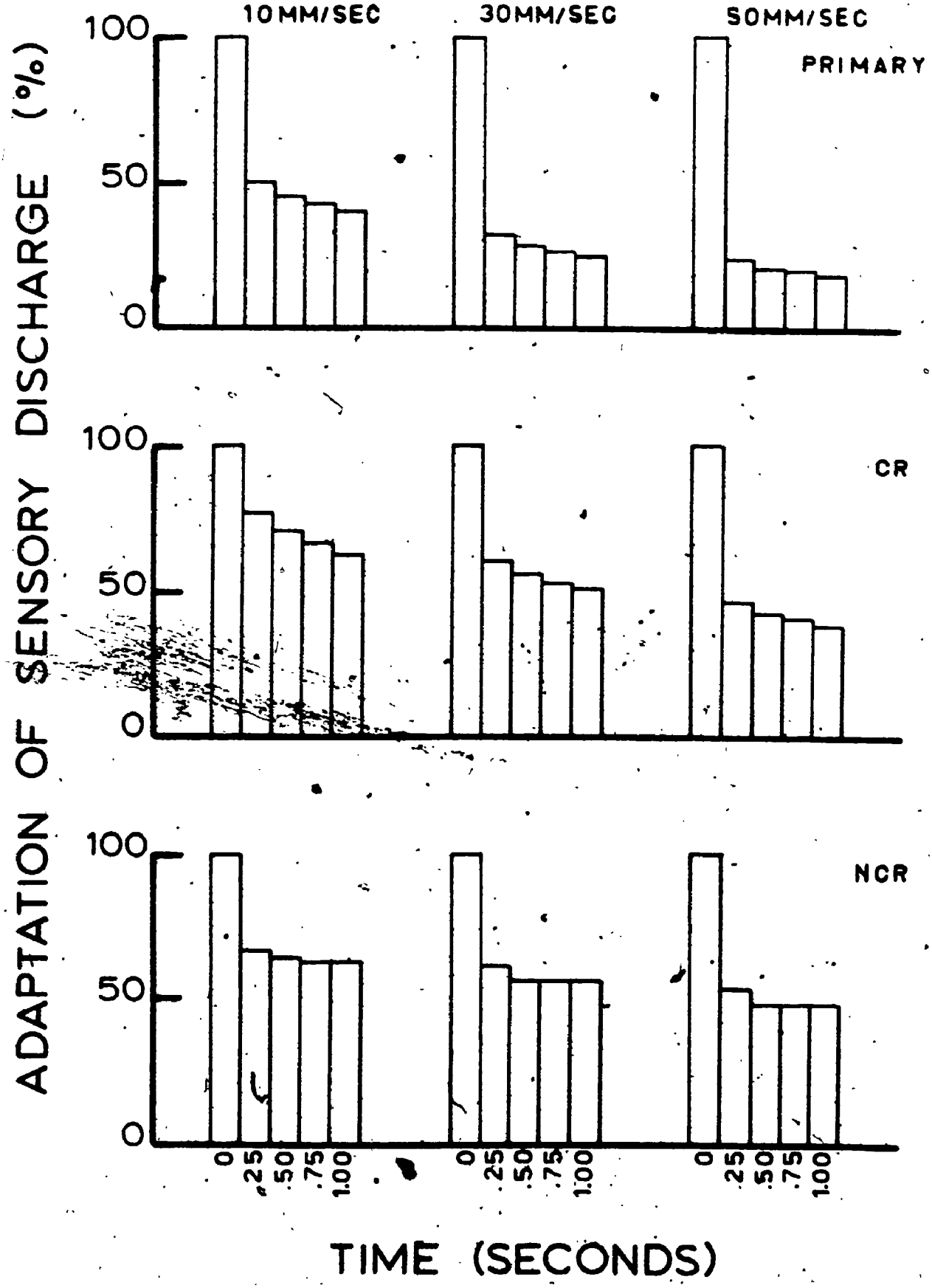
4. Adaptation of Muscle Spindle Sensory Discharge

The sensory discharge of a muscle spindle is known to adapt from the peak value at the end of dynamic stretch to a constant level, when stretch is maintained (Matthews, 1933). The finding that the frequency of discharge of an NCR secondary ending during muscle stretch hardly exceeded the discharge rate at the maintained length, suggested that these endings adapt quickly to a new muscle length. A comparison of the rates of adaptation of the three types of spindle ending showed that the NCR secondaries had the greatest rate of adaptation, reaching a steady sensory discharge before either primary or CR secondary endings. To determine the amount of adaptation of the sensory ending the decline in impulse frequency from the peak value to that value one second later was taken as an index of the adaptive change of the response. The time course of the decay of the discharge was studied by measuring the decrease in discharge frequency at successive time intervals (0.25, 0.50, 0.75, 1.0 sec) from peak frequency at the end of ramp stretch which was taken as zero time. The decrease in discharge frequency at each time interval was expressed as a per cent of the peak frequency which was taken as 100%.

The mean values of adaptation of 10 primary, 10 CR and 5 NCR secondary endings at three different velocities of stretch are illustrated in Figure 14. Figure 14 shows that for each type of

FIGURE 14

Illustrates the course of adaptation for the three types of endings at 36°C. The mean values calculated from 10 primary, 10 CR secondary and 5 NCR secondary endings are plotted at three different velocities of stretch 10, 30 and 50 mm/sec with a stretch amplitude of 10 mm. For each velocity of stretch the sensory discharge of each unit was measured at successive time intervals (.25, .50, .75, 1.00 sec) from the peak frequency during ramp stretch, (0) time. Column heights represent mean frequency of discharge at the respective time intervals expressed as a per cent of the peak frequency (0 time) which represents 100%. The NCR endings have the greatest rate of adaptation reaching a steady sensory discharge within 0.5 sec with most velocities of stretch.


10MM/SEC
30MM/SEC
50MM/SEC
PRIMARY
CR
NCR
100
50
0
ADAPTATION OF SENSORY DISCHARGE (%)
0
.25
.50
.75
1.00
TIME (SECONDS)

unit, for a given amplitude of stretch (10 mm) adaptation varied with the velocity of muscle length change. With slow stretches the adaptive fall in the response was slow; as the velocity of stretching increased, the rate of adaptation increased. As shown in Figure 14 the NCR endings adapted to a constant value of 63% of their peak level within 0.75 sec at 10 mm/sec stretch velocity, 56% within 0.5 sec at 30 mm/sec and 48% within 0.50 sec at 50 mm/sec. The sensory response of primary and CR secondary endings continued to decline from the initial peak value throughout the one second time interval. The NCR endings approached a regular static discharge more rapidly than either the primary or CR endings. Indeed at the higher velocities of stretch the NCR static discharge generally reached a constant frequency within 0.5 sec after peak frequency. Thus the NCR ending is discharging at a steady rate appropriate to the new level of extension before adaptation in primary and CR secondary endings is complete.

C. Effects of Muscle Cooling on the Response of the Muscle Spindles to Stretch.

1. Changes in Dynamic and Static Response of Spindle Endings During Cooling

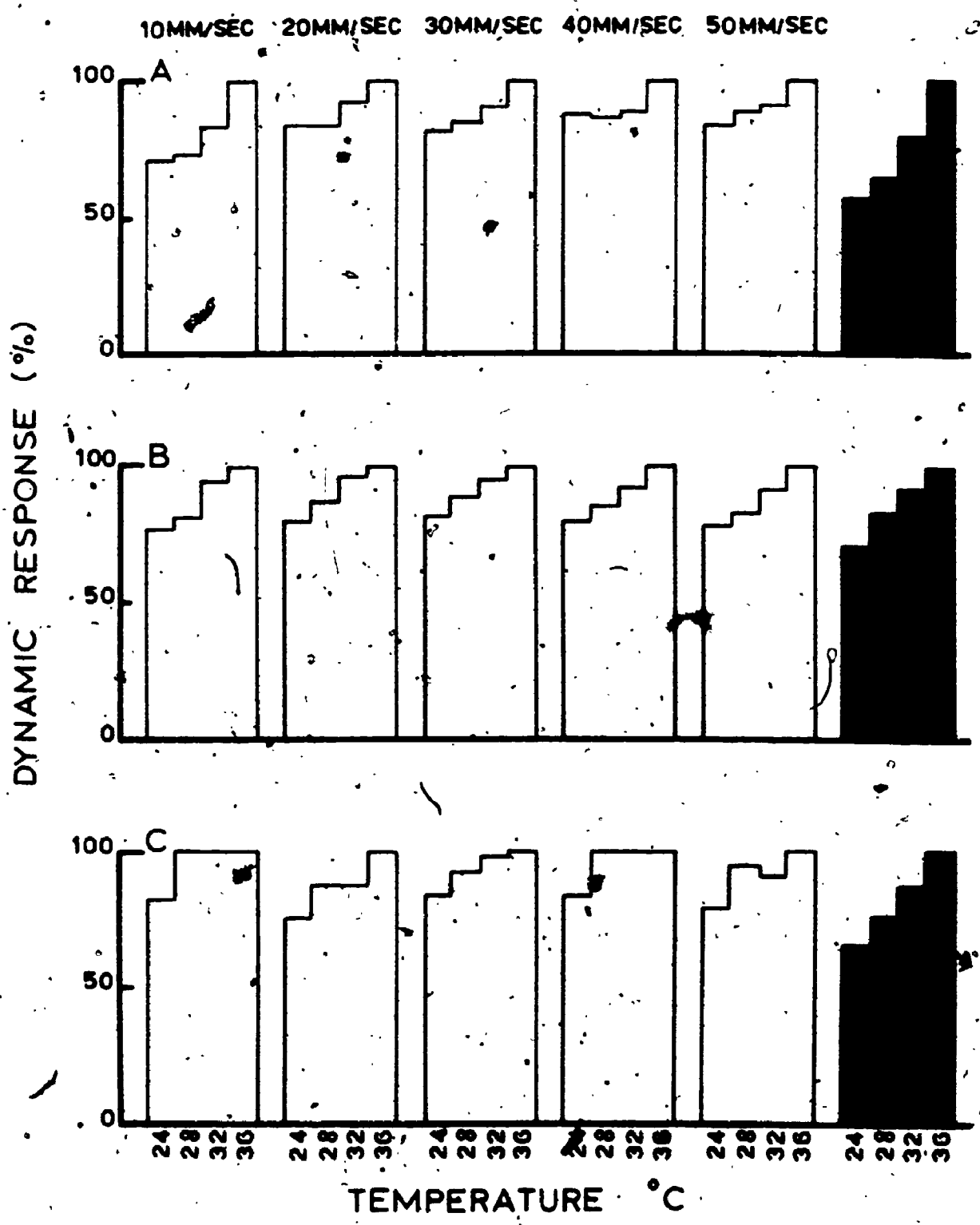
Other aspects of the effect of muscle cooling on spindle

discharge were examined also as outlined below. It was thought that the results might help elucidate the origin of the 'cold response'. In order to illustrate changes in dynamic and static frequency during muscle cooling, the peak frequency during ramp stretch, which is the dynamic response, and that occurring 0.5 sec later, the static response, were compared at 36, 32, 28, and 24°C. In Figure 15 the mean dynamic and static responses of 11 primary, 10 CR and 5 NCR secondary endings are expressed as a per cent of the respective mean values at 36°C, the latter being taken as 100%. The dynamic response of primary and CR secondary endings, Figure 15A and B, decreased at all stretch velocities during muscle cooling. In contrast the NCR dynamic response decreased at some velocities of stretch (20 mm/sec) and remained constant at other velocities (10 mm/sec). Cooling (36 - 24°C) decreased the mean dynamic response of primary endings at all stretch velocities, but this decrease was statistically significant ($P < 0.05$) only for a velocity of 10 mm/sec at 24°C. In contrast the mean dynamic response of the CR secondaries was significantly less ($P < 0.05$) at 24 than at 36°C at all velocities of stretch. The NCR secondary endings resembled the primary endings; that is, decreases in temperature of 36 to 24°C produced small decreases of the mean dynamic response and these were not statistically significant at any stretch velocity.

For all three types of endings the static response

FIGURE 15

Comparison of the relation between muscle temperature and the dynamic and static response of spindle discharge during muscle stretch. The mean dynamic response of 11 primary, 10 CR secondary and 5 NCR secondary endings is represented in the light histograms of part A, B and C respectively, for five velocities of stretch (10, 20, 30, 40 and 50 mm/sec) at four temperatures (36, 32, 28 and 24°C). The muscle temperatures are indicated on the bottom abscissae. The shaded histograms represent the mean static response of the corresponding sensory endings. The mean dynamic and static responses are expressed as a per cent of the mean values at 36°C which was 100%. For the three types of ending the static response was consistently decreased to a greater extent by cooling than the dynamic response.

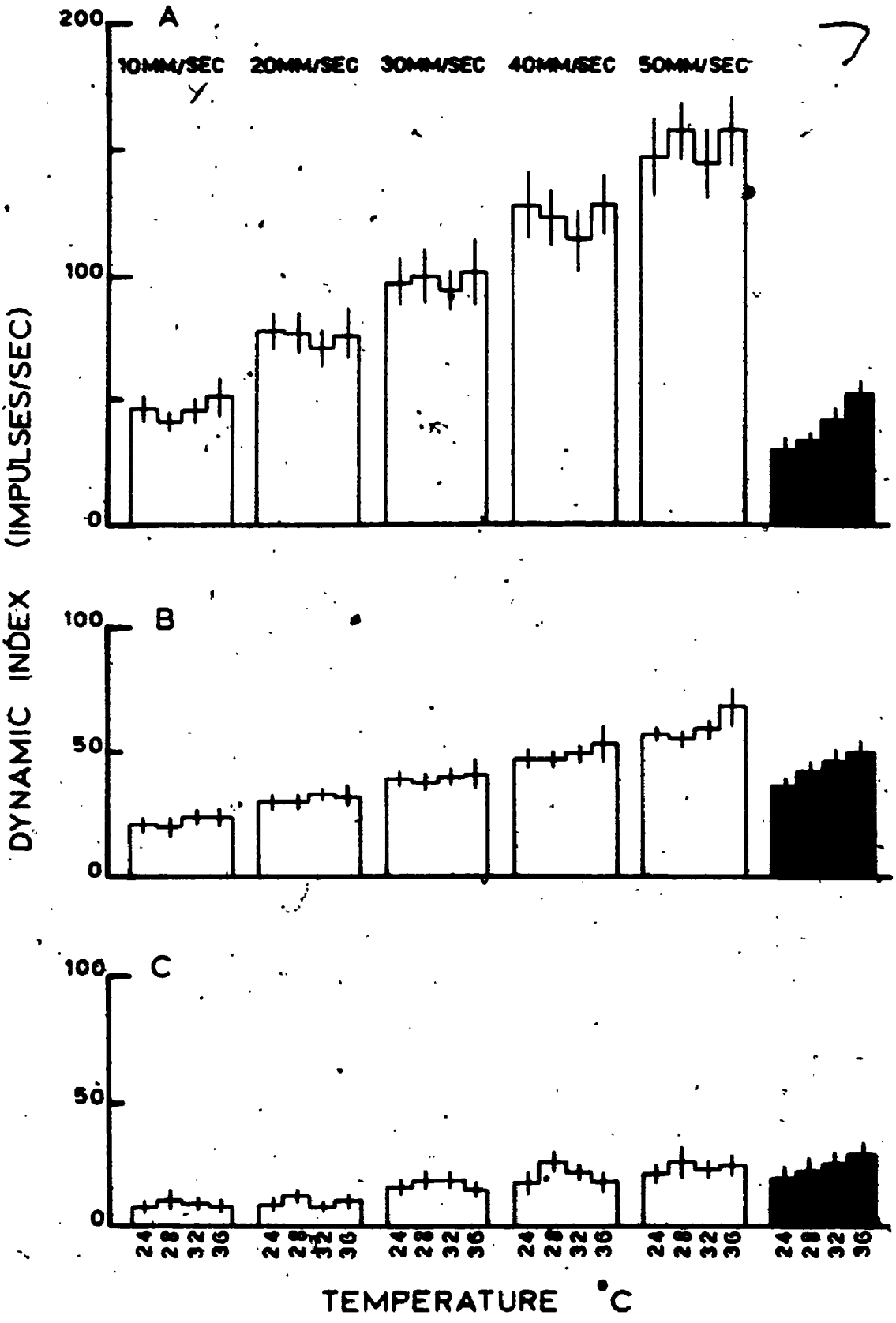

10MM/SEC
20MM/SEC
30MM/SEC
40MM/SEC
50MM/SEC
A
B
C
100
50
0
DYNAMIC RESPONSE (%)
24
28
32
36
TEMPERATURE °C

consistently decreased to a greater extent than the respective dynamic response. At 24°C the mean static response of the primary, CR and NCR secondary endings declined to 57%, 65% and 66% respectively, while the dynamic component of the three types of sensory ending generally decreased to only 80% of the initial value. For the primary endings and CR endings there was a statistically significant difference between the mean static response at 36°C and that at 24°C ($P < 0.05$) but there was no significant difference in static response of the NCR secondaries between 36 and 24°C. Thus the dynamic response of the stretch evoked sensory discharge appears to be less affected by low muscle temperatures than the static response. A possible functional significance of these results became apparent, when they were plotted in terms of dynamic index as shown in Figure 16. This shows that muscle cooling, during any velocity of stretch, caused no statistically significant change in the dynamic indices of any of the endings.

Considering the results in more detail, at 32°C the mean dynamic index of the primary endings decreased at all velocities of stretch (Figure 16A); with further cooling the mean dynamic index generally increased. Muscle cooling decreased the mean dynamic index of the CR secondary endings to a greater extent during fast (50 mm/sec) than during slow (10 mm/sec) muscle

FIGURE 16

Comparison of the relation between muscle temperature and dynamic index during muscle stretch at different velocities for the primary, CR and NCR endings illustrated in Figure 15. The mean dynamic indices of the 11 primary, 10 CR and 5 NCR secondaries are plotted in the light histograms of A, B and C respectively. The velocity of stretching is shown above each grouping of muscle temperature range. The muscle temperatures are indicated on the abscissa of the NCR's in plot C. The shaded histogram represents the mean static response (0.5 sec after completion of stretch) of the corresponding sensory endings. Static response measurements are plotted in imp/sec using same scales as the dynamic index. The mean dynamic indices of the 3 types of ending are not significantly changed by muscle cooling despite a significant decrease in the static response of primaries and CR secondaries ($P < 0.05$) when cooled from 36 to 24°C.


A
10MM/SEC
20MM/SEC
30MM/SEC
40MM/SEC
50MM/SEC
200
100
0
B
100
50
0
C
100
50
0
DYNAMIC INDEX (IMPULSES/SEC)
24 28 32 36
TEMPERATURE °C

stretch. At the lower velocities of muscle stretch the CR secondary mean dynamic index remained relatively constant. In contrast, the mean dynamic index of the NCR secondary endings followed an irregular pattern during muscle cooling (Figure 16C). Within the temperature range of 36 to 28°C the mean dynamic index of the NCR secondary endings generally increased at all stretch velocities but lower temperatures decreased the response.

2. The Pause Between Dynamic and Static Components of Sensory Discharge During Muscle Cooling

It was demonstrated by Matthews (1933) that immediately following the dynamic phase of stretching there was, under certain conditions of muscle stretch, a pause in the discharge before it reached a steady state. In the present experiments at 36°C the pause was seen regularly in the response of all primary endings and that of some CR secondary endings. On the other hand, the pause was never seen in the response of NCR secondary endings. In view of these observations it seemed of interest to study the transition period from dynamic to static stretch at different temperature levels in the three types of endings. It was found that the duration of the pause was related to the rate of applied stretch and the temperature. Figures 17 and 18 show

stretch. At the lower velocities of muscle stretch the CR secondary mean dynamic index remained relatively constant. In contrast, the mean dynamic index of the NCR secondary endings followed an irregular pattern during muscle cooling (Figure 16C). Within the temperature range of 36 to 28°C the mean dynamic index of the NCR secondary endings generally increased at all stretch velocities but lower temperatures decreased the response.

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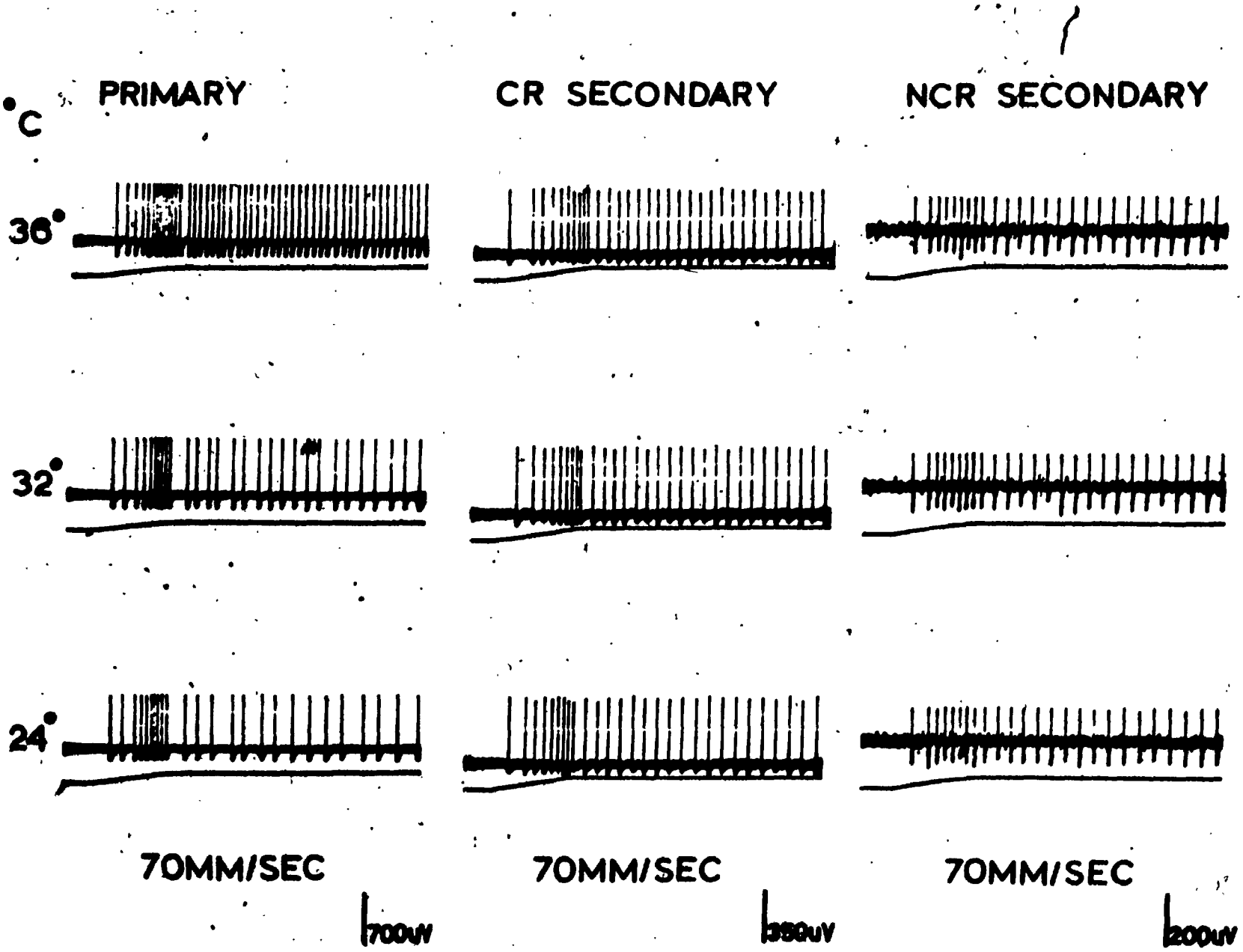
FIGURE 17

Examples of stretch evoked afferent discharges from a single primary, CR and NCR secondary ending at 36°C, 32°C and 24°C. A pause was evident between the dynamic and static component of sensory discharge of the primary ending at each temperature level and increased in duration with decreasing temperature. The CR secondary pause, just perceptible at 36°C was enhanced by muscle cooling. A pause was not evident in the discharge of the NCR ending even following muscle cooling.

Amplitude of extension for each unit was 10 mm from the initial muscle length.

Velocity of stretch for each unit was 70 mm/sec.

Conduction velocity of primary, CR and NCR secondary 101, 38 and 40 m/sec respectively.

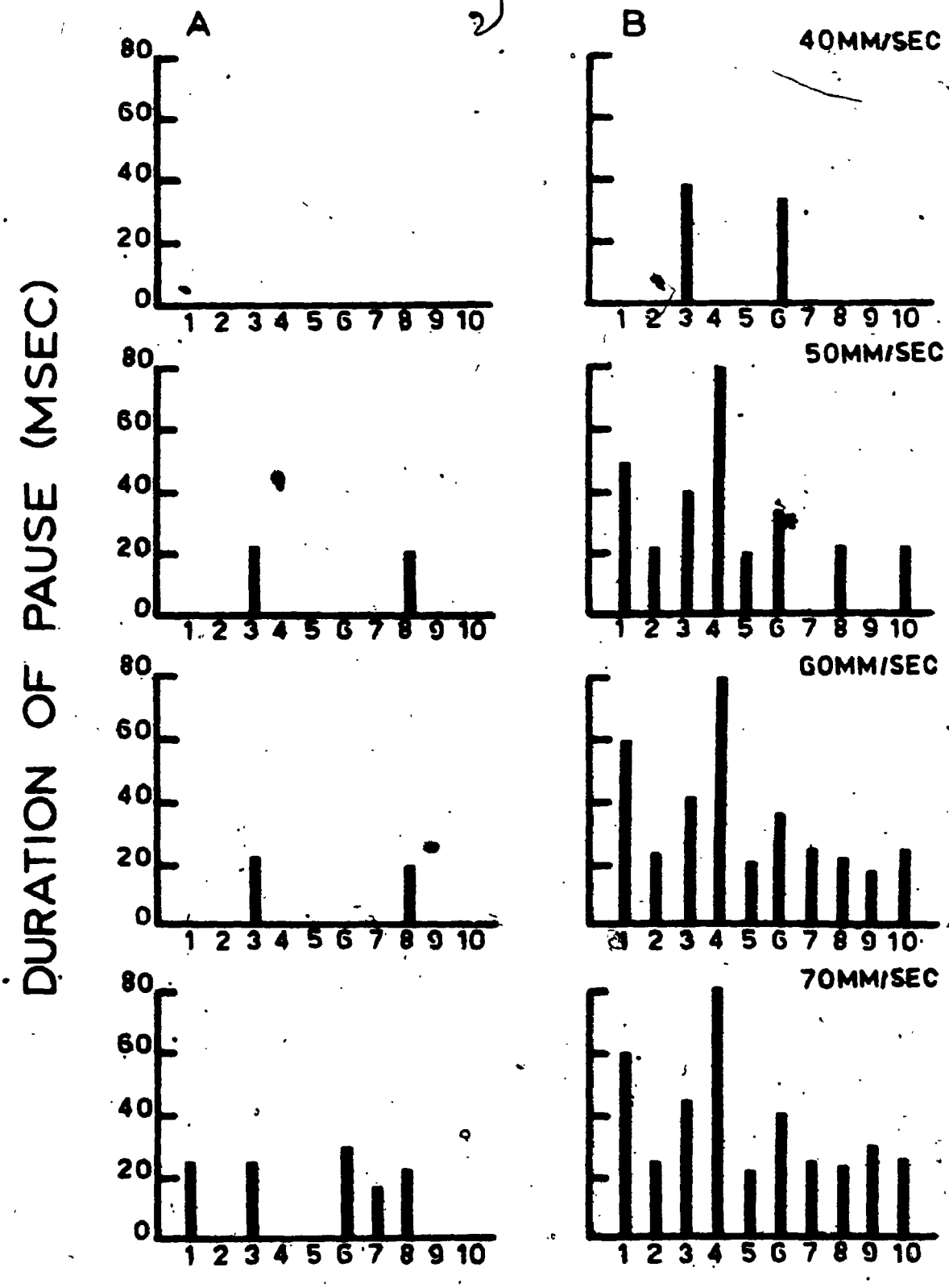

°C
PRIMARY
CR SECONDARY
NCR SECONDARY
36°
32°
24°
70MM/SEC
700uV
70MM/SEC
350uV
70MM/SEC
200uV

that a decrease in muscle temperature resulted in an increase in the duration of the pause. For example, in Figure 17, with cooling of the primary ending to 24°C, the pause increased from 23 msec at 36°C to 50 msec at 24°C. In general, CR secondary endings showed only a slight pause in discharge at 36°C, the transition from dynamic to static stretch being almost continuous. However, with cooling of the muscle a clear separation of the dynamic and static components of stretch became evident in all CR endings. In contrast to the above, all the NCR secondary endings had a continuous discharge in the transition from dynamic to static frequency levels. A pause in discharge was not evident at any rate of stretch even with muscle cooling.

An increase in the rate of stretch also made the pause of the primary and CR endings more prominent. This is illustrated in Figure 18 which shows changes in the duration of the pause for individual CR secondary endings at 36 and 24°C with increasing velocities of stretch (40 to 70 m/sec). With the muscle at 36°C only 5 of the 10 units displayed a pause in discharge at a velocity of 70 mm/sec. At 24°C a pause in discharge frequency was evident in 8 of 10 units at 50 mm/sec stretch and all 10 units possessed the pause when the muscle was stretched only 60 mm/sec. While muscle cooling initiated a pause in all CR secondary endings the pause was present in all primary endings at 36°C at all velocities of stretch and was enhanced by a decrease in muscle temperature.

FIGURE 18

The duration of the pause between dynamic and static discharge of 10 CR secondary endings. Each of the 10 endings is represented by a corresponding unit number on the abscissa of each plot. The column heights illustrate the duration (in msec) of the pause. A and B represent results measured at 36 and 24°C respectively at increasing velocities of stretch, 40-70 mm/sec. At 36°C and a low velocity of muscle stretch, 40 mm/sec, the transition from the dynamic to static component of discharge was continuous, and only 5 of 10 units show the pause at the highest rate of stretch, 70 mm/sec; with muscle cooling, B, the pause now appeared in more units at low stretch velocities, 40-50 mm/sec, and in all units at 60 mm/sec or above.


A
B
40MM/SEC
50MM/SEC
60MM/SEC
70MM/SEC
80
60
40
20
0
1 2 3 4 5 6 7 8 9 10
DURATION OF PAUSE (MSEC)
UNIT NUMBER

As mentioned previously, there was no pause in NCR discharge at any rate of stretch regardless of temperature.

D. Effects of Muscle Cooling on the Heteronymous Monosynaptic Reflex of an Extensor Muscle.

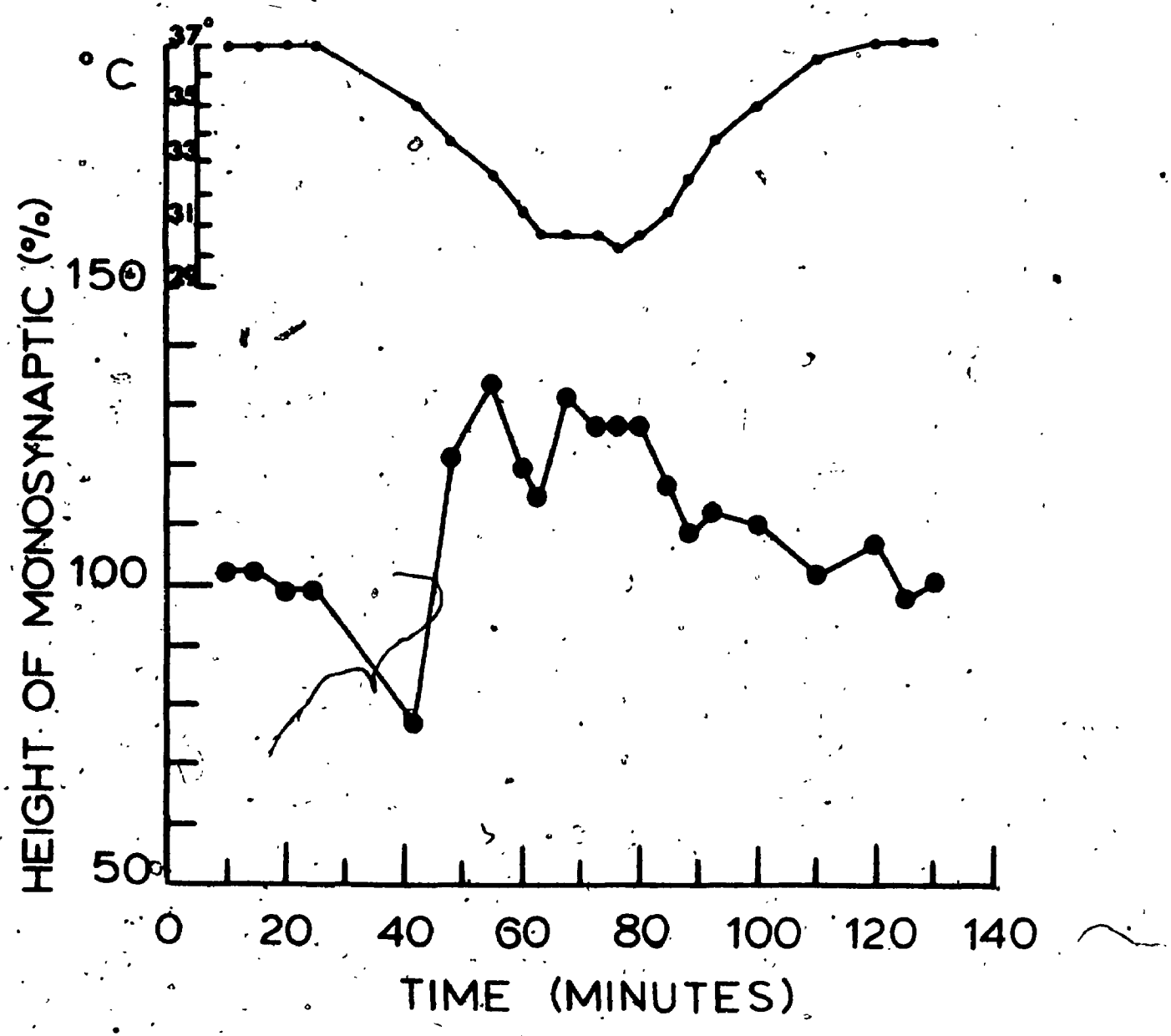
Cold-Induced Increase of the Monosynaptic Response in Decerebrate Cats

The finding that muscle cooling selectively stimulated secondary endings provided a method for investigating the role of the CR secondary endings in spinal reflex activity. The effects of cooling the relaxed medial gastrocnemius muscle on the monosynaptic response (MSR) elicited by stimulation of the lateral gastrocnemius - soleus nerve (LGS) was studied in 12 decerebrate cats. Care was taken to avoid spread of stimulus along the LGS. Since cooling of the spinal cord augments ventral root reflexes (Koizumi et al., 1954) great care was taken to maintain the temperature of the cord at 37°C. Figure 19 illustrates the effect of cooling the relaxed medial gastrocnemius muscle on the MSR evoked by single shocks to the LGS nerve in a decerebrate cat. Each point represents the mean height of the 20 MSR's plotted as a per cent of the control MSR (100%). After the MSR had

FIGURE 19

The effect of cooling the medial gastrocnemius muscle upon the heteronymous MSR evoked in the S_1 ventral root by stimuli to the LGS nerve every two seconds (0.2 volts and 0.1 msec duration) in a decerebrate cat. Each point on the MSR curve represents the mean of 20 responses. Reflex response is plotted as a per cent of the control MSR amplitude which represents 100%. The upper curve shows the medial gastrocnemius muscle temperature. The oil pools of the LGS nerve and the spinal cord were maintained at 37 and 36°C respectively.

The initial decrease in the MSR to 76% of the control value at 35°C is thought to be due to depression of residual spontaneous primary activity. Further cooling (32.5°C) increased the MSR 134% above control levels while subsequent rewarming returned the MSR to the control level.


37°
°C
35
33
31
29
150
100
50
HEIGHT OF MONOSYNAPTIC (%)
0
20
40
60
80
100
120
140
TIME (MINUTES)

stabilized, the mean amplitude was measured at intervals every two minutes before muscle cooling (0-10 minutes) and used as the control. There was no significant change in the height of the mean MSR when the muscle was maintained at 37°C for 15 minutes (10-25 minutes). Cooling the relaxed muscle to 35°C reduced the MSR to 76% of the control level but further cooling increased it. The MSR reached a maximum amplitude of 134% at 32.5°C, decreased slightly with further cooling (30 - 31°C) and returned to the control value as the muscle was rewarmed to 37°C. In all experiments cooling of the relaxed medial gastrocnemius muscle produced these characteristic changes in the MSR. The MSR cooling curves of the individual preparations, however, varied in the threshold temperature for increasing the MSR, maximum amplitude of the response and the optimal temperature at which it occurred. The mean threshold temperature of the MSR increase was 32.5, S.E.M. ± 0.60°C (28 - 38°C) and the mean maximum response was 155, S.E.M. ± 13.8% (115 - 270%) at a mean temperature of 29.3, S.E.M. ± 0.80°C (23 - 33°C). It is suggested that the heteronymous MSR was initially decreased because of a reduction in background activity from primary endings and was subsequently increased because of activity provided by the response to cooling ('cold response') of the CR secondary endings.

2. Procaine Blocking of the Increase in Monosynaptic Response During Muscle Cooling

In order to rule out a possible contribution to the MSR facilitation by receptors other than those of the cooled medial gastrocnemius muscle the sensory activity of the medial gastrocnemius nerve was blocked by the application of procaine (Matthews and Rushworth, 1957). The extent of nerve paralysis was monitored by recording the size of a compound action potential set up by stimulating the medial gastrocnemius nerve at its insertion into the muscle and recorded at a position 1 to 2 cm proximal to the point of application of procaine.

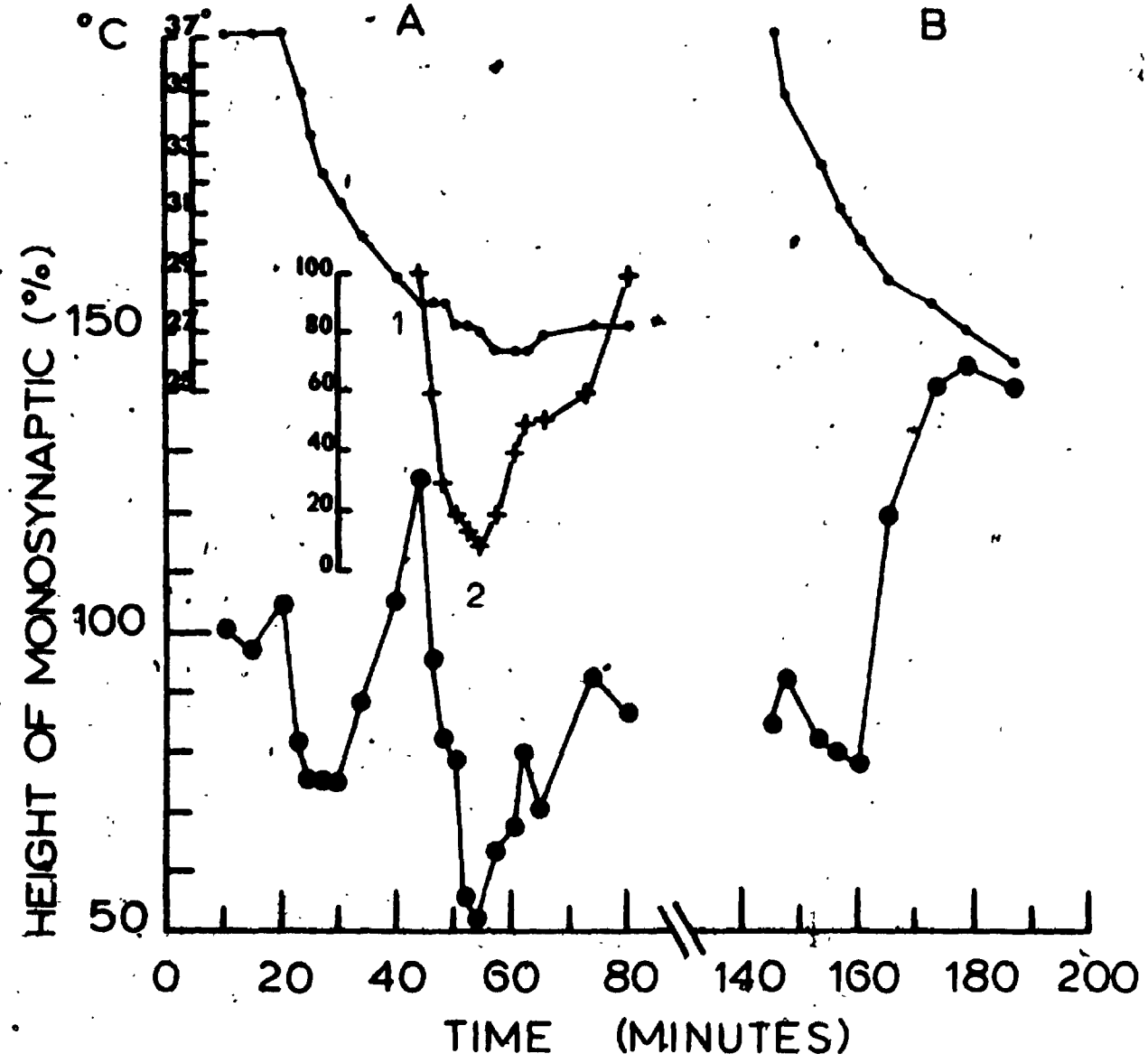
Figure 20 demonstrates the effect of blocking the medial gastrocnemius nerve upon the cold-induced increase of the MSR. Cooling the muscle to 31°C decreased the response, but further cooling increased the response. When the response had reached 127% of the control amplitude (muscle temperature, 28°C) procaine was applied to the medial nerve. The MSR showed a decrease which parallelled the decline in amplitude of the compound action potential of the nerve to the cooled muscle. Recovery of the MSR and compound potentials was produced by enclosing the medial gastrocnemius nerve in Ringer soaked filter paper. After return of the nerve conduction (Figure 20B) a second cooling of the medial gastrocnemius muscle resulted in an increased MSR throughout the cooling range. In

FIGURE 20

Illustrates the effects of medial gastrocnemius muscle nerve block by 0.3% procaine solution upon cold induced changes in the heteronymous MSR. The MSR was recorded from the S_1 ventral root and elicited by stimulation of the LGS nerve every 2 seconds (0.3 volts intensity and 0.1 msec duration). Each point on the MSR curve represents the mean of 20 responses. The upper curve (—●—●—●—) shows the temperature of the MG muscle. The compound action potentials (—+—+—+—represent means of 10 responses) evoked by stimulating the MG nerve (0.7 volts intensity and 0.1 msec duration) near its insertion into the muscle were recorded from an appropriate proximal position on the MG nerve. Procaine was applied to the nerve between stimulating and recording electrodes and the disappearance of the potential monitored.

Cooling the muscle to 31°C decreased the MSR but further cooling increased the response. When the response reached 127% of the control level (at 28°C), procaine was applied at time 1 as shown on the compound potential curve. The MSR and the compound potential decreased in amplitude. Ringer soaked filter paper placed on the MG nerve at time 2 reversed the block and allowed the compound action potential to return to the control level. The MSR did not recover fully since the muscle temperature was now below the optimal temperature for increasing the MSR.

After allowing the nerve to recover for 1 1/2 hours the cooling was repeated, Figure 20B. The typical changes in MSR appeared during muscle cooling, that is, after an initial decrease the MSR increased to 140% of the control level.


°C
37
A
B
HEIGHT OF MONOSYNAPTIC (%)
150
100
50
100
80
60
40
20
0
1
2
0
20
40
60
80
140
160
180
200
TIME (MINUTES)

other experiments cutting of the medial gastrocnemius nerve abolished the increase in the MSR observed during muscle cooling. These results strongly suggest that the cold-induced activity of the secondary endings of the medial gastrocnemius muscle increases the heteronymous monosynaptic LGS response in decerebrate cats.

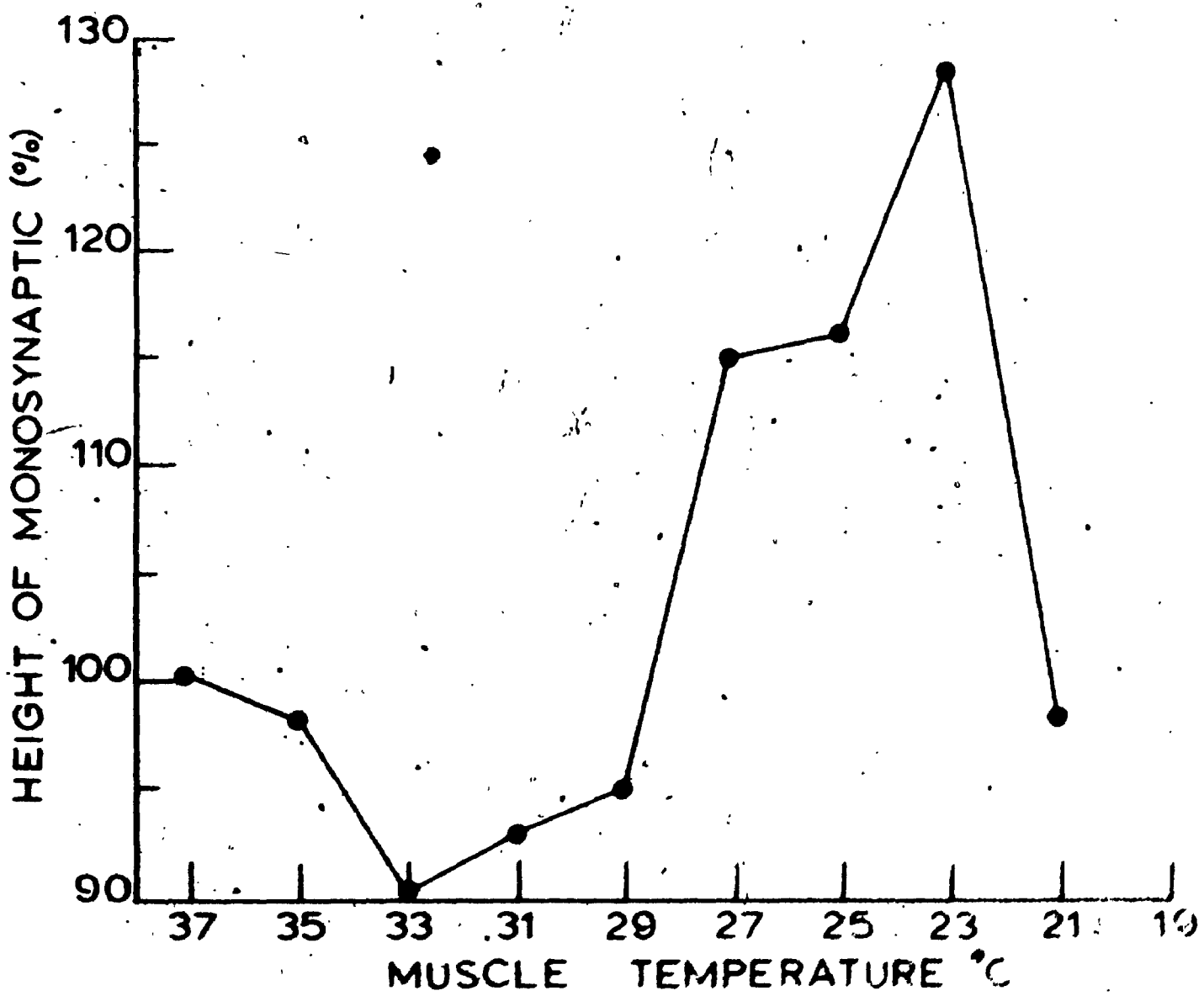
3. Cold-Induced Increase of the Monosynaptic Response in Spinal Cats

Results similar to those described for the decerebrate preparation were caused by muscle cooling in the spinal animal. Figure 21 represents the results obtained during cooling of the medial gastrocnemius muscle in 4 spinal animals. Each point represents the mean of the four MSR's, of the LGS nerve, calculated for each preparation at the same temperatures. Muscle cooling initially decreased the MSR but the increase initiated at 31°C reached a mean maximum of 128% and then declined with further cooling. In addition to the change in the MSR pattern shown above, Figure 21 shows that a decrease in MSR occurred during cooling of MG muscle to less than 23°C. Since the single unit analysis showed that the maximum frequency of the 'cold response' occurred at 29°C, it is suggested that the decreased MSR at the lower cooling range results from a reduction of the activity from CR secondary endings.

FIGURE 21

The effect of cooling the medial gastrocnemius muscle upon the heteronymous MSR evoked in the S_1 ventral root by stimuli to the LGS nerve every 2 seconds in 4 spinal cats. Each point represents the mean of the MSR of the four preparations at that temperature. Reflex response is plotted as a per cent of the control MSR amplitude which represents 100%. The LGS nerve and spinal cord oil pools were maintained at 37°C and 36°C respectively.

Cooling the muscle to 33°C decreased the MSR. Further cooling increased the mean MSR to 128% (23°C). The cooling response curve is similar to that obtained in the decerebrate preparations. The decrease of the MSR with muscle cooling to less than 23°C is thought to result from a decrease in CR secondary sensory activity at that temperature.


130
120
110
100
90
HEIGHT OF MONOSYNAPTIC (%)
37
35
33
.31
29
27
25
23
21
19
MUSCLE TEMPERATURE °C

V. DISCUSSION

1. The Specificity of the 'Cold Response'

The results show clearly that the afferent discharge elicited by cooling of the relaxed muscle, the 'cold response', originates only in the secondary endings of muscle spindles. 'Cold response' endings were identified on the basis of their afferent conduction velocities (20-70 m/sec) which is the conduction velocity range of secondary endings in the cat (Hunt, 1954). This finding is supported by a similar one in rat muscle. Michalski and Séguin (1971) reported that the 'cold response' of spindles of the rat anterior tibial muscle appeared only in fibres with conduction velocities characteristic of secondary ending afferents, that is, 20-50 m/sec (Andrew, Leslie and Thompson, 1973).

In the present study, isolation of spindle afferents and measurement of their conduction velocities yielded a representative sample of fibres which comprise the group I and II afferents of spindle endings. Historically the conduction velocities of cat hindlimb primary and secondary endings have been divided by an arbitrary value of 72 m/sec (Hunt, 1954) which in effect was Lloyd's (1943) distribution of group I and II afferent fibres. This bimodality of conduction velocities was often noted in cat spindle afferents (Merton, 1953; Hunt,

1954) and was confirmed in this study. From the histogram of Figure 4 it is clear that spindle endings in the present investigation can be divided into two groups of afferents with conduction velocities between 20-70 m/sec and 70-130 m/sec. The 76 primaries and 86 secondaries examined in the medial gastrocnemius (Figure 4) are grouped respectively in two peaks centred at 45-55 m/sec and 85-95 m/sec, a bimodal distribution similar to that reported by Hunt (1954). The overlap in conduction velocities (65-75 m/sec) may be explained by the overlap in spindle afferent fibre diameter (Adal and Barker, 1962; Hunt, 1954). Despite the observed overlap in conduction velocities, muscle cooling selectively stimulated only endings conducting below 70 m/sec. Indeed the highest conduction velocity of a 'cold response' secondary was 65 m/sec.

The finding that the 'cold response' was not characteristic of all spindle endings was not unexpected, since Lippold et al. (1960) reported that only two-thirds of the endings studied in the cat tenuissimus carried the 'cold response'. The spindle afferents which did not possess the 'cold response' responded to muscle stretch and the steady sensory discharge evoked by muscle stretch decreased during muscle cooling. The present investigation demonstrated that the lack of a 'cold response' in some secondary and all primary endings was genuine and not because of insufficient muscle cooling, rate of cooling,

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or nerve fibre damage produced by muscle cooling. It might be argued that primary and NCR secondary endings are localized in a portion of the MG muscle which was not cooled completely. However, Swett and Eldred (1960a) have shown that spindles of the MG are concentrated mainly in the middle two-thirds of the muscle, while the MG origin and insertion are relatively free of spindles. A similar distribution was reported by Chin, Cope and Pang (1962). This distribution corresponds to positions 2-5 in the muscle as shown in Appendix A. Measurement of the intramuscular temperature changes during cooling demonstrated that cold spread readily to these parts of the muscle as well as the origin and insertion of the muscle. Primary and secondary endings which did not possess the 'cold response' responded to stretch and during a maintained stretch gave a steady discharge which decreased during muscle cooling. Thus the method employed in the present study was sufficient to adequately cool all the spindles. Also, Lippold *et al.* (1960) studied the 'cold response' *in vitro* in the isolated tenuissimus in a temperature controlled bath that ensured a uniform cooling of all areas of the muscle. Using this technique, these workers noted that many spindle sensory endings remained silent during cooling of the relaxed muscle.

The lack of a 'cold response' in some spindle endings cannot be attributed to differences in the rate of temperature change

in different regions of the muscle since the 'cold response' is dependent upon temperature and not the temperature gradient (Lippold et al., 1960). Nerve damage or cold nerve block were not responsible for lack of 'cold response' in primaries and NCR secondaries since muscle stretch during muscle cooling (20 - 24°C) invariably evoked a sensory response from each quiescent ending. Therefore it seems valid to conclude that two types of secondary ending (CR and NCR) may be distinguished by their response to cooling of the relaxed muscle.

2. The Effect of Muscle Stretch on the 'Cold Response'

Lippold et al. (1960) described the 'cold response' in unidentified spindle afferents in relaxed muscle, whereas Eldred et al. (1960) reported that cooling of stretched muscle resulted in a slowing of afferent discharge of spindle primary and secondary endings. The present results provide an explanation for these contradictory findings. It was found that slightly stretching the muscle resulted in an increase in frequency and a decrease in the threshold of the 'cold response'. However, a depressant effect such as that reported by Eldred et al. (1960) became evident during cooling with the muscle under stretch (> 4 mm). It is probable that the 'cold response'

remained undetected by Eldred and his co-workers, since their experiments were performed with the muscle stretched and the spindle afferents already firing at normal body temperature. Presumably the 'cold response' from secondary endings was masked in such experiments.

3. Comparison of the Sensory Response of Primary, CR and NCR Secondary Endings

The present results showed two distinct kinds of secondary ending response. In contrast to Lippold et al.'s (1960) observation that spike height was the only difference between nerve endings with and without a 'cold response', it was found in the present study that dividing spindle secondaries into two groups on the basis of the 'cold response' produced two distinct groups also with respect to stretch sensitivity. The dynamic response of the CR secondary endings was considerable compared to that of the NCR secondary ending. The differences in the mean dynamic indices of the two groups of secondaries were statistically significant at all velocities of stretch. Thus the two types of ending differ in their sensitivity to muscle stretch; and it would appear that those that possess the 'cold response' measure length plus velocity, whereas the remainder (NCR) measure mainly

length.

It has been stressed in earlier investigations that secondary endings of muscle spindles are relatively insensitive to the velocity of muscle stretch (Cooper, 1961; Matthews, 1963). So it was an unexpected finding that CR secondary endings have such a high dynamic response. This discrepancy might be accounted for by the fact that the present experimental muscle and amplitude of stretch were different from those of earlier studies.

Cooper (1959, 1961) was the first to describe the response pattern of secondary endings. Her finding that "during the application of stretch the rate hardly exceeds that reached during a maintained stretch" is still widely accepted as an adequate description of secondary ending response. Cooper (1961) studied only eight secondary endings in the cat soleus using stretches of 4 mm. Matthews (1963) confirmed Cooper's finding in a larger number of secondary endings in the soleus muscle. But Matthews found some secondary endings which had an atypical response. The stretch response of CR secondary endings closely resembles that of the atypical secondary activity described by Matthews (1963, see his Fig. 4, record C). Matthews found 4 such atypical secondaries out of a total of 27 examined. It is of interest that he used stretch amplitudes of 5-6 mm and the question arises: how much greater would have been the dynamic responses of some of these secondary endings, if the amplitude of stretch had been

greater?

Also it is possible that the number of atypical secondaries (15% in the soleus) might be more numerous in a different muscle. For instance, Bianconi and van der Meulen (1963) found that secondary endings could be divided into two equal groups with respect to their response to stretch and vibration. Secondaries that were sensitive to vibration of the muscle surface differed from secondaries that did not respond to vibration. The former had a dynamic response similar to that of Matthews' atypical secondaries and our CR secondaries, while the latter responded only to muscle length like the classical secondary (Cooper, 1961) and the NCR secondary. It is noteworthy that Bianconi and van der Meulen (1963) were able to distinguish between the dynamically sensitive and non-sensitive secondaries by using a stretch of large amplitude (10-20 mm). It is suggested therefore that a comparative study of secondary ending response with large extension in a variety of cat hindlimb muscles would reveal a significant number of secondary endings with a relatively large dynamic sensitivity.

In the present investigation, the mean dynamic index of the primary endings was significantly greater than that of the CR secondary endings at all velocities of stretch. Nevertheless the high dynamic sensitivity of the CR secondary ending suggested that this type of spindle afferent had functional properties

similar to those of the primary ending. Thus these results have produced some uncertainty about the extent to which primary and secondary groups of spindle ending are truly distinct functionally. Considerable evidence has accumulated now that indicates that there is an overlap of the responses of primary and secondary endings from any one muscle. For example, Alnaes, Jansen and Rudjord (1965) found considerable overalp between the dynamic indices of primary and secondary endings in the anterior tibial muscle of the cat. A rather similar situation has been reported in the jaw muscles of the cat; Cody, Lee and Taylor (1972) reported that they could find no evidence of two distinct populations of afferent fibres in terms of dynamic index. Bianconi and van der Meulen (1963) found that dividing spindle afferents into two groups using the conventional dividing line of 72 m/sec did not produce two homogenous groups with respect to vibration as a dynamic stimulus. Overlap was also noted by Andrew, Leslie and Thompson (1972) who examined spindle afferents of the rat caudal and hindlimb muscles and found no clear separation between primary and secondary endings with respect to their vibration sensitivity and dynamic index.

Since the rate of adaptation of the CR secondary dynamic response was slower than that of the primary ending, it is

obvious that the use of the arbitrary measurement, dynamic index (Crowe and Matthews, 1964) can influence the degree of difference or overlap between primary and CR secondary dynamic indices. For example, if the CR secondary dynamic behaviour had been assessed by measuring the fall in frequency 1 second after completing the stretching their dynamic index would have been larger and would have overlapped the primary region to a greater extent. In contrast if their dynamic response had been measured 0.4 sec rather than 0.5 sec after stretch they would have fallen into the NCR range. Despite such limitations the dynamic index serves as a useful measurement of velocity responsiveness of an ending and allows the present results to be compared to those of earlier investigations.

Our observations can be compared with the corresponding observations by Matthews (1963) on the soleus muscle. Matthews found that with 60 mm/sec stretch the soleus primary afferents had dynamic indices in the range of 97-200 imp/sec, while secondaries had dynamic indices in the range of 13-78 imp/sec. In comparison the dynamic indices of the primary endings of the medial gastrocnemius muscle were between 44-245 imp/sec; while the CR and NCR secondaries fell within the range of 35-125 imp/sec and 15-40 imp/sec respectively. Undoubtedly the greater amplitude stretch in the present study (10 mm vs. 5-6 mm for Matthews) accounted for the higher magnitudes of dynamic

response; however, it should be noted that the dynamic index values of Matthews (1963) were obtained after exclusion of all units with conduction velocities between 60-80 m/sec. In addition, 10% of the other units were omitted, including 3 primaries which overlapped the maximum of the secondary dynamic indices and 4 secondaries which fell into the primary region of indices. The present investigation included units of all conduction velocities; of these 8 had conduction velocities between 60-80 m/sec, but these units did not appear to contribute appreciably to the overlap observed. Rather the greater overlap between primary and CR secondary endings of the present study is mainly due to the large dynamic index of CR secondary endings.

The results obtained in static response measurement, especially, make the case for a functional separation of primary and CR secondary endings difficult to support. The static response (measured 0.5 sec after the end of ramp stretch) of these two types of ending was the same and both were significantly greater than the mean static response of the NCR endings. However the NCR secondary endings had the greatest rate of adaptation, reaching a steady sensory discharge before either primary or CR secondary endings. The rate of adaptation of the NCR secondary makes this ending unique in that it rapidly monitors a change in static muscle length. Once the new length has been reached, however, the static discharge of each type of ending is proportional to muscle length.

The similarities between primary and CR secondary endings do not support the 'classical' role for spindle endings, namely that primary endings measure muscle length and velocity, while secondary endings measure only muscle length. The question arises as to whether primary and secondary endings should be classified on the basis of their conduction velocities or described in terms of their position in a graded distribution of sensory response. The attribution of a graded input from all spindle afferents to the CNS is more satisfying than the previous view that they produced distinctly different responses which function centrally in an opposing manner. Indeed the earlier view is supported mainly by the fact that most workers have emphasized the functional distinctiveness of most primary and secondary endings and excluded those endings which did not fit a normal primary or secondary response pattern. Since primary and secondary endings are thought to have opposing reflex effects the overlap of response noted in the present study requires some explanation and encourages further investigation into the role of secondary endings in spinal reflex activity.

4. The Role of Spindle Secondary Endings in Spinal Reflex Activity

The selective stimulation of the secondary endings by

cooling provided a method for studying the role of secondary endings in spinal reflex activity. Cooling of an extensor muscle resulted in an increase of the heteronymous monosynaptic reflex of its synergist in both decerebrate and spinal preparations. In general a reduction in height of the MSR to stimulation of the LGS nerve was found upon cooling of the relaxed MG muscle to approximately 33°C. Further cooling caused an increase in the MSR which reached a maximum at temperatures below 30°C. It was suggested that during cooling of the muscle the MSR was initially decreased because of a reduction in background activity from the primary spindle endings and was subsequently increased by afferent activity from CR secondary endings.

Eldred et al. (1960) in observations on the effect of cooling the stretched MG muscle of the cat found depression of monosynaptic responses rather than enhancement. Their method of cooling led to muscle temperatures of only 30°C. In the present study a 'cold response' fibre analysis of the relationship between frequency of discharge and temperature showed that the maximum response to muscle cooling occurred at 29°C. So it seems likely that these workers failed to decrease muscle temperature sufficiently to observe a clear increase in the MSR. In addition, the 'cold response' may have been masked in this earlier study (Eldred et al., 1960) by the use of a stretched

muscle, since the present experiments have shown that the 'cold response' is masked by muscle stretch.

An explanation of the reflex responses observed in the present investigation requires the assumption that the alteration in central excitability, MSR, resulted from changes in the afferent discharge produced by cooling of the MG muscle. Concrete evidence for this is provided by the finding that blocking the MG nerve with procaine during muscle cooling, or cutting the MG nerve, abolished the cold induced increase of the MSR. Although mechano and cutaneous receptors respond to local cooling in the cat hindlimb (Hensel and Iggo, 1960; Iggo, 1960), the complete ipsilateral and contralateral hip and leg denervation in the present preparation would have eliminated the possible influence of these receptors upon the MSR. From the above observations, it would appear that receptors outside the MG muscle do not contribute to changes in the MSR. It might be suggested, however, that the cold induced increase in the MSR resulted primarily from activation of muscle afferent endings other than those of CR secondary endings. In this respect there is evidence that cooling excites non-myelinated afferent fibres in muscle (Iggo, 1960). Iggo found pressure sensitive afferents in the gastrocnemius and soleus muscles of cats which responded with a persistent discharge to muscle cooling ($< 25^{\circ}C$) and muscle warming ($> 41^{\circ}C$). A few of the endings were most

sensitive around 28 - 32°C. Whether muscle cooling activated such fibres in our experiments cannot be answered on the basis of the present observations. However, to attribute the cold induced MSR increase to activity in fine unmyelinated afferents requires the conclusion that muscle C fibre activity can elicit, in some way, an excitation of extensor motoneurones. In this respect reports of reflex effects associated with C fibre activity are conflicting. Some workers have found that stimulation of muscle C fibres (Mendell, 1970) and cutaneous C fibres (Mendell and Wall, 1964; Dawson, Merrill and Wall, 1970; Mendell, 1970) elicited a positive dorsal root potential and presumably a presynaptic facilitation rather than an inhibition. This conclusion however, is not supported by the majority of workers (Burke, Rudomin, Vyklicky and Zajac, 1971; Franz and Iggo, 1968; Jänig and Zimmerman, 1971; Zimmerman, 1968) who have shown that C fibre stimulation produces a negative dorsal root potential and presynaptic inhibition. Thus no decisive conclusion can be drawn on the reflex role of C fibres; however, the bulk of the experimental evidence indicates that these afferents, if stimulated by muscle cooling, should have decreased rather than increased extensor motoneurone excitability.

Observations in the present experiments do not support the suggestion that muscle C fibre afferents contributed to the MSR. Most of Iggo's (1960) cold sensitive fine afferents were stimulated by temperatures less than 25°C. If muscle C fibres produce

presynaptic facilitation as suggested by Mendell (1970), an increase in the MSR would be expected at this temperature. In the present experiments this was not the case, since the MSR began to decrease in amplitude as muscle cooling progressed below 25°C.

It would appear that activity from the CR secondary endings is most responsible for the increase in the MSR during muscle cooling. Other evidence in favour of this assumption is the finding that during muscle cooling the increase in MSR amplitude began at a mean temperature of 32.5°C and reached a maximum amplitude at the mean temperature of 29.3°C. This agrees well with the mean temperature of initiation of the 'cold response', 31.7°C and the mean temperature of optimal 'cold response' discharge, 29.5°C. Nevertheless further investigation of the role of secondary endings on spinal reflex activity, using muscle cooling, may necessitate a study of the effect of cold upon non-myelinated afferents of the relaxed MG muscle.

At present the reflex actions of secondary endings are not clear. The main reason for this is the difficulty of activating these fibres selectively without the simultaneous activation of primary endings. Most experiments have depended upon electrical stimulation of nerves for activation of reflex pathways. Using such electrical stimuli it was shown by monosynaptic testing (Lloyd, 1943a, 1946a, b; Brock, Eccles and Rall, 1951) and by motoneurone intracellular studies (Eccles and Lundberg, 1959a)

that the group II afferents excited flexor and inhibited extensor motoneurones in the spinal cat, while they had little effect in the decerebrate cat (Eccles and Lundberg, 1959b; Kuno and Perl, 1960). On this basis the group II spindle afferents were defined as a part of the general flexor reflex system described by Lundberg and his colleagues (Eccles and Lundberg, 1959a; Holmqvist, Lundberg and Oscarsson, 1960) that is, whatever their muscles of origin impulses in group II secondary fibres produced facilitation of ipsilateral flexor muscles and inhibition of ipsilateral extensor muscles.

Exceptions to this pattern have been noted. [illegible]citation of muscle afferent nerves with stimuli of group II strength has been shown to result in excitation of ipsilateral extensor motoneurones (Eccles and Lundberg, 1959a; Wilson and Kato, 1965) and facilitation of the monosynaptic reflex (Holmqvist and Lundberg, 1961). If, as suggested above, secondary (CR) ending activity increases the heteronymous MSR, the finding that not all group II spindle endings showed a 'cold response' may be important in explaining the divergent results of these workers. The contradictory findings for reflex responsiveness to group II input would seem appropriate, if the reflex arises not only from secondary endings causing extensor excitation but also from some secondary endings causing extensor inhibition. It is possible therefore to suggest a role of excitation for some

secondary endings (CR) without excluding the general flexor pattern of group II spindle afferents. It may be speculated that NCR secondaries could contribute to extensor inhibition. Moreover it would be appropriate for CR secondary endings to have similar central connections as the primary endings, since both have a similar discharge response under static conditions of stretch and an overlap in the range of their dynamic responses. At any rate the earlier investigations do not invalidate the present reflex findings which suggest that some secondary endings of the muscle spindle are responsible for increasing the MSR in spinal and decerebrate cats.

It is possible that the use of electrical stimulation in spinal reflex studies has contributed to the conflicting results concerning the reflex activity of secondary endings. Although it is accepted that increasing electrical stimulus to group II strength does excite afferent fibres from spindle secondary endings the concurrent excitation of afferents from other types of receptor cannot be excluded. Hunt's (1954) study suggested that all but a few of the afferents examined in the soleus and gastrocnemius muscles came from spindles. In contrast Paintal (1960) found "pressure - pain" receptors in the same muscles which had conduction velocities in the group II and group I range. Barker, Ip and Adal (1962) provided further examples of fibre 'contamination'; they reported that about 10% of

group I fibres and 35% of group FF fibres to the soleus could not be related to muscle spindles. Anatomical work of Boyd and Davey (1968) suggested that such contamination existed in all muscle nerves, though in variable numbers.

Thus electrical stimulation of peripheral nerves at group II intensity activates several fibre types indiscriminately and more or less synchronously. Such an input to the spinal cord is improbable under normal circumstances and it would seem that sensory activity arriving at the cord asynchronously over a period of time might represent a more natural stimulus. In the present experiments the test shocks were electrical and confined to the Ia fibre spectrum, whereas the conditioning stimulus was low temperature. Thus the reflex effects of muscle cooling were presumed to depend upon an asynchronous and sustained 'cold response' secondary afferent activity.

The persistent discharge of CR secondary endings during muscle cooling may produce central effects which are different from those elicited by electrical stimulation. Such differences have been noted by other workers. Matthews (1969) and McGrath and Matthews (1973) used muscle stretch rather than electrical stimulation to excite secondary endings and obtained results which suggested that these afferents contributed to the tonic stretch reflex by autogenetic excitation of extensor motoneurones. These findings contradict the inhibitory role previously

assigned to secondary afferents as a result of electrical stimulation studies. In addition Burke et al. (1971) have shown that electrical stimulation of cutaneous and muscle C fibres produced a positive dorsal root potential, while a natural stimulus, skin heating, caused negative dorsal root potentials. These findings suggest that afferent fibres activated by a natural stimulus may have effects on the spinal cord pathways which are different from the effects exerted by electrical stimulation of the same afferents.

On the other hand Laporte and Bessou (1959) performed experiments which were based on the use of muscle stretch rather than electrical stimulation and found that stretch evoked excitation in group II fibres, during block of impulses in group I fibres, has an inhibitory influence on monosynaptically activated gastrocnemius soleus motoneurones in the spinal cat. However the method was apparently not invariably successful and Laporte and Bessou did not test the method by recording from single secondary endings during group I block (Matthews, 1972). This latter test was performed in a more recent study (Cangiano and Lutzemberger, 1972) which fortified the findings of Laporte and Bessou (1959). Cangiano and Lutzemberger found that selective activation (muscle stretch) of group II afferents in the decerebrate preparation did not produce a stretch reflex but rather gave rise to hyperpolarization of the gastrocnemius motoneurones. However the number of cells studied

was small and the majority were identified as phasic as opposed to tonic (Granit, Phillips, Skoglund and Steg, 1951).

Other workers have also noted the absence of the stretch reflex after blocking the group II afferents (Emonet-Denand, Jami, Joffroy and Laporte, 1972). Such blocking experiments may only suggest that secondary afferent activity cannot by itself produce a direct excitation of motoneurones but rather secondary afferent activity must modify the reflex effects of some other group of afferents. Indeed the hypothesis by Matthews (1969) that muscle spindle secondary endings excite extensor motoneurones and contribute to the tonic stretch is based upon experiments utilizing the simultaneous activation of primary and secondary endings. The present type of experiment was unable to show the nature of the central mechanisms which mediate the reflex effects of spindle secondary activity. However, it would appear that the excitatory process occurs in the spinal cord, since muscle cooling caused an increase in the MSR in both decerebrate and spinal animals. The simplest suggestion is that the increase in MSR amplitude during muscle cooling resulted from a facilitation of extensor motoneurone connections. However the finding that only a portion of the MG secondary endings could have contributed to the MSR increase during muscle cooling suggested a second possibility, namely that of alternative reflex pathways from CR and NCR secondary endings; one excitatory (CR) and one inhibitory (NCR). The two pathways

could be independent, switching on or off or could function concurrently, the final output being a resultant of the two opposite inputs.

More direct evidence is necessary before an extensor excitatory role for spindle group II fibres and the pathways involved may be regarded as established. The present experiments explored the possibility that muscle cooling could provide a selective input for the study of secondary afferent effects on spinal reflex activity. In view of the results, it would be of value to extend these experiments to include a study of the effects of muscle cooling upon the tonic stretch reflex. Such an investigation may elaborate differences of the effect of secondary afferent activity upon the phasic and tonic components of the stretch reflex. This may demonstrate more precisely the role of secondary afferents in spinal reflexes and firmly establish the extensor excitatory role of spindle secondary endings suggested by Matthews (1969).

5. Relation of Spindle Dynamic Sensitivity to Receptor Structure

The graded dynamic sensitivity of the primary, CR and NCR secondary endings may be explained in several ways. The most obvious explanation is to attribute the differences in sensitivity to anatomical differences, that is, that the three kinds of spindle ending lie on regions of intrafusal fibres with different mechanical

properties.

B. H. C. Matthews suggested in 1931 that the typical dynamic sensitivity of many muscle receptors might reflect visco-elastic properties of the receptor system. It has since been shown by P. B. C. Matthews (1964) how a simple mechanical arrangement of viscous and elastic intrafusal fibre elements can in fact account for a position and rate sensitive pattern of discharge.

Recent studies have confirmed Matthews' model by showing that NC and NB intrafusal fibres have quite different mechanical properties; NC, behave in a purely elastic manner, whereas NB, have viscous properties. By using high speed cinematographic recording techniques Boyd (1966a, b, 1971) demonstrated "weak and sluggish" NB fibre contractions that may develop over one-half a second. NC fibres show a much faster contraction rate. Smith's mechanical studies (1966) included another important point. Following a step increase in length, a point in the central region of the NB fibre was observed to return gradually towards the direction of its original location during a time period of one-half second. A similar displacement of the central point of the smaller chain fibres did not do this. More recently these results have been confirmed and extended by Boyd and Ward (1968) who showed that dynamic response of a spindle primary ending was due to the viscous damping exhibited by NB intrafusal fibres. These workers showed that during muscle stretch the polar regions of the NB

fibres continued to extend slowly toward and with consequent shortening of the equatorial zone. Thus the dynamic component of the spindle afferent discharge was attributed to structural differences between the central zone and the polar zones of NB intrafusal fibres.

A demonstration of the presence of elastic tissue in the spindle (Gladden, 1972) supported the above conclusion and suggested that elastic fibres may contribute to the production of the primary ending dynamic response. Gladden (1972) found that thick extracapsular elastic fibres ran intracapsularly forming a network along the NB intrafusal particularly in the equatorial region, while scarcely any elastic fibres lay amongst the NC fibres. It seems likely that the main purpose of elastic fibres in the spindle is to ensure that after a spindle has been stretched it is rapidly returned to its resting shortened position ready for its next episode of stretching. Therefore, the effect of muscle stretch upon NB and NC intrafusal fibres is modified by innate properties of intrafusal elasticity and viscosity as well as by the characteristics of the accompanying connective tissue.

On the basis of current knowledge of spindle anatomy the viscosity would be lowest and therefore the dynamic sensitivity greatest in the equatorial region of the NB fibre and the viscosity and lack of dynamic sensitivity would be at a maximum in the NC fibre and polar regions of the NB fibre. An area of intermediate

sensitivity would exist in the low viscosity myotube or S_1 region (Boyd, 1962) of the NB intrafusal fibre. One possible explanation for the discharge pattern of the CR secondary endings may be that these afferents represent secondary fibres with branches to both the NC fibre and the NB myotube region. On this basis, CR secondary endings would be expected to have a significant dynamic response to muscle stretch.

Despite the fact that many workers (Barker and Ip, 1963; Barker, 1967; Mayr, 1971) have stated that secondary endings innervate NB as well as NC fibres, it is generally believed that, in accordance with Boyd's observations (1962), secondary endings are located exclusively on NC fibres; Boyd says "although most of each (secondary) nerve ending lies on NC fibres it is usual for some sprays associated with it to lie on NB fibres". The absolute dynamic response of a CR secondary ending may not require extensive NB innervation. A single spray to the NB myotube region may serve as the site of highest frequency during muscle stretch (Crowe and Matthews, 1964). Indeed Boyd's recent cinematographic studies (1971) have led him to conclude that the "magnitude of the secondary ending response is shown to depend on the extent to which the terminations lie on the highly viscous nuclear bag intrafusal fibre".

In the above scheme the NCR secondary endings emerge as structurally simpler than the primary or CR secondary endings.

The lack of an appreciable dynamic response suggests that NCR endings may innervate the more distal NC regions, that is, Boyd's (1962) S_2 - S_4 region.

The dynamic sensitivity of primary and CR secondary endings may be related also by similarities in the association of their sensory fibres to the underlying intrafusal fibre. Electron microscope studies (Landon, 1966) revealed trough-like structures beneath the terminal coils of primary fibres innervating the intrafusal equatorial bag region. Such troughs were not present in the NC fibres. This applies to both primary and secondary terminations on NC fibres. Recently, cup-like cavities have been described for the branches of secondary endings on the bag fibre, although they were found to be not as deep as those for the primary ending (Banker and Girvin, 1971). It is of interest to speculate that these similarities in mechanical structures may contribute in some way to the observed difference in firing rate between primary and CR secondary endings.

A second possibility which might account for the difference in dynamic sensitivity between CR and NCR secondary endings may be the length of the NC fibre. Long NC fibres, particularly if they extend beyond the spindle capsule would in theory extend greater lengths during muscle stretch than shorter NC fibres. The NB fibres always extend an appreciable distance beyond the capsule (Boyd, 1962), a structural feature that might contribute to the

great dynamic sensitivity of the primary ending. In contrast the majority of NC fibres end within the capsule or at the end of the capsule, while a few project beyond it (Boyd, 1962; Bridgman, Shumpert and Eldred, 1969; Cooper and Daniel, 1963). If CR secondaries are assumed to innervate only the longer NC fibres and if the length of the intrafusal fibre has an influence on the dynamic sensitivity it would follow that in those spindles in which long extracapsular and short intracapsular fibres existed, there might also be a difference in dynamic sensitivity in the secondaries innervating the two kinds of NC intrafusal fibre.

Further, the possibility exists that the dynamic response of a CR secondary ending might originate from terminals on a separate intrafusal fibre like the one of intermediate type described by Barker and Gidumal (1961). These workers described an intrafusal fibre having properties intermediate between bag and chain intrafusals in its gross morphological features. Against this argument for the origin of the CR secondary termination is the further observation by Barker and Gidumal (1961) that intermediate fibres do not predominate and are indeed rarely found. In view of the large number of secondaries having a 'cold response' the above interpretation cannot be supported histologically.

Perhaps the most intriguing explanation for the high dynamic sensitivity of CR secondaries is the suggestion that these endings

are found in simple spindles. Using the nomenclature of Ruffini (1898) those spindles with a single primary ending and no secondary endings are termed simple. Adal and Barker (1962) in a study of the rectus femoris muscle of the cat showed that simple spindles were smaller in length and were attached to smaller diameter primary fibres than were complex spindles. At present the sensory discharge of simple spindles has not been identified but the small length of these spindles together with their smaller (group II range) afferent diameter make them an attractive choice to serve as CR secondaries. Indeed simple spindles are thought to contribute to the overlap in fibre diameter between the afferents from spindle primaries and secondaries (Adal and Barker, 1962), a finding that may correlate with the overlapping dynamic indices of CR secondaries. The 'cold response' secondary ending may be served by most of the above possibilities or some combination thereof. It would be of interest to compare the properties of CR and NCR secondary discharge with the anatomy of their respective afferent fibre innervation. Electrophysiological recording supported by histological examination can only be applied to small muscles with few spindles. In this respect the distal lateral segmental muscles of the rat tail have been examined for complexity (Andrew, Leslie and Thompson, 1973) and would appear to present a possible site of study, since many muscles here contain only a single spindle.

6. The Effect of Muscle Cooling on Spindle Sensory Discharge

In the present experiments it was found that the dynamic and static responses of spindle endings were decreased during muscle cooling; however, the two parameters were not equally affected by temperature. As shown in Figure 15 the static response of primaries, CR and NCR secondary endings declined to a greater extent than the respective dynamic response, when the muscle was cooled. Within the temperature decrease of 36 - 24°C the decline in static frequency was statistically significant for primaries and CR secondaries but not for the NCR secondaries. Lack of significance in the latter group was unexpected since muscle cooling (36 - 24°C) caused a significant decrease in the stretch evoked (8 and 12 mm) mean sensory discharge of the NCR secondary endings illustrated in Figure 6. With respect to the dynamic response only the CR secondary endings demonstrated a significant decrease from 36 to 24°C at all velocities of stretch. Thus the dynamic response of stretch-evoked sensory discharge appears to be less affected by the low muscle temperature than the static response. In addition the significant decreases noted for the dynamic and static response of CR secondaries suggested that this type of ending is most susceptible to temperature change.

The cause of the decrease in the dynamic and static components of the sensory discharge during cooling is not clear.

Theoretically the rate of fall of the dynamic and static phase may depend on a number of factors such as, extrafusal fibre tension, location of sensory terminations, ischemia and the visco-elastic properties of intrafusal fibres. Thus the decrease may mirror a decay of tension occurring in the extrafusal fibres which might be transmitted to the intrafusal fibres. Hill (1972) has shown in rat hindlimb muscles that tension elicited by muscle stretch is decreased as temperature is decreased. Various workers (Husmark and Ottoson, 1970; Nakajima and Onodera, 1969) have provided evidence that there is a close quantitative relationship between receptor potential and muscle tension; however, they point out that tension alone is not responsible for receptor potential changes. Further the mechanism does not appear to have a specific effect upon the spindle sensory wrappings, since dynamic and static discharges of primary and secondary endings, are not equally affected. Ischemia is probably not involved since muscle cooling did not produce blanching of the muscle and since spindle sensory response has a high threshold to hypoxia (Zimmerman and Grossie, 1969). It also has to be considered that changes in the visco-elastic properties of the intrafusal fibres might affect the time course of the dynamic and static parameters of discharge during muscle cooling. However similar thermal effects have been shown in Golgi tendon organs (Figure 8) which have no intrafusal fibres. It would appear that further investigation is

required in order to determine the site of action of cooling.

It is of interest that the dynamic index of all three types of sensory ending remained unaltered during muscle cooling. The functional significance of such a finding is not clear. It might be suggested that the cold-induced decrease in dynamic and static discharge could result in a decrease in spinal motoneurone excitability under conditions of low muscle temperature. However the lack of a significant dynamic index change with cooling suggested that the spindle sensory input to the CNS remains constant. Such a factor may be beneficial in an intact animal exposed to low environmental temperature since the muscle sensory input would be relatively unaffected.

It was expected that a study of the effect of muscle cooling upon the stretch evoked sensory discharge would reveal the origin of the 'cold response'. However muscle cooling altered the dynamic and static discharge of the three types of ending in a similar manner. Indeed the dynamic index of each type of ending remained unaltered during muscle cooling. The results suggested that the 'cold response' is a feature of the relaxed muscle and that a CR secondary, in a muscle under stretch, cannot be distinguished from a primary or NCR secondary ending by muscle cooling.

Of considerable interest was the observation that muscle cooling produced a clear separation of the dynamic and static components of sensory discharge of the primary and CR secondary

endings. In contrast the NCR afferents always discharge a few action potentials during the transition from dynamic to static stretch. This finding suggests that the NCR secondary ending lacks an appreciable dynamic component and serves mainly to measure muscle length. In addition the different responses of CR and NCR secondaries lend support to the earlier suggestion that these two types of ending have different arrangements in their sensory innervation. Finally, the smaller duration of the pause in CR secondaries compared to the larger pause in primaries and its absence in NCR secondaries provides further evidence that spindle endings produce a graded continuum of dynamic responses as mentioned previously.

7. Muscle Spindle Sensory Endings and Thermal Sensation

The frequency characteristics of the 'cold response' were established in a large number of secondary endings in the medial gastrocnemius muscle. A comparison of these results with similar observations by earlier workers suggests that the 'cold response' is a general phenomenon with consistent characteristics in spindle endings in a variety of species. Thus in the cat tenuissimus the 'cold response' was initiated at 32°C and reached maximum activity, 12 imp/sec, at 30°C (Lippold et al., 1960). In mice the 'cold

response' began at 32.9°C and reached optimal activity at 26.6°C (Banet and Séguin, 1967). In the rat the 'cold response' was initiated at 32.3°C and became maximal at 27.6°C (Michalski and Séguin, 1971). In the present study the temperatures of initiation and maximum response were 32.5°C and 29°C respectively. The optimal activity was slightly less than 12 imp/sec. The 'cold response' appears to be a special and constant feature of some muscle spindle endings.

The ability of some mechanoreceptors to respond to temperature changes has been known since the work of Hensel and Zotterman (1951). It is now becoming clear that thermosensitivity is a special feature of slowly adapting mechanoreceptors. Rapidly adapting mechanoreceptors such as the Pacinian corpuscle (Loewenstein, 1961) and the hair follicle (Brown and Iggo, 1967) are weakly excited by cold, if at all. However a variety of slowly adapting mechanoreceptors in cats and primates have been shown to respond to temperature changes by maintaining different firing rates at different maintained temperatures. For example the primate T + M mechanoreceptors (Poules and Lende, 1970) and cat type II receptors (Burton, Terashima and Clark, 1972) respond to constant temperatures with frequency responses that indicate low firing rates at 41°C, maximum activity around 29°C and slowing of the discharge rate at lower temperatures. It seems obvious therefore that the temperature responses of slowly adapting

mechanoreceptors, including CR secondary endings, may be compared to the response of specific thermoreceptors.

Temperature sensitivity curves for cutaneous thermoreceptors in the cat, rat and primate are bell shaped with some narrow range of temperature at which the frequency of discharge is maximal and a range of higher and lower temperatures at which the discharge is less frequent. The average maximum static discharge of cold fibres from the infraorbital nerve of the cat was 8.5 imp/sec at 28°C; the cold fibres became active below 41°C and decreased in frequency below 28°C (Hensel and Wurster, 1970). Iggo (1968) found that cold fibres in the scrotal skin of the rat have a regular discharge at different temperatures with a maximum activity of slightly less than 10 imp/sec at 28°C. The discharge of cold fibres in hairy and glabrous skin of the primates appeared within the temperature range of 18 - 40°C with optimal activity at 30°C.

The frequency of the cold response may be compared to that of a cold temperature receptor in three ways. First the 'cold response' has a different frequency for different temperatures over a wide range of maintained temperatures. Second the 'cold response' reaches a steady discharge rate at a constant temperature almost immediately after temperature change. Finally the 'cold response' has a frequency curve similar to that of a true cold thermoreceptor. But in contrast several characteristics distinguish the 'cold response' from that of true cold

thermoreceptors. The conduction velocities of CR secondaries are much higher than those of thermoreceptors, ranging from 20-70 m/sec which corresponds to an axon diameter of 3 to 12 μ (Hursh, 1939). The fastest cold receptor axon in primates and sub-primates were less than 20 m/sec; 15.3 m/sec in monkeys and 18 m/sec in the dog and could be as low as 0.6 m/sec (Iggo, 1969). Thermoreceptors reported in the skin of the rat, cat and dog (Iggo, 1959; Hensel, Iggo and Witt, 1960; Iriuchijima and Zotterman, 1960) had conduction velocities less than 1.5 m/sec. It is well documented that thermoreceptors fire at a higher frequency during a change of temperature than they do at a constant temperature. The finding by Iggo and Iggo (1971) that impulses from cold receptors occurred in bursts during temperature changes is in agreement with previous results in the lingual nerve of cats (Hensel and Zotterman, 1951; Dodt, 1952) in the infraorbital nerve of cats (Hensel and Wurster, 1970) and dogs (Iggo, 1969). This capacity to detect both temperature and the rate of change of temperature is not demonstrated by the 'cold response' whose frequency depends upon the absolute temperature (Lippold et al., 1960). Third, true cold thermoreceptors have a high sensitivity to temperature stimulation and are able to respond to cooling some tenths of a degree below 40°C (Hensel and Zotterman, 1951; Hensel and Wurster, 1970; Iggo, 1968). In contrast the 'cold response' was initiated only near 32°C. Finally the high sensitivity of CR secondaries to the

velocity and length of muscle stretch indicates that such afferents should function primarily as stretch receptors. This latter difference is supported by the finding that the 'cold response' decreased or even disappeared, when the stretched muscle was cooled.

Despite the dual sensitivity of a CR secondary to two forms of stimuli it would not seem possible that the activity from the CR ending could be confused with a true thermoreception by the CNS. While the similarities between the 'cold response' and the frequency of a cold thermoreceptor raise the problem of receptor specificity, there is no evidence that the 'cold response' contributes in any way to thermal reflexes or perception. Further work would be required before the 'cold response' may be assigned a positive role in thermal sensation.

8. Possible Mechanisms for the Origin of the 'Cold Response'

The mechanism by which the CR endings respond to thermal stimulation is not known. Lippold et al. (1960) suggested several possible explanations for the origin of the 'cold response' in muscle spindles. Their most attractive explanation was that muscle cooling acts directly by depolarizing the membrane of nerve endings. Such an explanation is doubtful in view of the present experiments which have shown that the 'cold response' is

specific to one type of spindle ending. It is difficult to imagine how muscle cooling has an excitatory action on the CR secondary ending, while the primary and NCR secondary endings are unsusceptible to the same stimulus.

Two further hypotheses may be invoked to explain the origin of the 'cold response'. Common to both is the assumption that muscle cooling alters the physical properties of muscle surrounding the spindle, such that the CR secondary endings are depolarized. In a study of the effect of temperature upon tension Hill (1972) noted that resting tension in rat hindlimb muscles was less at lower than at higher temperatures. With respect to the 'cold response' the hypothesis may be advanced that during muscle cooling tension in the relaxed muscle decreased allowing extrafusal fibres to lengthen. This slight stretch of the extrafusal fibre would exert an influence on the longer NB intrafusal fibres of the muscle spindle. If it is assumed that CR secondaries are represented by those secondaries with terminals on both NB and NC intrafusal fibres it follows that a small stretch of the NB fibre might initiate a depolarization of the branch of the CR secondary on the NB myotube region. The suggestion that the 'cold response' is specific to only one branch of the sensory innervation of a CR secondary ending is supported by the finding that muscle stretch decreased or abolished the 'cold response'. This disappearance of the 'cold response' may be explained by the pacemaker hypothesis of Crowe and Matthews

(1964). These workers suggested that impulses in the spindle are initiated in one or more pacemaker regions and that the discharge seen in the main afferent fibre at any time is that of the pacemaker with the highest frequency. This could lead to 'occlusion' of the 'cold response' and there is some suggestion that this is occurring in the present experiments (Figure 5). A similar form of occlusion has been repoted by Bessou, Laporte and Pages (1968) for the effects of static stretch on the responses elicited by dynamic fusimotor fibres.

A second alternative for the 'cold response' mechanism is the suggestion that muscle cooling initiates a 'cold tension' similar to that described by Hill (1972). Hill reported that cooling of the rat soleus below 15°C initially decreased the resting muscle tension but further cooling caused an increase in tension. Although the cold tension was not large (< 1 gm) it might be sufficient to stretch NB intrafusal fibres and excite the branch of the CR secondary ending innervating the NB myotube region. Hill further noted that the magnitude of 'cold tension' decreased when the muscle was extended, a finding that might relate to the occlusion of the 'cold response' with stretch. Moreover the 'cold tension' developed slowly at first but more rapidly as cooling proceeded. .It is noteworthy that the 'cold response' had a temperature threshold, i.e. 32°C.

The 'cold tension' was initiated below 16°C in the rat soleus

(Hill, 1972) while the 'cold response' begins at approximately 32°C. However in the same study Hill found that the extensor digitorum longus had a smaller 'cold tension' than the soleus and a much lower temperature of initiation. Unfortunately a comparative study of 'cold tension' is not available but it is of interest to speculate that different hindlimb muscles of the cat might have a wide magnitude and optimum temperature range for 'cold tension'.

The above hypotheses raise the question of specific excitation of NB myotube secondary terminals as opposed to NB equatorial or NC sensory endings. Such specificity may be attributed to the mechanical arrangement of the NB intrafusal fibre. The mechanical studies of Boyd and Ward (1968) as well as those of Smith (1966) have revealed that during spindle stretch the equatorial region of the NB fibre shortens, returning to its pre-stretch length, whereas the more polar regions continue to extend after stretch and remain elongated during maintained stretch. Thus the myotube area of the NB fibre would be under slight extension which could lead to excitation of the secondary ending. Since the tension changes in both schemes would be small, the short and usually intracapsular NC intrafusal fibres would be relatively insensitive to the stretch.

Despite the above suggestions it is clear that an explanation of the 'cold response' mechanism requires further experimentation. It is suggested therefore, that an exploration of the

muscle spindle intrafusal fibres and associated nerve terminals by microelectrode techniques is a necessity, if the origin of the 'cold response' is to be completely understood.

VI. SUMMARY AND CONCLUSIONS

Cooling of the relaxed medial gastrocnemius muscle in the cat caused an afferent discharge, 'cold response', in previously silent, de-efferented sensory endings of muscle spindles. The origin of this response and its reflex effects were studied in 61 cats.

1. The mean temperature initiating sensory discharge in 30 'cold response' spindle endings was 31.7°C and the mean maximum frequency reached 11.8 imp/sec at a mean temperature of 29.5°C.

2. An analysis of 162 single afferent fibres showed that the 'cold response' originated only in the spindle secondary endings, those having group II afferent conduction velocities (20-70 m/sec). The remainder of the secondary endings and all of the primary endings were activated only by stretch of the muscle. On the basis of their response to cooling of the relaxed muscle, secondary endings were classified into two different types, CR and NCR secondary endings.

3. Muscle spindle endings which did not have a 'cold response' gave a steady discharge during maintained stretch that decreased during muscle cooling. The CR secondary endings still showed

some evidence of a 'cold response' superimposed upon the steady discharge elicited by moderate stretch (up to 8 mm). However the 'cold response' was abolished by further stretch.

4. Investigation of the sensory discharge of primary, CR and NCR secondary endings was performed by stretching the muscle 10 mm at 5-70 mm/sec. Increasing the velocity of stretch increased the mean dynamic indices for the primary and CR secondary endings, but at any given velocity the mean dynamic index was always significantly greater for primary endings than for CR secondary endings. However some of the CR secondary endings were as sensitive to stretch as the least sensitive of the primary endings. The NCR secondary endings were relatively insensitive to the dynamic stimulus of muscle stretch and had stretch response characteristics similar to those classically ascribed to secondary endings (Cooper, 1959, 1961).

5. The mean static responses (measured 0.5 sec after the end of ramp stretch) of primary and CR secondary endings were the same and both were significantly greater than those of the NCR secondary endings.

6. The rate of adaptation was greatest for the NCR secondary endings. These endings were discharging at a steady rate

appropriate to the new level of maintained stretch before adaptation was complete in primary and CR secondary endings.

7. The response of single afferent spindle endings was studied at different temperatures (36 - 24°C) and at different velocities of muscle stretch (10-50 mm/sec). The mean dynamic response of the CR secondaries was significantly less at 24°C than at 36°C at all velocities of stretch. Cooling decreased the mean dynamic response of primary and NCR secondary endings but this decrease was not statistically significant at all velocities of stretch. In contrast cooling depressed the mean static response more than the mean dynamic response for all endings. There was a significant difference between the mean static response at 36°C and that at 24°C for primary and CR endings but not for the NCR secondary endings. The mean dynamic indices for each of the three types of ending were not significantly changed by muscle cooling.

8. Muscle cooling increased the duration of the 'pause' between the dynamic and static components of the sensory discharge of primary and CR secondary endings but not that of the NCR secondary endings.

9. It is concluded that CR secondary endings have dynamic properties intermediate between those of the primary and NCR

secondary endings. The static properties of primary and CR secondary endings are the same. It is suggested that secondary endings differ in their sensitivity to muscle stretch in as much as those that respond to cold measure length plus velocity, whereas the remainder mainly measure length. Further, the high dynamic sensitivity of CR secondaries suggests that these endings are functionally similar to primary endings.

10. Selective stimulation of secondary endings by cooling of the de-efferented muscle combined with monosynaptic testing provided a method for studying the role of secondary endings in spinal reflex activity. In both decerebrate and spinal cats cooling the relaxed medial gastrocnemius muscle initially decreased the heteronymous monosynaptic response from the lateral gastrocnemius soleus nerve but further cooling increased the reflex response. These changes in central excitability originated in the medial gastrocnemius muscle, since section of the nerve to that muscle or blocking it with procaine abolished the cold-induced increase of the monosynaptic response.

It is suggested that during cooling of the relaxed muscle the monosynaptic response was initially decreased because of a reduction in background activity from the primary spindle endings and was subsequently increased by afferent activity from the CR secondary endings. These results provide further evidence for

the hypothesis (Matthews, 1969) that muscle spindle secondary endings may excite extensor motpneurones.

APPENDIX A

Determination of Intramuscular Temperature Changes During Cooling of the Relaxed Medial Gastrocnemius Muscle

Figure 1 of Appendix A demonstrates the intramuscular temperature changes taking place during cooling of the medial gastrocnemius muscle. The intramuscular temperature decrease in the various depths of the muscle was computed from the temperatures recorded at the tip of a 24 gauge needle thermistor (YSI Co., Model 524). The thermistor was mounted on a micromanipulator and the intramuscular temperature was measured at 6 different positions (part A) along the muscle length by the following procedure. At each position the thermistor tip was first fixed at the muscle surface (level 0) and the muscle cooled using the method outlined above. The time interval for each 0.5°C change in temperature from 36.5°C to 24°C was measured. The muscle was then rewarmed, the thermistor advanced, B, to a depth of 1 mm from the surface (level 1) and muscle cooling repeated. Upon subsequent rewarming the thermistor was again advanced until the temperature had been sampled at each position at all muscle depths. For each cooling the frigistor was operated at a constant DC level and the heat sink cooled with water at 2 to 3°C. Thus the time interval for each 0.5°C cooling increment at successive muscle depths was measured at six sites along the muscle length and corresponding cooling curves constructed. The curves of part C

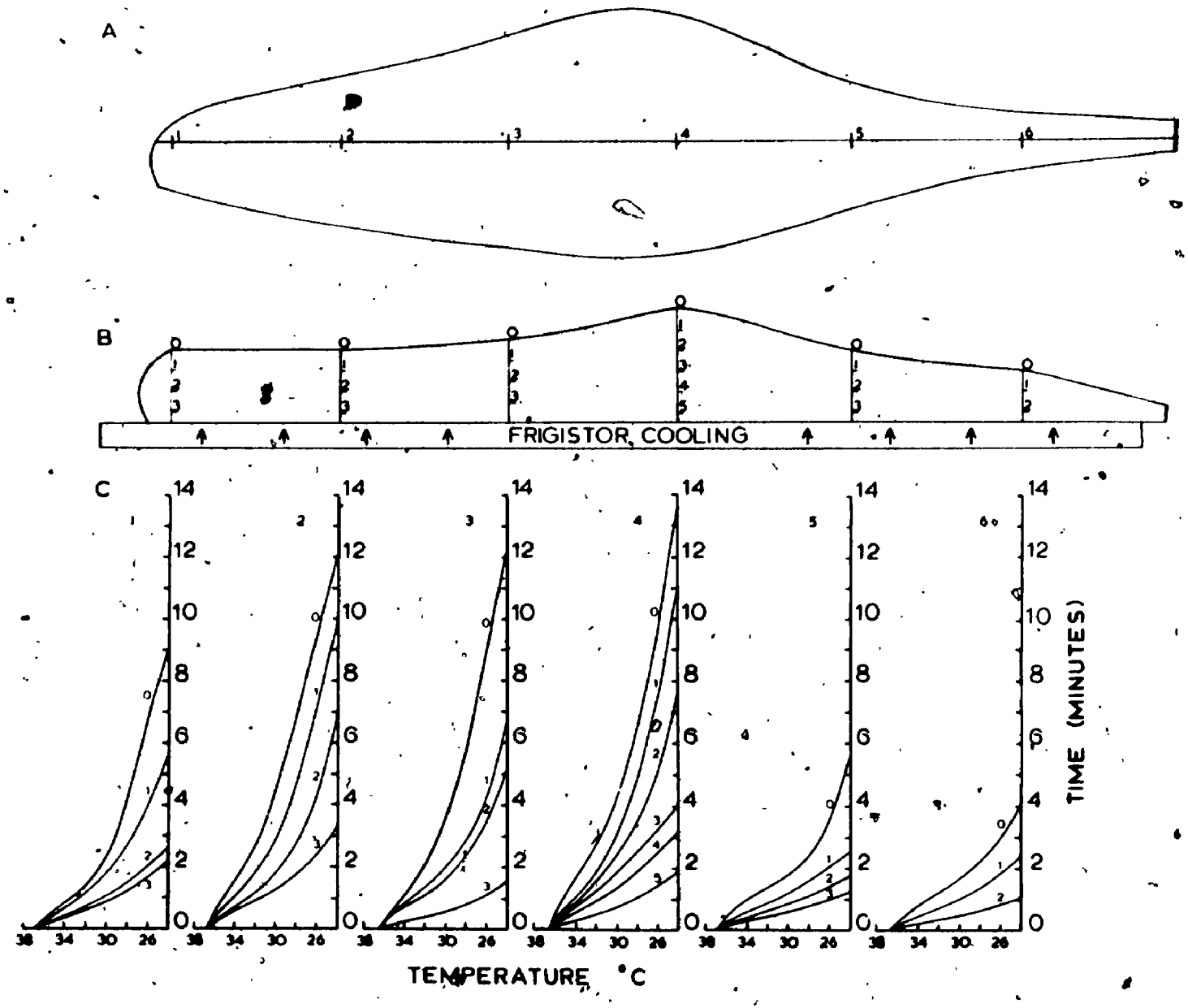

A
B
FRIGISTOR COOLING
C
TIME (MINUTES)
TEMPERATURE °C

FIGURE 1

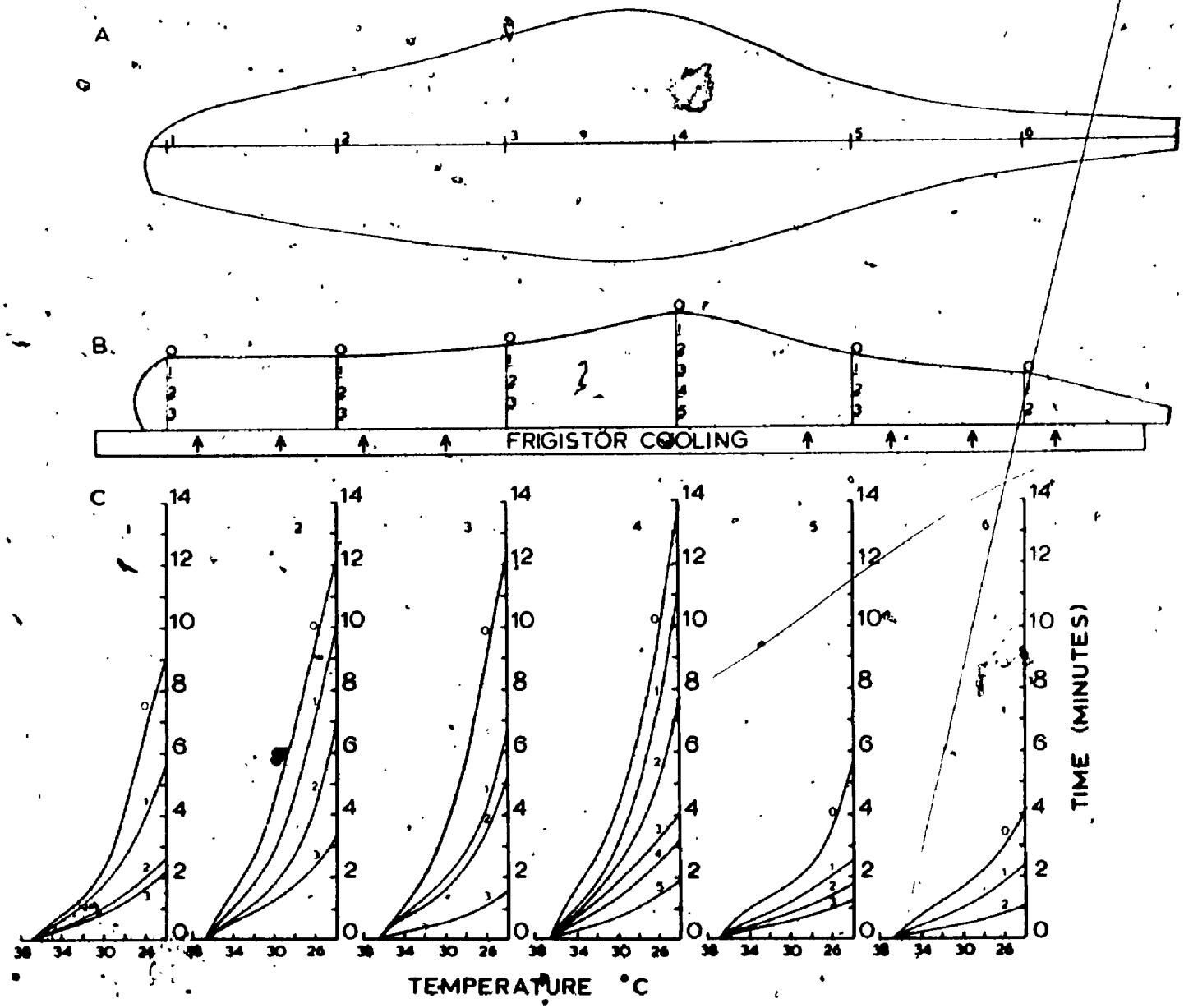
Illustrates intramuscular tempefature changes when the MG muscle was cooled *in vivo* by placing the frigistor on the skin of the lateral surface of the muscle.

A. Surface view of the MG muscle. A 24 gauge needle thermistor mounted on a micromanipulator was used to measure the intramuscular temperature changes at 6 different positions, 1 cm apart, along the muscle length. Position 1 is located at the muscle origin, position 6 at the muscle insertion.

B. Cross sectional view along the position line illustrated in part A. Intramuscular temperature changes were measured first at all levels of position 1, then all depths of the successive muscle positions, 2, 3, 4, 5 and 6, were monitored.

C. The rate of change of intramuscular temperature at each level for the 6 positions of part B is shown in the curves of part C. Each cooling curve represents the time (ordinate) required to cool the muscle from 36.5°C to 24°C (abscissae). For each of the 6 positions the series of cooling curves corresponds to the temperature changes recorded at the different levels.

In each experiment muscle cooling was monitored at position 4 level 0. The cooling curves show that all areas of the muscle are cooled to 24°C before position 4 level 0.


A
B.
FRIGISTOR COOLING
C
TIME (MINUTES)
TEMPERATURE °C

show the intramuscular depth to which muscle cooling proceeds as a function of time. From these findings it follows that muscle cooling spreads in the form of a gradient throughout the muscle tissue. For example at position 5 when the temperature reached 30°C at level 3, it was 32.6°C at level 2 and 34.6°C at the muscle surface (level 0). In addition the temperature gradient is not uniform at different positions along the muscle; that is, the temperature diffusion was slower in the thicker regions than in the thin regions. At position 5 level 0 reached 24°C in 5 minutes 30 seconds, while the same level at position 2 required 12 minutes 8 seconds to reach 24°C. Despite these differences in the rate of temperature change at different regions of the muscle it must be noted that muscle cooling spread to all muscle depths from the frigistor surface to the opposite muscle surface. Since in the present experiments muscle cooling was measured at the thickest part of the medial gastrocnemius, 5.5 mm, (level 0, position 4), it is suggested that all parts of the muscle are exposed to temperature changes from at least 37 to 24°C and that the method of cooling employed in the present study is sufficient to reach all spindles. At this position muscle cooling (37 - 24°C) in each experiment generally required 15 min, a rate of 0.9°C/minute.

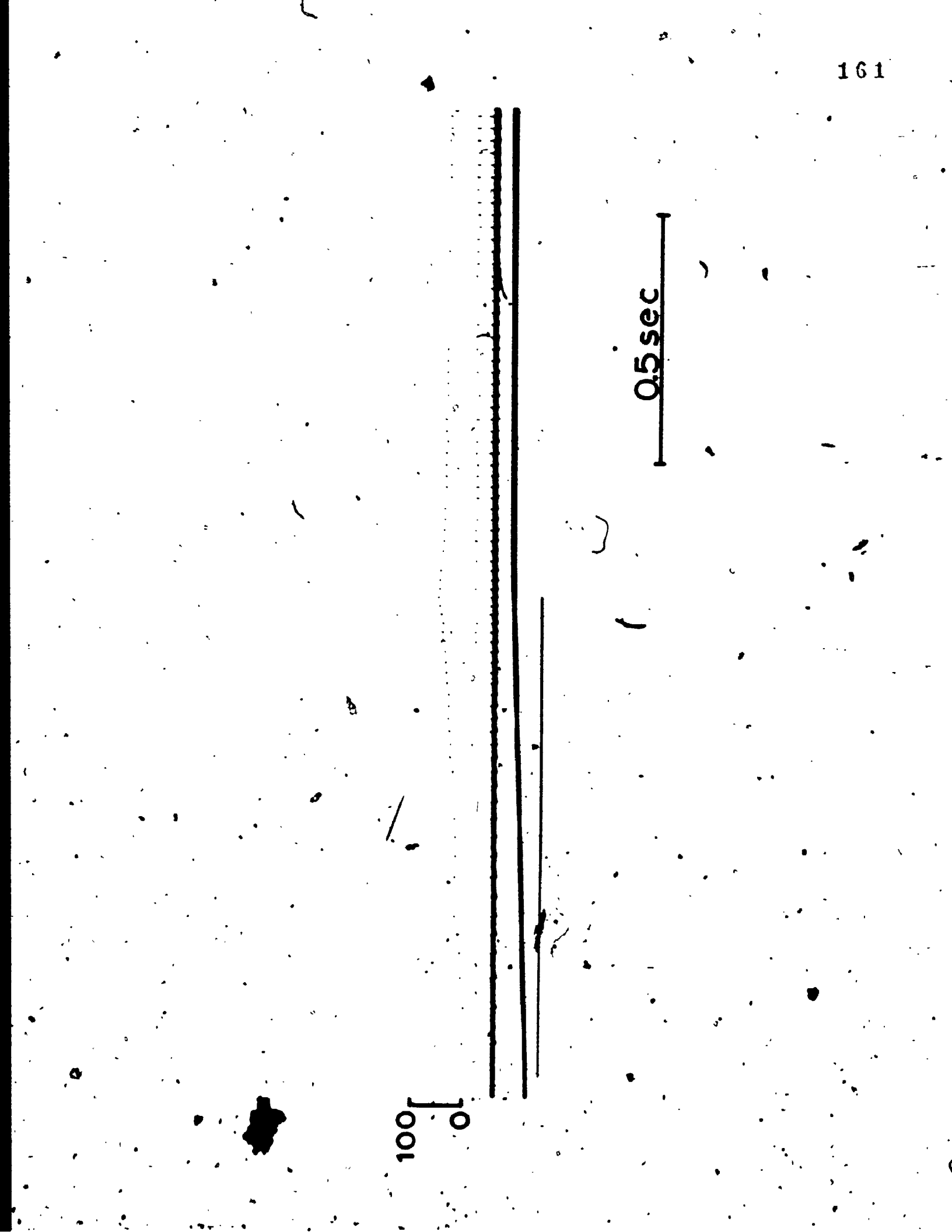
APPENDIX B

Method of Display of Instantaneous Frequency

The frequency of discharge of spindle endings was determined by a direct display of their instantaneous frequency. The action potentials triggered a PDP-12 Digital computer and the computer output could be displayed on a Tektronix 565 oscilloscope. The computer program of instantaneous frequency analysis utilized in the present experiments was developed for the PDP-12 computer by Dr. G. K. Smith, Associate Professor, Department of Psychology, McMaster University, Hamilton, Ontario. An example of the instantaneous frequency display is illustrated in Figure 2 of Appendix B.

FIGURE 2

The response of a primary ending shown by means of a direct display of its frequency. Each spot represents one action potential and its height above zero (see scale on left) is proportional to the reciprocal of the time interval since the preceding action potential (i.e. instantaneous frequency). The record shows the response of an ending to a stretch of 10 mm applied at 10 mm/sec. The dynamic phase of stretching is indicated by the bar beneath the record. Afferent fibre conduction velocity 86 m/sec.


0.5 sec
100
0

APPENDIX C

List of Abbreviations

CR	cold response secondary
LGS	lateral gastrocnemius soleus
MGS	medial gastrocnemius soleus
MSR	monosynaptic reflex
NCR	non cold response secondary
NB	nuclear bag
NC	nuclear chain
T + M	thermal and mechanical

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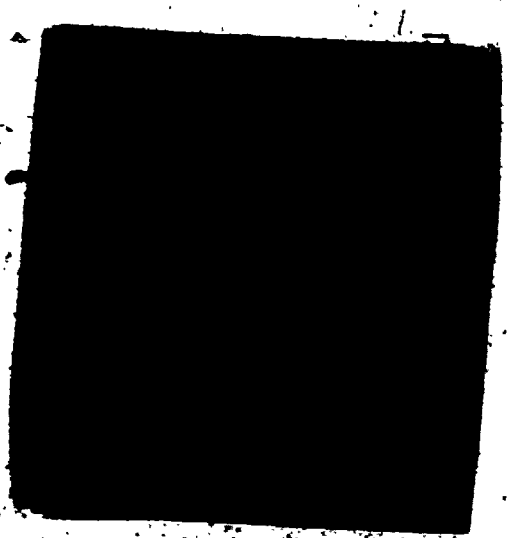

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