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Research report

Temperature effects on the discharge frequency of primary and secondary endings of isolated cat muscle spindles recorded under a ramp-and-hold stretch

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Abstract

The effects of changes in temperature on primary and secondary endings of isolated cat muscle spindles were investigated under ramp-and-hold stretches and different degrees of pre-stretch. Temperature-induced alterations of the discharge frequency were compared over a temperature range of 25–35°C. Both primary and secondary endings responded to warming with increasing discharge frequencies when the spindle was pre-stretched by 5–10% of its in situ length. The following differences between the temperature effects on primary and secondary endings were observed: (1) The temperature coefficients (Q_{10}) obtained from the discharge frequencies during the dynamic and static phase of a stretch were similar for endings of the same type, but they were larger in primary endings (range of Q_{10}: 2.3–3.3; mean: 2.9) than in secondary endings (range of Q_{10}: 1.6–2.2; mean: 2.0); (2) With primary endings, but not with secondary endings, the temperature sensitivity (imp s^{-1} $°C^{-1}$) was larger during the dynamic phase than during the static phase of a stretch; (3) In primary endings, the fast and slow adaptive components occurring in the discharge frequency during the static phase of a stretch clearly increased with warming while in secondary endings, the slow decay was less affected, and the fast decay showed no change; (4) In relaxed spindles, the excitatory effect of warming was overlaid by a strong inhibitory effect as soon as the temperature exceeded about 30°C, resulting in an abrupt cessation of the background activity in most secondary endings, but not usually in primary endings. In general, warming induced an enhanced stretch sensitivity in both types of ending, and additionally an inhibitory effect that is obvious only in secondary endings of relaxed spindles. The different effects of temperature on the discharge frequency of primary and secondary afferents are assumed to be caused by different properties of their sensory membranes.

Keywords: Isolated muscle spindle; Primary ending; Secondary ending; Temperature coefficient; Ramp-and-hold stretch; Adaptation

1. Introduction

Mammalian muscle spindles are influenced by changes in temperature in an excitatory or an inhibitory manner, depending on the degree of pre-stretch of the receptor: It was shown by Lippold et al. [24] that all muscle spindle afferents of the isolated cat tenuissimus muscle are inactive at body temperature (38°C) if the muscle is totally relaxed. However, some afferents produced discharges at temperatures ranging from 15°C to 30°C. Their discharge frequency rose with increasing temperature. But the discharges suddenly ceased when the temperature exceeded 30°C. Michalski and Séguin [26] recognized during in vivo studies on the relaxed gastrocnemius muscle that two-thirds of the secondary endings were active when the muscle was cooled, but that these endings were abruptly inactivated when the temperature was increased above 32°C. All primary endings and the remaining secondary endings were inactive in the relaxed muscle (temperature range: 24–37°C). If the gastrocnemius muscle was pre-stretched, however, the primary and secondary endings were active and increased their discharge frequencies when the temperature was raised from 28°C to 38°C [7]. Experiments on slightly pre-stretched gastrocnemius muscles supported these findings over an increased temperature range (29–43°C) [25]: All primary and some secondary endings were activated by warming and inhibited by cooling, whereas most of the secondary endings were inactivated by warming and activated by cooling.

It has been assumed that the site of action of the thermal stimuli is the muscle spindle itself, and that warming or cooling alters the properties of the membrane of its

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sensory endings [7,24,25]. Effects on the viscoelastic properties of the muscle have been excluded, because the tension of the muscle was found to remain nearly constant when the temperature changed. This assumption was supported by the finding that muscle spindle afferents were affected when the muscle was cooled only locally at the receptor site [7]. In addition, studies on isolated frog muscle spindles have shown that the thermal stimuli directly influence the receptor [27]: Afferents of the isolated and relaxed frog muscle spindle did not discharge spontaneously, but only when the receptor was briefly stretched. The discharge frequency rose nearly linearly if the receptor was warmed from 3°C to 30°C. However, the afferents stopped firing abruptly if the temperature was further increased.

In this study, we compare temperature effects on the primary and secondary endings of isolated cat muscle spindles, since the mammalian and frog muscle spindles differ in some morphological and functional aspects. It is of particular interest to study the isolated receptor because all the temperature effects that have been observed using non-isolated cat muscle spindles include a possible effect on the extrafusal muscle tissue. Moreover, we studied the effects of temperature changes not only on the background activity but also on the afferent discharge frequency during the dynamic and static phases of a ramp-and-hold stretch. In addition, we describe the influence of temperature changes on muscle spindle endings when the receptor is held at different degrees of pre-stretch. The discussion mainly focuses on the possibility that the different effects of thermal stimuli on primary and secondary endings are caused by differing properties of their terminal membranes: We assume that either the sensory membranes of primary and secondary endings contain different types of ion channel, or else that the two types of ending contain varying numbers of the same types of channel.

2. Materials and methods

2.1. Muscle and spindle preparation

The tenuissimus muscle and its nerve supply were excised from the right hind limbs of cats anesthetized with sodium pentobarbital (45 mg/kg i.v.). The nerve–muscle preparation was transferred into a modified Ringer's solution [30] and fixed in a dissecting chamber according to its length in situ for further preparation. The ionic composition of the modified Ringer's solution was: NaCl 118.6 mM; KCl 4.75 mM; $CaCl_2$ 1.80 mM; $NaHCO_3$ 23.2 mM; KH_2PO_4 1.19 mM; $MgSO_4$ 0.84 mM; glutamine 2.40 mM; glycine 3.20 mM; histidine 0.97 mM; glutamic acid 1.02 mM; glucose 1 g/l. The solution was continuously aerated with 95% O_2 and 5% CO_2. The pH was adjusted to 7.4.

Isolation of a muscle spindle and its nerve supply was carried out under a binocular (magnification: 10 to 60-fold). Extrafusal muscle fibers and connective tissue were removed from the spindle and its nerve. A number of extrafusal fibers were usually left around the poles of the isolated spindle. All branches of the nerve that did not supply the spindle were cut. The length of the nerve was kept as great as possible (>7 mm) with the intention of minimizing any depolarizing effect from the cut end that might influence the receptor potential or the generation of action potentials (APs) at the encoder site.

The isolated muscle spindle and its nerve were transferred into an experimental chamber and its poles were fixed to the holding rods of a device for stretching, using a histoacryl glue (B.Braun-Melsungen). The experimental chamber (volume: 0.5 ml) was continuously perfused with the modified Ringer's solution (perfusion rate: 3–5 ml/min). The spindle nerve was drawn via a small groove into a neighboring chamber, which was filled with oil. It was placed on an Ag-electrode for extracellular recording of afferent APs. A second Ag-electrode was placed in the experimental chamber. The first experiments were carried out 1 h after the end of the preparation.

2.2. Thermal stimulation and temperature recording

The temperature of the bathing solution surrounding the isolated spindle was regulated and varied by a heat exchange process. For this purpose, an additional chamber was installed underneath the experimental and the oil chamber. This additional chamber was perfused with warmed or cooled water coming from two separate temperature-regulated water baths. By switching the source of the water supply to the additional chamber, the bathing solution in the experimental chamber could be warmed or cooled by 10°C in approximately 2 min. Ninety percent of the temperature change was achieved within the first minute. The temperature of the bathing solution was measured continuously with a thermistor (PT 100) placed near the muscle spindle.

2.3. Determination of the initial length L_0 of the muscle spindle

The initial length L_0 of the isolated spindle was determined in two different ways. First method: The relaxed isolated spindle was stretched under visual control until the kinked intrafusal chain fibers were just straightened [9,31,32]. The length of that part of the spindle that was placed between the two rods of the stretching device was defined as the initial length L_0. This method was used in a first set of experiments in which the dependence of the activity of muscle spindle afferents on temperature was investigated under different amplitudes and velocities of ramp-and-hold stretch. Second method: The length of that

part of the tenuissimus muscle that was to be removed from the cat's hind limb was measured in situ before being excised (angle of femur/tibia joint: ≈ 135°). Then, the excised muscle was pinned in a dissecting chamber in such a way as to retain its measured length. In the same way, the length of the isolated muscle spindle was measured before it was transferred to the experimental chamber. The isolated spindle could then be placed in the stretching device in accordance with its length in situ. Again, L_0 was determined as the length of that part of the spindle that was placed between the two holding rods. This method was used in a second set of experiments in which the dependence of the activity of muscle spindle afferents on temperature changes was studied under different degrees of pre-stretch of the receptor.

Using the second method, the chain fibers of the spindles were often slightly kinked. Usually, it was possible to eliminate this kinking by stretching the spindle by 5–10% of L_0. Consequently, the muscle spindles of the first set of experiments had a pre-stretch level of 5–10% of their length in situ. Values of L_0 were 3–5 mm.

2.4. Stretching of the isolated muscle spindle

Isolated muscle spindles were stretched by the movements of two holding rods fixed to the membranes of two loudspeakers. The movements of these membranes were recorded with photocells which transformed the intensity of a beam of light reflected from mirrors attached to the membranes into a DC signal.

We chose amplitudes of ramp-and-hold stretches which ranged from 2% to 10% of the spindle's initial length L_0. The velocities of the ramp phase ranged from 5% to 100% of L_0/s. The plateau phase was held for a period of 3 s. Each stretch was repeated at least five times with constant parameters. There was a pause of 8 s between individual stretches.

Pre-stretch of the spindle was varied with the aid of a micrometer screw which adjusted the distance between the two holding rods. The following pre-stretch positions were chosen: $L_0 - 20\%$, $L_0 - 10\%$, L_0 and $L_0 + 10\%$.

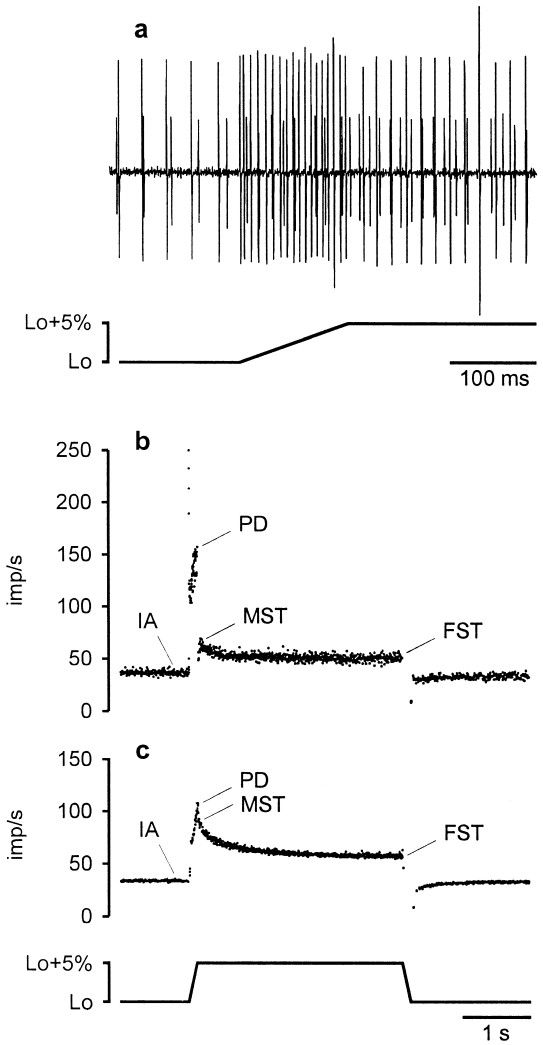


Fig. 1. Afferent activity of a primary and a secondary ending under a ramp-and-hold stretch at 35°C. (a) Oscillogram of the simultaneously recorded afferent discharges at the beginning of a ramp-and-hold stretch (large spikes = primary ending; small spikes = secondary ending). (b, c) Discharge patterns of the same endings (b: primary ending; c: secondary ending) with five responses superimposed. IA: initial activity; PD: peak dynamic discharge; MST: maximum static value; FST: final static value. The graphs under the oscillogram and under the discharge patterns represent the change in spindle length. Velocity of stretch: 40% L_0/s. L_0: a pre-stretch by 5–10% of the spindle length in situ.

2.5. Differentiation between primary and secondary endings

Discharge patterns of 28 primary endings and 35 secondary endings from 42 isolated muscle spindles were investigated. The activities of one to three afferents were recorded simultaneously from one spindle (Fig. 1a: large spikes = primary ending; small spikes = secondary ending). The following criteria were used to discriminate between primary and secondary endings. (1) Vibration test: Hunt and Ottoson [16] have shown that with primary endings driving (one discharge per cycle of a sinusoidal stretch) occurred at frequencies of 25–50 Hz and amplitudes < 5 μm. Secondary endings require stretch amplitudes of 50–100 μm to discharge in a similar way. We used sinusoidal stretches with amplitudes of 5 μm and raised the frequency from 10 Hz to 100 Hz. With primary endings, but not with secondary endings, driving occurred over the whole frequency range. (2) Primary endings respond to the beginning of ramp-and-hold stretches with an initial burst, secondary endings do not [15]. (3) The discharge frequency of a primary ending declines at the beginning of the plateau phase of a ramp-and-hold stretch to a postdynamic minimum [6,34]. No postdynamic minimum is observed in the discharge patterns of secondary endings. (4) Primary endings often fall silent during the

release of a ramp-and-hold stretch. Secondary endings usually continue to fire [6]. (5) When afferent activity is extracellularly recorded, the APs of primary endings are often larger than those of secondary endings, as a consequence of different axon diameters. All the criteria mentioned were used in association to classify the afferent activities. However, it was the vibration test that afforded the most reliable differentiation between primary and secondary endings.

2.6. Evaluation of discharge patterns

All the data that would be relevant for a subsequent evaluation of discharge patterns (i.e., extracellularly recorded APs, DC signals dependent on the temperature and on the spindle length, markers at the beginning of each stretch and at the start and end of a change in temperature) was stored on tape. A computer-aided evaluation of the data was used after the analog/digital conversion of all signals (16-bit A/D-converter; 10 kHz sample rate). Simultaneously recorded APs of different endings (see Fig. 1a) were distinguished by their amplitude and the instantaneous discharge frequencies of each ending were determined. Discharge patterns as shown in Fig. 1b for a primary ending and in Fig. 1c for a secondary ending were built up by superimposing the ending's responses to five successive ramp-and-hold stretches. Sometimes, the response to the first stretch was observed to be stronger than the response to subsequent stretches. In such cases, only the subsequent responses were superimposed on each other. Four basic discharge frequencies were taken from each discharge pattern (Fig. 1b and c): The initial activity (IA) is the median value of the instantaneous discharge frequencies during the last 500 ms before the start of the stretch. The peak dynamic discharge (PD) is the median value of the discharge frequencies during the last 25 ms of the ramp phase, where the stretch velocity was $< 80\%\ L_0/\text{s}$. If the stretch velocity was $\geq 80\%\ L_0/\text{s}$, the PD was determined during the last 15 ms of the ramp phase. The highest discharge frequency during the plateau of the stretch is the maximum static value (MST). MST was evaluated as the median frequency over a period of 50 ms beginning at 20 ms after the start of the plateau phase. Sometimes, the highest discharge frequencies were found up to 70 ms later in the plateau phase, in these cases the period of evaluation was shifted correspondingly. The median value of the discharge frequencies during the last 250 ms of the plateau phase is defined as final static value (FST).

3. Results

3.1. Temperature sensitivity of the basic discharge frequencies of primary and secondary endings

In the first set of experiments, the effects of changes in temperature on the basic discharge frequencies of primary and secondary endings were studied under ramp-and-hold stretches. The isolated muscle spindle was pre-stretched by 5–10% of its length in situ. The discharge pattern of a primary ending is shown in Fig. 2a at 35°C and in Fig. 2b at 25°C. At both temperatures, the discharge patterns showed all the typical features of a primary ending: The highest discharge frequency was that of the initial burst occurring at the beginning of the stretch, which is not further investigated in this study. The discharge frequency increased during the ramp, reaching the PD at the end of the ramp. The discharge frequency underwent abrupt decay following PD and preceding MST at the beginning of the plateau. This decay is the fast component of the receptor adaptation; this is followed by the slow component which is represented by the decay of the discharge frequency from MST to FST. The release of the stretch induced a pause in the firing. The background activity returned to its initial level after a few seconds. The main effect of raising the temperature from 25°C to 35°C was an increase in all the basic discharge frequencies: the IA increased from 9 imp/s at 25°C to 38 imp/s at 35°C, the PD from 41 imp/s to 91 imp/s, the MST from 22 imp/s to 66 imp/s and the FST from 17 imp/s to 55 imp/s.

Fig. 3 generalizes the temperature effect obtained from the data of 10 primary (Fig. 3a) and 14 secondary endings (Fig. 3b), each of them tested under the same experimental

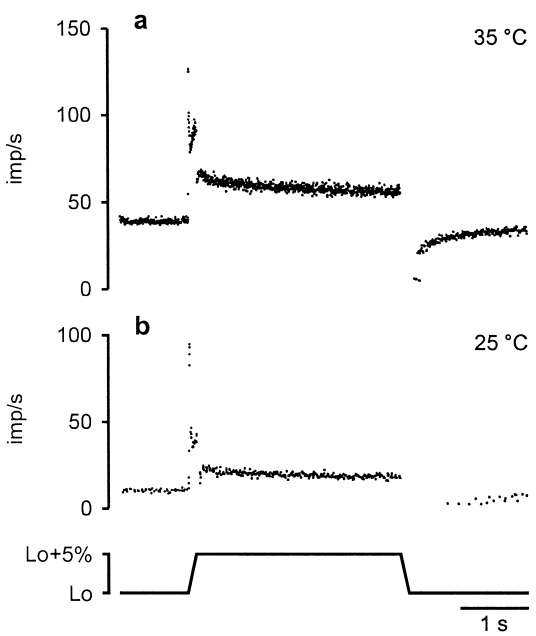


Fig. 2. Discharge pattern of a primary ending under a ramp-and-hold stretch at 35°C (a) and at 25°C (b). An increase in the temperature results in an increase in the discharge frequency during each phase of the stretch stimulus. The stretch is represented in the bottom graph (same parameters of stretch as in Fig. 1).

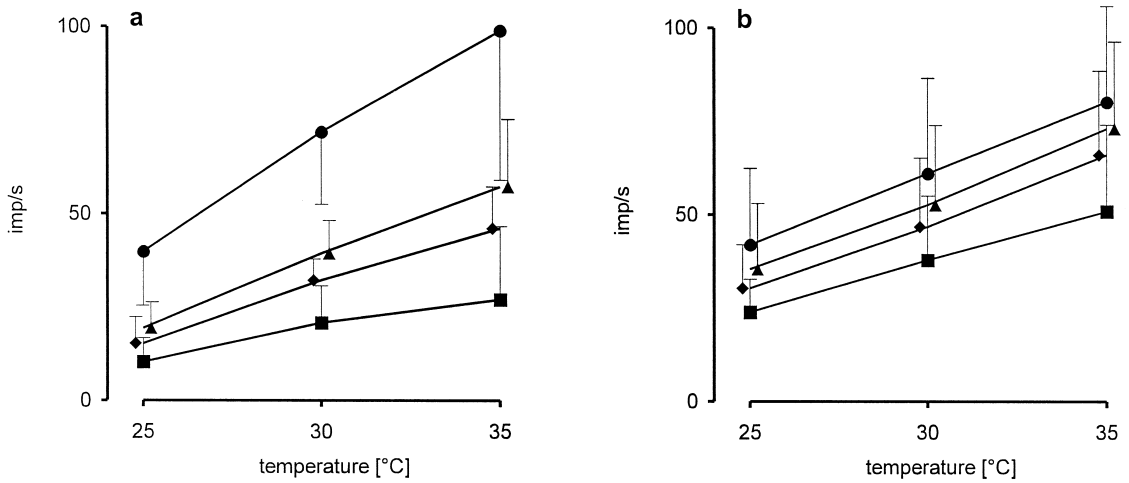


Fig. 3. Dependence of the mean basic discharge frequencies (PD: ●; MST: ▲; FST: ♦; IA: ■) of primary endings (a; $n = 10$) and secondary endings (b; $n = 14$) on the temperature (same conditions of stretch as in Fig. 1). Each basic discharge frequency increased with warming, but note the varying temperature sensitivities (= slopes of one curve). The symbols for MST and FST are plotted with a slight horizontal displacement to avoid overlapping standard deviations.

conditions as shown in Fig. 2. In both panels, the mean values of each basic discharge frequency are plotted against the temperature. For the sake of greater clarity, the symbols of MST and FST were displayed with a slight horizontal displacement. The standard deviations included in this and the next figure are not only due to different temperature characteristics of different endings. They also reflect the different specific levels of activity of each individual ending. Therefore, the standard deviations do not represent a valid estimation of the variance of the temperature effects.

The mean basic discharge frequencies of both primary and secondary endings rose with increasing temperature. However, the temperature sensitivity (imp s^{-1} $°C^{-1}$), i.e., the slope of the curve, differed between the basic discharge frequencies of primary endings, while remaining nearly constant as between the basic discharge frequencies of secondary endings. The temperature sensitivity of primary endings was ranked as follows (Fig. 3a): PD (6.2 imp s^{-1} $°C^{-1}$) > MST (3.9 imp s^{-1} $°C^{-1}$) > FST (3.1 imp s^{-1} $°C^{-1}$) > IA (1.6 imp s^{-1} $°C^{-1}$). The temperature sensitivity of secondary endings (Fig. 3b) was nearly the same for PD, MST and FST (3.5–3.9 imp s^{-1} $°C^{-1}$). Only the temperature sensitivity of IA was lower (2.4 imp s^{-1} $°C^{-1}$).

How do the temperature sensitivities change if the parameters of the stretch change? In order to investigate this question, we varied the velocity of the ramp-and-hold stretch between 5% L_0/s and 100% L_0/s, while keeping the amplitude of the stretch constant (5% L_0). Thereafter, we kept the velocity of the stretch constant (10% L_0/s) and varied the amplitude between 2% L_0 and 10% L_0. The temperature sensitivity was calculated as the increase in the discharge frequency per °C during warming from 25°C to 35°C. Fig. 4 shows the mean temperature sensitivities of PD, MST, FST and IA of primary and secondary endings in terms of their dependence on stretch velocity (a: primary endings, $n = 9$; b: secondary endings, $n = 8$) and stretch amplitude (c: primary endings, $n = 8$; d: secondary endings, $n = 11$). The endings used in the compilation of the various panels of Fig. 4 are those which were tested under a complete set of experiments. Again, standard deviations are included in this figure, even though they only partly reflect the variability of temperature effects on different endings. The excessively large standard deviations of the PD temperature sensitivities in Fig. 4a were mainly related to the differing dynamic properties of the individual primary endings.

The mean values in Fig. 4a show that the PD temperature sensitivity of primary endings clearly rose with increasing stretch velocity. The temperature sensitivity of PD was 4.4 imp s^{-1} $°C^{-1}$ at a stretch velocity of 5% L_0/s and 7.0 imp s^{-1} $°C^{-1}$ at 100% L_0/s. The temperature sensitivity of the other basic discharge frequencies did not show dependence on the stretch velocity.

The PD temperature sensitivity of secondary endings (Fig. 4b) did not greatly change with an increasing stretch velocity ranging from 3.3 to 4.2 imp s^{-1} $°C^{-1}$. Similarly, the temperature sensitivities of MST, FST and IA remained unchanged when the stretch velocity was increased. Fig. 4c and d show that the temperature sensitivities of the four basic discharge frequencies of both types of ending were almost independent of the amplitude of stretch. But there was, nevertheless, a clear difference between primary and secondary endings: the temperature sensitivities of primary endings were ranked in the order PD > MST > FST > IA under the various experimental conditions, whereas the temperature sensitivities of secondary

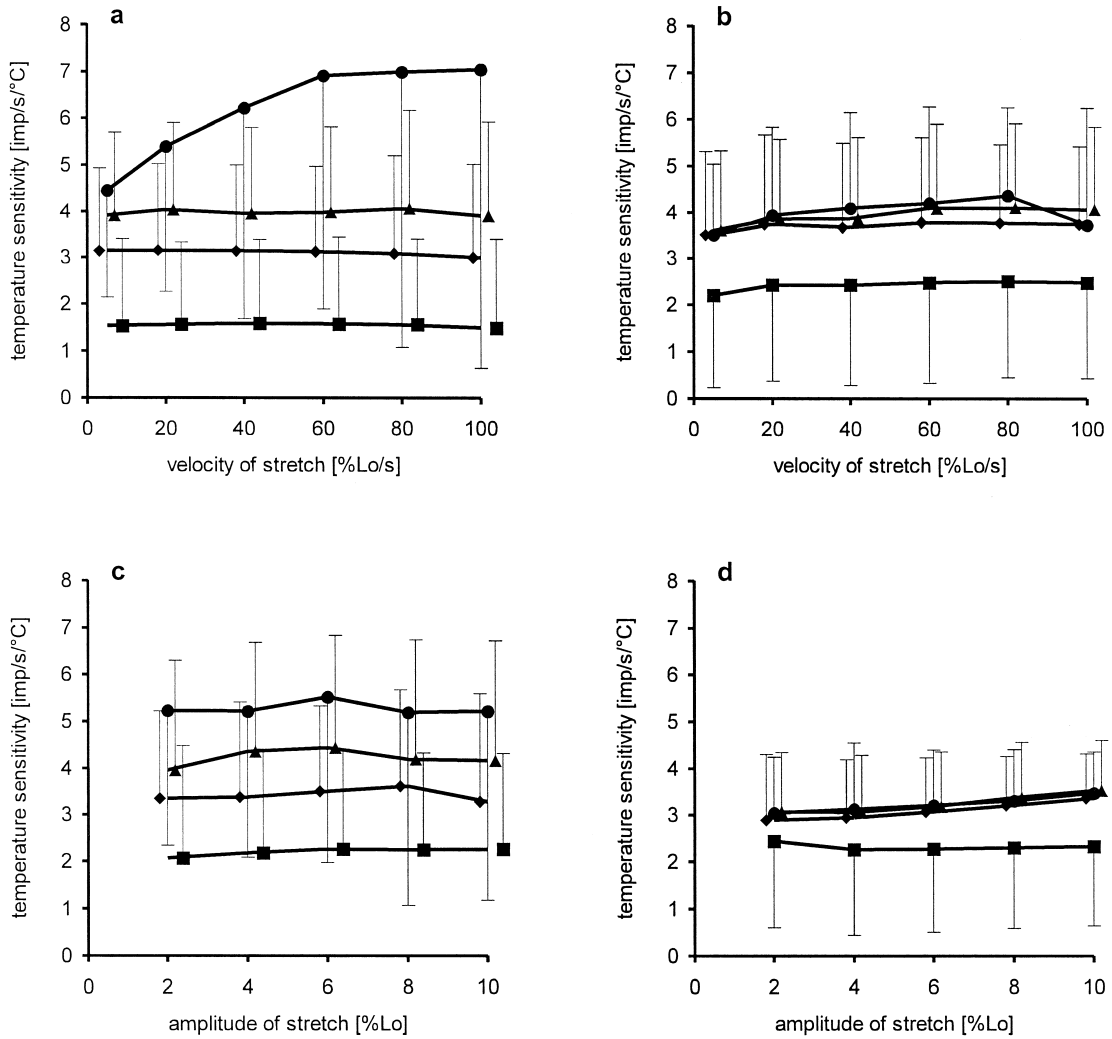


Fig. 4. Dependence of the temperature sensitivity of the mean basic discharge frequencies (PD: ●; MST: ▲; FST: ◆; IA: ■; note that the symbols are plotted with a slight horizontal displacement) on the velocity of stretch (a and b) and on the amplitude of stretch (c and d). (a) Primary endings ($n = 9$); (b) secondary endings ($n = 8$); (c) primary endings ($n = 8$); (d) secondary endings ($n = 11$). Temperature sensitivities are ranked in the order PD > MST > FST > IA in primary endings. In secondary endings, the temperature sensitivities of PD, MST and FST are very similar, but greater than the temperature sensitivity of IA.

endings were similar for PD, MST, and FST and lower only for IA.

3.2. Temperature coefficient (Q_{10}) of the basic discharge frequencies of primary and secondary endings

In general, the temperature coefficient Q_{10} is calculated as the quotient of the rates of physical, chemical or biological processes measured at two different temperatures with an interval of 10°C. Ottoson [27] used Q_{10} to describe changes in the impulse activity of isolated frog muscle spindles when the temperature was increased by 10°C. We used the temperature coefficient Q_{10} in a very similar way. Q_{10} was calculated as the quotient obtained by dividing each mean basic discharge frequency at 35°C by the mean basic discharge frequency at 25°C. Calculating the Q_{10} value certainly represents a simplification when comparing temperature effects on primary and secondary endings, because it is not known how many temperature-dependent processes contribute to the overall reaction or what profiles the individual processes have. Nevertheless, the calculation is useful because different temperature coefficients of the overall reaction indicate differences in at least one of the underlying processes.

The Q_{10} values of the basic discharge frequencies are plotted in Fig. 5 against the velocity of stretch (Fig. 5a) and the amplitude of stretch (Fig. 5b). The temperature coefficients of primary endings are shown in dark blocks, those of secondary endings in light blocks.

The Q_{10} values of primary endings were larger than the Q_{10} values of secondary endings. This observation was valid for every basic discharge frequency regardless of the

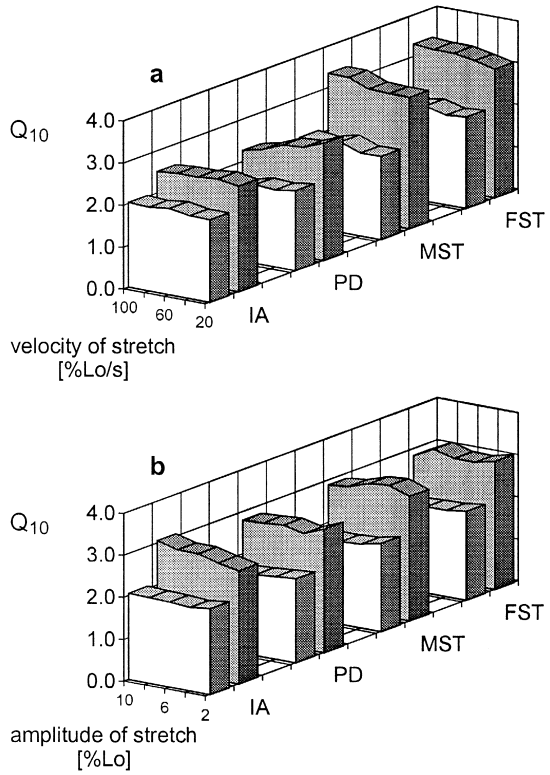


Fig. 5. Temperature coefficients (Q_{10}) of the mean basic discharge frequencies of primary endings (dark blocks) and secondary endings (light blocks). Q_{10} values were similar for all basic discharge frequencies in each type of ending and nearly independent of the stretch parameters. However, they were always larger in primary endings than in secondary endings.

parameters (velocity or amplitude) of the applied stretch. Additionally, the two diagrams show that the temperature coefficients of the primary and secondary endings, respectively, were very similar for all four basic discharge frequencies, whereas the temperature sensitivities were not (Fig. 4).

The Q_{10} values of secondary endings were within a very narrow range of 1.9–2.2, and were independent of the velocity and amplitude of the stretch. There was one exception to this: Under a high velocity of stretch ($\geq$ 80% L_0/s) the Q_{10} value of PD was smaller (minimum: 1.6). The mean Q_{10} value of secondary endings was 2.0.

In panel (a) the Q_{10} values of the basic discharge frequencies from primary endings were within a range of 2.3–3.3. The smallest temperature coefficient of 2.3 resulted from the small PD temperature coefficient at a rate of 100% L_0/s. Thus, the primary and the secondary endings displayed a similar behavior of their PD temperature coefficients. The mean of all Q_{10} values of primary endings was 2.9. If the velocity of the stretch was held constant and the amplitude of the stretch varied (panel b), the Q_{10} values were within a narrow range of between 2.7 and 3.1. The mean value was again 2.9.

3.3. Temperature effects on the adaptation of the isolated muscle spindle

The decay of the discharge frequency observed during the plateau phase of a ramp-and-hold stretch represents the adaptation of a sensory afferent of the isolated receptor. This decay breaks down into the fast component of adaptation, being the decrease in the discharge frequency from PD to MST, and the slow component of adaptation, which is the decrease from MST to FST [34].

Mean values of the fast and the slow component of adaptation of primary and secondary endings are shown in Fig. 6. The mean values are plotted against the temperature and the velocity of stretch. The fast adaptive component of primary endings was dependent on the velocity of stretch at all temperatures (25°C, 30°C, and 35°C; Fig. 6a). By contrast, the slow adaptive component of primary endings was not dependent on the velocity of stretch (Fig. 6c). The adaptation of secondary endings was qualitatively similar to that of primary endings when the velocity of stretch was varied (Fig. 6b and d). However, the amount of the fast adaptive decay was smaller in secondary endings than in primary endings.

The dependence of the adaptation on temperature was clearly different for primary and secondary endings. The adaptation of primary endings was influenced by temperature changes: The mean value of the fast decay doubled if the spindle was warmed by 10°C from 25°C to 35°C. The slow component of adaptation rose as well, and by a factor of as much as 3.2. Nevertheless, only a small proportion of the adaptive process was accounted for by slow decay (see different scales of the ordinates in Fig. 6a and c). In secondary endings, the fast component of adaptation was unaffected by temperature changes (Fig. 6b), whereas the slow component was affected (Fig. 6d). However, this effect was much smaller than in primary endings. Slow decay increased by a factor of only 1.4 when the temperature rose from 25°C to 35°C.

If the amplitude of the stretch was varied (not shown), the fast component of adaptation was influenced by changes in temperature in primary endings only (factor 2.4 when warmed from 25°C to 35°C). The slow component of adaptation increased much more in primary endings (factor 3.3) than in secondary endings (factor 1.5) when the spindle was warmed from 25°C to 35°C.

With regard to non-isolated muscle spindles, it has been shown that the slow component of adaptation of the afferent discharge frequency represents an approximately exponential decay with a time constant of about 0.5 s [5,34]. With isolated muscle spindles, such an exponential approximation was found not to apply to every ending. The time constants that were estimated for those primary and secondary endings that displayed a nearly exponential decay were within the range of 1–5 s. These values were larger than those reported for non-isolated spindles, possibly because the viscoelastic properties of the extrafusal fibers

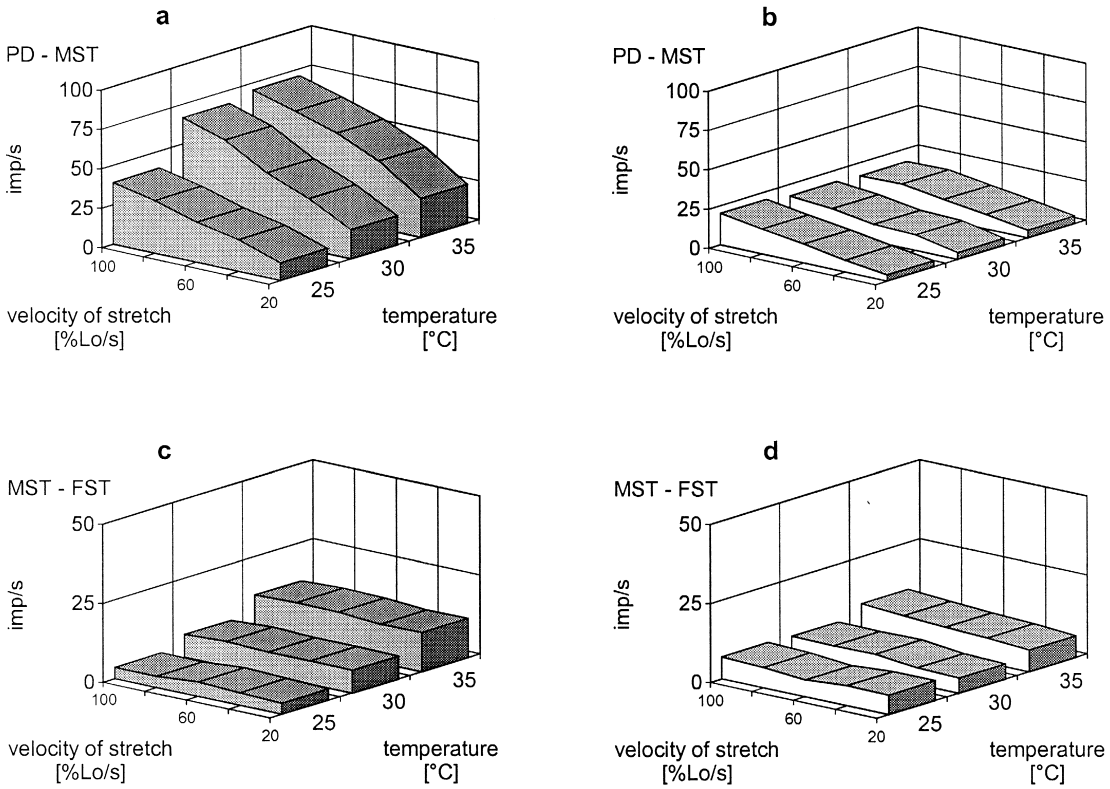


Fig. 6. Temperature effects on the adaptation of primary (a and c; $n = 9$) and secondary endings (b and d; $n = 8$) evaluated under different velocities of stretch. The fast (a and b) component of adaptation of both endings was dependent on the velocity of stretch, but not the slow component (c and d). In primary endings, both the fast (a) and the slow (c) components of adaptation were strongly influenced by temperature. In secondary endings, by contrast, neither component of adaptation (b and d) was generally influenced by changes in temperature.

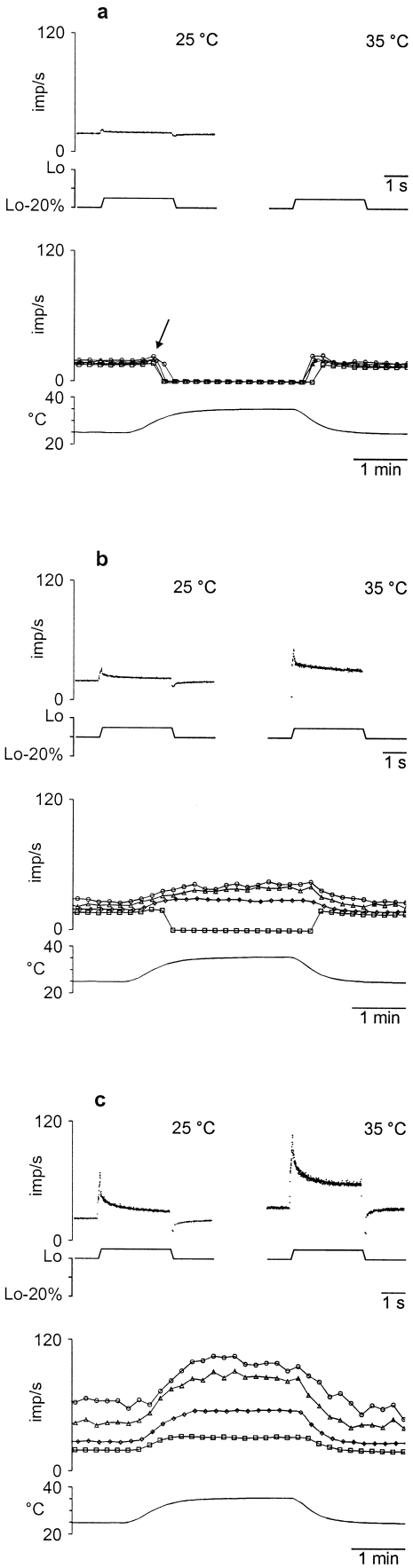
contributes to the course of adaptation in the non-isolated receptor. We investigated the time course of the slow adaptive component in the isolated muscle spindle at temperatures of 25°C, 30°C, and 35°C. However, we did not find an effect of the temperature on the time constants in either type of ending.

3.4. Temperature effects on the discharge frequency of sensory afferents under different pre-stretches of the isolated muscle spindle

In a further set of experiments, we tested the influence of temperature change on the discharge frequency of primary and secondary endings when the pre-stretch of the isolated spindle was altered. Four different levels of pre-stretch were chosen: $L_0 + 10\%$, L_0, $L_0 - 10\%$, $L_0 - 20\%$. At a pre-stretch of $L_0 - 20\%$, almost all the spindles were totally relaxed; they fell slack between the two holding rods. At each degree of pre-stretch, the spindle was stimulated by ramp-and-hold stretches. The amplitude of the stretches was 5% of the spindle's new length. The velocity of the stretches was 40% of the spindle length per second.

Fig. 7 shows a representative example of the responses of one secondary ending at different degrees of pre-stretch (a: $L_0 - 20\%$; b: $L_0 - 10\%$; c: L_0). The lowest section of each panel shows the temperature curve, first increasing from 25°C to 35°C and then reducing to 25°C again. In the middle section of each panel, the alterations of the basic discharge frequencies IA, PD, MST and FST are plotted against time. In the upper section of each panel, two discharge patterns are given. The discharge pattern on the left-hand side was recorded at 25°C and that on the right-hand side at 35°C. The ramp-and-hold stretch is depicted beneath each discharge pattern, starting from the appropriate degree of pre-stretch in each case.

In the totally relaxed spindle ($L_0 - 20\%$; Fig. 7a), the secondary ending was active only if the temperature was low (left-hand side discharge pattern). Under this condition, the response of the secondary ending to the ramp-and-hold stretch was small. If the temperature was enhanced to 35°C the ending was not active any more (silence of the ending on the right-hand side in the upper section of the panel). In the lower section of the panel the curves of PD, MST, FST and IA lie very close together when plotted against time. However, a small increase in the activity of the ending was to be observed (see arrow in Fig. 7a) before the basic discharge frequencies dropped to zero imp/s when the temperature passed 30°C. This small increase in discharge frequency was caused by warming. The ending totally recovered from inactivity when the spindle was cooled to 25°C again.



In a less relaxed state of the spindle ($L_0 - 10\%$; Fig. 7b), the secondary ending was more affected by ramp-and-hold stretches. The responses of the secondary ending to the ramp-and-hold stretches became greater even though the ending did not develop any IA in the discharge pattern recorded at 35°C (IA = 0 imp/s). However, the remaining basic discharge frequencies (PD, MST and FST) were higher at 35°C as compared to their values at 25°C. Plotting the basic discharge frequencies against time, one can see that IA ceased abruptly when the temperature exceeded 32°C, whereas PD, MST and FST increased further with warming. It should be emphasized that at this degree of pre-stretch warming to 35°C resulted in an increase in the ending's activity during the ramp-and-hold stretch and a decrease in activity during the pauses between individual stretches. The effect was reversible.

When the isolated spindle was held at its length in situ (L_0; Fig. 7c) the basic discharge frequencies increased with warming and decreased with cooling, as shown by the discharge patterns recorded at 25°C and 35°C, as well as by the curves of the basic discharge frequencies plotted against time. The ending generated continuous background activity and responded strongly to ramp-and-hold stretches at the test temperatures.

A total of 18 endings were tested under the same conditions as shown in Fig. 7. Six of these endings continued firing at each degree of pre-stretch. The background activity of seven endings ceased during warming under low pre-stretch levels ($L_0 - 10\%$ or $L_0 - 20\%$). In the remaining five spindles, the background activity broke off if the spindle was kept at its length in situ (L_0). These endings were totally inactivated by warming if they were relaxed by 10–20% of L_0. They did not even discharge during ramp-and-hold stretches at 35°C.

The abrupt cessation of the background activity was investigated in more detail under the four degrees of pre-stretch. For this purpose, the background discharge was recorded continuously while the temperature was increased from 25°C to 35°C. The temperature at which firing stopped was defined as the break-off temperature. The break-off temperature was most frequently found to be

Fig. 7. Temperature effects on the basic discharge frequencies of one secondary ending under different degrees of pre-stretch of the isolated muscle spindle. Pre-stretch levels were $L_0 - 20\%$ (a), $L_0 - 10\%$ (b) and L_0 (c). In each panel, the discharge patterns of the ending are shown by the two upper curves, obtained at 25°C and 35°C, respectively. The ramp-and-hold stretch is depicted under each discharge pattern (same conditions as in Fig. 1). In the middle section of each panel the changes of the basic discharge frequencies PD (○), MST (△), FST (◇) and IA (□) are plotted against time. The interval between individual data was about 11 s. Alterations in temperature plotted against time are presented in the lowest section of each panel. If the muscle spindle was relaxed (a), the activity was inhibited by warming. If the spindle was pre-stretched (c), warming had an excitatory effect. For further explanation, see text.

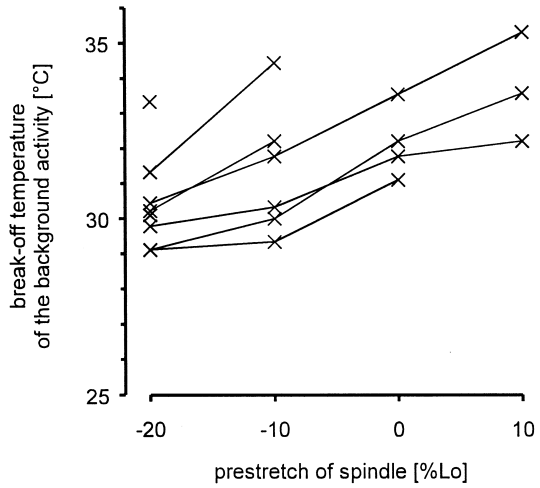


Fig. 8. Dependence of the temperature at which background activity ceased abruptly during warming on the pre-stretch of the muscle spindle. Data of eight secondary endings is included: the data of each individual ending is connected by a line. The break-off temperature of the background activity increased with increasing pre-stretch of the spindle.

within the range of 29–33°C. It was specific to each ending and dependent on the degree of pre-stretch. Fig. 8 shows the dependence of the break-off temperature of eight secondary endings on the pre-stretch of the spindle. Each curve represents one ending. Two endings are represented by a single diagonal cross at a pre-stretch level of $L_0 - 20\%$, because at the other degrees of pre-stretch, these endings continued firing over the whole temperature range. The remaining endings were inactivated even if the spindle was not totally relaxed. The positive slopes of the curves demonstrate that the break-off temperature increased as the pre-stretch of the spindle increased. Thus, the lowest curve shows that at a pre-stretch level of $L_0 - 20\%$, the background activity of this ending ceased when the temperature exceeded 29.1°C. Under a relaxation of only $L_0 - 10\%$ the ending stopped discharging at a temperature of 29.3°C, and at a pre-stretch level of L_0 the background activity ceased at 31°C. If the spindle was pre-stretched by $+10\%$ of L_0, the background activity did not stop during warming. On average, the break-off temperature increased by 1.7°C when the pre-stretch level of a spindle was increased by 10%.

Michalski and Séguin [26] classified secondary endings of gastrocnemius spindles in vivo by their responses to temperature changes as CR (cold response) neurones or NCR (non-cold response) neurones. The authors studied the afferent background discharge: CR neurones were not active in the relaxed muscle at 37°C, but they were active if the relaxed muscle was cooled. NCR neurones were active in a pre-stretched muscle; in a relaxed muscle, neither warming nor cooling could activate NCR afferents. Additionally, Michalski and Séguin investigated the dynamic index (DI) and the static response (SR) of the classified secondary endings under ramp-and-hold stretches at 37°C. The DI is the difference between the discharge frequency at the end of the ramp (= PD) and the discharge frequency during the plateau phase of the stretch as measured 0.5 s after the end of the ramp [5]. The SR is the discharge frequency 0.5 s after the end of the ramp. Michalski and Séguin stated that both the DI and the SR were smaller in NCR neurones than in CR neurones.

In contrast to the findings of Michalski and Séguin, our secondary endings of isolated tenuissimus muscle spindles did always discharge at 25°C with a discharge frequency of between 10 and 20 imp/s. Moreover, at this temperature, the discharge frequency was only slightly influenced by changes in the degree of pre-stretch. During warming the background activity either increased to 20–40 imp/s, depending on the pre-stretch of the spindle, or else it ceased. The criteria used by Michalski and Séguin to distinguish between CR and NCR neurones were not applicable to our data. Thus, we had to find other criteria to group secondary endings. These criteria needed to be as similar as possible to the classification features mentioned. We therefore assigned to Group 1 those secondary endings which stopped discharging during warming at any degree of pre-stretch of the spindle (12 out of 18 secondary endings). The remaining six secondary endings which displayed no break-off temperature were assigned to Group 2. We measured the values of DI and SR under different pre-stretch levels of the spindles at temperatures of 25°C and 35°C. The mean values of DI and SR did not differ greatly between the two groups of endings at any one pre-stretch level, either at 25°C or at 35°C. Thus, the dynamic and static properties of the secondary endings of both groups were very similar, and it was not possible to separate our endings into two groups by their stretch properties. This finding was supported by the following observation: One Group 2 ending reversibly stopped firing when the temperature was increased to above 42°C. At this very high temperature this secondary ending fulfilled the criteria of the Group 1 endings. Therefore, each secondary ending could possibly have a specific temperature at which it may be inactivated by warming.

The reason for the discrepancy between the findings of Michalski and Séguin and our observations may be that ramp-and-hold stretches influence non-isolated and isolated muscle spindles in a different way. Possibly, the sensitivity of non-isolated receptors to stretch is dependent on their position and fixation in the muscle tissue. It is not known how a mechanical stimulus is altered by its transmission via extrafusal fibers. In particular, it is not known whether such extrafusal fibers that are connected to the spindle capsule are capable of altering the effect of a stretch, so that the sensory nerve endings in the juxtaequatorial and in the equatorial region of the spindle are differently stimulated. In isolated muscle spindles, the stretch is not transmitted via extrafusal fibers. The poles of the intrafusal fibers transmit the stimulus directly to the sensory region of the spindles.

Primary endings were, in general, not inhibited by warming from 25°C to 35°C. A reversible cessation of the background activity occurred very seldom. No inactivity was observed during a ramp-and-hold stretch. If the temperature exceeded 40°C, the background activity of a small number of primary endings did break off; this process was, however, not reversible. Even if the basic discharge frequencies PD, MST and FST recovered after cooling, the background activity did not.

The temperature coefficients of the basic discharge frequencies IA, PD, MST and FST were calculated for primary and secondary endings under different pre-stretch values. Fig. 9 shows temperature coefficients in relation to the levels of pre-stretch. The Q_{10} values of primary endings (dark blocks; $n = 8$) were, in general, larger than those of secondary endings (light blocks; $n = 10$). In the case of secondary endings, the inhibitory effect of warming resulted in a decrease in the temperature coefficients of the four basic discharge frequencies with decreasing pre-stretch of the spindle. Thus, the Q_{10} values of the four basic discharge frequencies were smaller than 1 at the pre-stretch level $L_0 - 20\%$. Primary endings, by contrast, did not show this effect: on the contrary, the Q_{10} values of PD, MST and FST increased a little with decreasing pre-stretch of the spindle.

3.5. Temperature effects on the mechanical properties of isolated muscle spindles

In previous investigations studying non-isolated muscle spindles, temperature-induced alterations of the viscoelastic properties of the muscle tissue were excluded because muscle tension did not change significantly during warming or cooling [4,7,25]. Eldred et al. [7] concluded that the viscoelastic properties of intrafusal fibers would probably not be altered by thermal stimuli either. However, there was no direct evidence for this conclusion. Here we present our own observations on isolated muscle spindles, which contribute some additional indirect support to this assumption.

If alterations of the afferent discharge frequency were due to changes in the viscoelastic properties of intrafusal fibers or of intrafusal connective tissue, then changes in temperature should result in a stretching or compression of the equatorial sensory region of the spindle. We never observed any length changes in the sensory region after warming or cooling during our investigations, although the isolated spindle was observed at 600-fold magnification under the microscope. By contrast, experimentally applied stretches that increased the afferent discharge frequency by an amount similar to that being induced by warming the spindle were always accompanied by clearly visible length changes in the spindle's equatorial region. In other control experiments, contractions of the intrafusal bag_1 and bag_2 fibers were elicited without any change in the total length of the spindle by an application to the bath solution of the acetylcholine agonist succinylcholine. The contractions evoked by succinylcholine resulted in clearly visible length changes of the sensory region accompanied by an increase in the afferent discharge frequency. A further test supports the assumption that temperature-induced changes in the afferent discharge frequencies were not caused by alterations to the viscoelastic properties of intrafusal fibers: The activity of muscle spindle afferents was recorded at 25°C and at 35°C, with the spindle being fixed to the holding rods at their poles as usual. Subsequently, the measured activity was compared with the activity of the same spindle afferents after the polar regions of the intrafusal fibers had been stiffened by the application of a histoacryl glue, so that only the sensory region of the spindle was available for stretching. As a result of this manipulation, the amount of the viscoelastic elements that could change their properties during warming or cooling was enormously reduced. However, the temperature effects did not change.

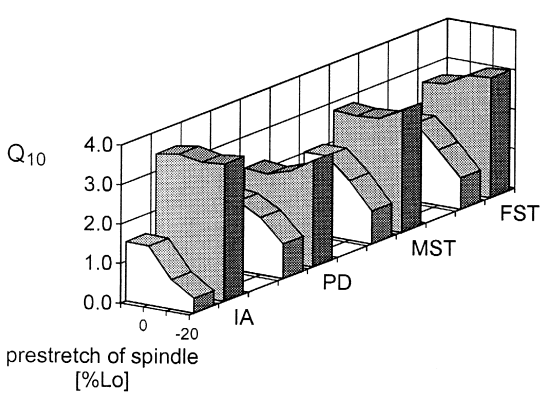


Fig. 9. Temperature coefficients (Q_{10}) of the mean basic discharge frequencies of primary endings (dark blocks) and secondary endings (light blocks) at different degrees of pre-stretch of the muscle spindle. In most of these endings, the Q_{10} values of relaxed secondary endings are strongly reduced as a result of an inhibitory effect of warming.

4. Discussion

Our investigations on isolated cat muscle spindles show that warming often increases the activity of primary and secondary endings. However, depending on the degree of pre-stretch of the spindle, most secondary endings can be inhibited by warming as well. Before we discuss our results in detail, it should be clarified which sites of the isolated muscle spindle might be affected by changes in temperature. On the one hand, warming and cooling could influence the transmission of mechanical stimuli from the poles of the spindle to its sensory region. This would be the case if the viscoelastic properties of the intrafusal fibers or of the connective tissue were altered by changes in temperature. On the other hand, temperature changes could affect the electrophysiological processes of generat-

ing the receptor potential at the sensory ending membranes and of transforming the receptor potential into a sequence of APs at the spindle afferent encoder site.

In view of our observations, it is unlikely that viscoelastic processes play a decisive role in temperature-induced changes in the afferent discharge of the spindle. The relatively high Q_{10} values support this interpretation. However, Poppele and Quick [31] have shown that among the intrafusal fibers, the bag_1 fibers show a stretch-induced contraction that increases the sensitivity of primary endings to stretch. The sensitivity of secondary endings is not altered by this phenomenon because secondary endings generally do not contact bag_1 fibers. A temperature-dependent change in stretch activation cannot be ruled out. Therefore, it is reasonable to assume that the PD of primary endings is increased more by warming than the PD of secondary endings. However, differences in the temperature dependence of the other basic discharge frequencies that represent the static properties of primary and secondary endings are unlikely to be caused by the dynamic process of stretch-induced contractions.

We believe that the observed temperature effects can be explained by alterations in the properties of the sensory nerve endings. The receptor current passing through channels of the sensory membranes might be affected by warming or cooling. It is well-known that warming enhances the rates of gating of ion channels ($Q_{10} = 2–4$) [2,8,14] and to a smaller extent, increases the conductance of open channels ($Q_{10} = 1.2–1.5$) [13]. In addition to the rates of gating and the conductance, the open probability determines the amount of ions crossing through a channel per unit of time. The open probability of a channel may be increased or decreased by warming [1,22,35]. Unfortunately, there is little information about the channel composition of the sensory endings of muscle spindle afferents. It is very likely that stretch-activated channels (SA channels), which have been found in various tissues, exist in the muscle spindle afferents as well, although their existence has not yet been directly proved [11,12,18]. Voltage-gated calcium and potassium channels and calcium-dependent potassium channels have also been considered to be involved in the generation of the receptor potential in the muscle spindle and the crayfish stretch receptor [17,23,28,33].

Because the receptor current is composed of many different ionic currents, its temperature-induced alteration reflects the sum of effects on all the individual ionic currents. For a further discussion of our results, it might be helpful to divide the whole collection of ion channels into channels activated by stretch and channels not activated by stretch. Additionally, we should distinguish between those ionic currents that depolarize and those that hyperpolarize the receptor potential. We will discuss whether differences between temperature-induced changes in the discharge frequencies of primary and secondary endings may be caused by differences in the underlying ionic currents across their sensory membranes, because Hunt and Ottoson [15] have shown that the discharge frequency during the static phase of a ramp-and-hold stretch correlates linearly with the amplitude of the receptor potential, while changes in the discharge frequency during the dynamic phase of the stimulus correspond qualitatively to changes in the receptor potential. Effects of the thermal stimuli at the encoder site cannot be distinguished from effects at the sensory nerve endings. Even though some of the following interpretations may be speculative, they might contribute to a better understanding of the largely unknown membrane properties of muscle spindle endings.

4.1. Differences between temperature coefficients of primary and secondary endings

The temperature coefficients of the four basic discharge frequencies were larger in primary endings than in secondary endings (Fig. 5). The mean value of Q_{10} was 2.9 in primary endings and 2.0 in secondary endings, provided that the muscle spindles were pre-stretched by 5–10% of their length in situ. The value of Q_{10} depends on the influence of the temperature on the open probability and on the conductance of each ion channel at the sensory nerve endings. It also depends on the number of active channels and on the proportion of depolarizing to hyperpolarizing channels. Thus, the difference between the temperature coefficients of primary and secondary endings can be explained in two ways. (1) If an equal number of depolarizing and hyperpolarizing channels is assumed in primary and secondary endings, it would appear that different types of channel with specific temperature characteristics exist in primary and secondary endings. For example, the open probability of depolarizing channels might be increased more by rising temperatures in primary endings than in secondary endings. Thus, the receptor potential and the discharge frequency of primary endings would grow more and the Q_{10} values would be larger in primary endings than in secondary endings. (2) If it is assumed that primary and secondary endings use the same types of channel with identical temperature characteristics, then different temperature coefficients can be explained by there being different numbers of depolarizing and hyperpolarizing channels. Q_{10} values > 1 indicate that depolarizing effects dominate over hyperpolarizing effects during warming in both types of ending. The larger Q_{10} values of primary endings show that this dominance is stronger in primary endings than in secondary endings, indicating that there might be relatively more depolarizing channels in primary endings.

4.2. Differences between temperature sensitivities of primary and secondary endings

The temperature sensitivities (imp s^{-1} $°C^{-1}$) of primary endings were ranked in the order PD > MST > FST > IA. In secondary endings, by contrast, the temperature sensitiv-

ities of PD, MST and FST were very similar. Only the temperature sensitivity of IA was smaller (Fig. 4). This result is directly related to the finding that the Q_{10} values of the four basic discharge frequencies are each very similar in primary and in secondary endings (Fig. 5). Constant Q_{10} values indicate that raising the temperature from 25°C to 35°C induces an increase in the discharge frequency by a constant factor that is nearly independent of the phase of the ramp-and-hold stretch. Thus, differences between temperature sensitivities result from different levels of activity. The absolute increase in the high value of PD is larger than the absolute increase in the low value of IA, if both basic discharge frequencies are increased by the same factor and not by the same amount. In secondary endings, the temperature sensitivities of PD, MST and FST are very similar because the activity levels of all these basic discharge frequencies are very similar. However, these activity levels are higher than the activity level of IA, so that the temperature sensitivity of IA must be smaller as long as Q_{10} remains constant.

4.3. Differences between temperature effects on primary and secondary endings depending on changes of the pre-stretch of the spindle

In many cases, the activity of secondary endings was inhibited by warming the relaxed muscle spindle. The main feature of this inhibitory temperature effect was a sudden cessation of the background activity which could be observed if warming exceeded a temperature of about 30°C. In some cases, the activity during ramp-and-hold stretches also ceased, if the spindle was totally relaxed. A comparable inhibitory effect on primary endings was not generally observed. The inhibitory effect on secondary endings may be explained by the influence of a hyperpolarizing ionic current that is independent of stretch. Its contribution to the net ionic current is probably stronger in secondary endings than in primary endings, as will be explained below.

A hyperpolarizing ionic current that increases with rising temperature will shift the membrane potential of a sensory ending towards more negative values during warming. As a consequence, the discharge frequency of the afferent nerve fiber will decrease, as is seen in secondary endings. However, this hyperpolarizing current is likely to be only one component of the net ionic current. Thus, if the contribution of this current to the net ionic current is relatively large, the intense inhibitory effects which occur in secondary endings during warming of the relaxed spindle would be explained. By contrast, a relatively small contribution of this current would explain the low frequency of inhibitory effects during warming that is seen in primary endings.

It has been shown with regard to secondary endings that the inhibitory effect of warming was dependent on the pre-stretch of the spindle (Figs. 7 and 9) and that the break-off temperature of the background activity increased with increasing pre-stretch (Fig. 8). Both effects can be explained by the assumption that the postulated hyperpolarizing current passes through channels which open independently of the stretch. Thus, if the stretch of an isolated spindle is increased, the inhibitory effect of a current that is independent of the stretch becomes less effective as it is counteracted by a growing depolarizing current passing through SA channels. This SA current usually dominates the net ionic current in stretched spindles, while the hyperpolarizing currents could dominate the net ionic current in relaxed spindles. Moreover, it has been shown that in relaxed spindles most secondary endings which displayed background activity at 25°C, ceased firing if the temperature exceeded about 30°C. Thus, the excitatory depolarizing current dominated over the inhibitory hyperpolarizing current at 25°C, both currents were nearly balanced at 30°C and the inhibitory current was stronger than the excitatory current at 35°C. Therefore, the hyperpolarizing current was increased more by warming than the depolarizing current, possibly because the open probability of the hyperpolarizing channels increased by a larger degree.

Klussmann et al. [20,21] have shown that spinal motoneurones of the cat, like secondary muscle spindle endings, respond to warming with a decrease in their discharge frequency. An increase in temperature induces a hyperpolarization accompanied by an increase in the conductance of the motoneurone membrane, indicating an opening of channels [19,29]. Comparable parameters have not yet been measured from sensory nerve endings of muscle spindle afferents. However, if the inhibitory temperature effect in secondary endings is indeed caused by hyperpolarizing ionic currents that increase with warming, then in these endings warming should induce hyperpolarization and a reduction of the membrane resistance. Additionally, the electrogenic Na^+/K^+ pump may support hyperpolarization, because warming speeds up its rate of exchange. Beam and Donaldson [2] have shown that warming shifts the potassium equilibrium potential towards more negative values in frog muscle cells. This strengthens the electromotive force driving potassium ions across the membrane, which is likely to result in further hyperpolarization.

4.4. Differences between primary and secondary endings in terms of the temperature effects on the receptor adaptation

In primary endings, both the fast and slow components of adaptation were dependent on changes of temperature. In secondary endings, the fast adaptive component did not change during warming, while the slow adaptive component was slightly increased (Fig. 6). Boyd [3] has shown that the adaptation of the afferent discharges is accompanied by creep of the intrafusal fibers (bag_1 and bag_2) during the plateau of a ramp-and-hold stretch. This creep

probably results in the closure of some SA channels, so that the receptor potential is slightly repolarized because repolarizing channels remain open. The afferent discharge frequency decreases. Thus, the temperature effect on the slow decay of the discharge frequency seems to be due to temperature effects on SA channels in both types of ending. However, the stronger temperature effect on primary endings indicates that an additional mechanism underlies the slow adaptive process of these endings. This additional mechanism could be an increase of a hyperpolarizing current such as has been shown for the fast decay of the discharge frequency in primary endings: Hunt et al. [17] found a postdynamic hyperpolarization of the receptor potential which correlated with this fast decay. This hyperpolarization was dependent on the extracellular concentration of potassium and could be blocked by TEA. Kruse and Poppele [23] discussed the participation of a calcium-activated potassium channel, calcium having entered the sensory ending through SA ion channels under a ramp-and-hold stretch. We observed a strong temperature effect on the fast decay of the discharge frequency in primary endings, which supports the findings of the authors cited above. Possibly the repolarizing current through calcium-activated potassium channels is effective not only at the beginning of the plateau but also during the plateau. This current seems to be strong in primary endings and very weak in secondary endings. As a result, it is only in primary endings that the fast adaptive component is affected by changes in temperature, and the temperature effect on the slow component of adaptation is larger in primary endings than in secondary endings.

4.5. Functional implications

The body temperature of mammals is regulated within a narrow range by controlling elements of the hypothalamus. However, the temperature of peripheral muscles changes markedly with the ambient temperature. Therefore, a few remarks concerning the possible functional implications of temperature effects on peripheral movement control will be added, even though the experiments focused solely on the properties of the muscle receptor.

Our results indicate that an identical change in length applied to a cold and to a warm muscle elicits a rather different afferent activity pattern that contributes to the movement control of the spinal cord and higher centers of the central nervous system. In the cold muscle, the stretch results in a minor change of activity in Ia and group II afferents. In the warm muscle, the same stretch evokes dramatic changes in the discharge frequency, indicating an increased stretch sensitivity that might contribute to improved movement control. However, the activity of group II afferents might be either diminished or enhanced, depending on the degree of pre-stretch of the muscle. The inhibitory effect of warming that is obvious only in the relaxed muscle might be overcome in vivo by an increased γ-activation.

Chapman et al. [4] have shown that active tension of the stretch reflex in the decerebrate cat reaches its maximum when the muscle temperature is within the range of 30–34°C. The authors conclude that those secondary endings that show a loss of activity during warming are responsible for the decrease in the active tension in a higher temperature range. Our results may support this conclusion as long as the muscle is relaxed. However, the authors did not recognize that even if the background activity of a number of secondary endings is depressed by warming, the ending's sensitivity to stretch is significantly increased. Thus, in slightly pre-stretched muscles, a decrease in the active tension of the stretch reflex is not to be expected, since the discharge frequency of both primary and secondary endings will increase during stretch. In conclusion, our results indicate that reflex movements should be strengthened during warming by increasing afferent input from the muscle spindles to the motor nuclei, as long as the initial muscle length is not very short.

There is another aspect concerning the γ-control of muscle spindles that is worth mentioning: γ-motoneurones themselves show a temperature-dependent activity that is qualitatively similar to that of most secondary endings, i.e., their discharge frequency rises with warming but is suppressed at a temperature exceeding the normal body temperature [20,21]. Lowering the temperature of the spinal cord to a certain degree increases the discharge frequency and stretch sensitivity of both types of muscle spindle afferents due to an intensified γ-activation. This behavior counteracts the reduced stretch sensitivity of muscle spindle afferents when the muscle is cooled. Taking into account a positive feedback from secondary endings to γ-motoneurones that has been recently described by Gladden et al. [10], the temperature dependence of spinal movement control becomes even more complex.

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