Eur J Appl Physiol (1988) 57:409–414

European Journal of
Applied Physiology
and Occupational Physiology

Effects of leg activity and ambient barometric pressure on foot swelling and lower-limb skin temperature during 8 h of sitting

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Summary Prolonged immobilization in an upright position often leads to discomfort and oedema in the feet of otherwise healthy subjects. To determine the significance of leg activity and ambient pressure on oedema formation, skin temperature (T_{sk}) and discomfort, 6 volunteers sat for 8 h with one leg immobilized and the other spontaneously active; one day at "sea level" (750 mmHg) and one day at reduced barometric pressure (540 mmHg). Foot swelling was measured by water plethysmography. Leg movements were continuously monitored by a Vitalog computer, and foot discomfort was estimated by analog-visual scales. The 8 hour swelling averaged 5.7% in the inactive foot, and 2.7% in the active foot ($p < 0.001$). T_{sk} of the inactive foot levelled off towards ambient temperature (21 °C) within 4 h. For the active foot this fall was reduced by 2–3 °C ($p < 0.025$). The increase in foot discomfort during the day was lowest in the active foot ($p < 0.005$). High foot T_{sk} was associated with a high foot swelling rate. Reduced ambient barometric pressure had no effects on foot swelling or T_{sk}. It is concluded that modest leg activity during 8 h of sitting has several effects on the circulation in the feet: some effects promote and some prevent oedema formation. However, the net result is a reduction in foot swelling.

Key words: Muscle pump — Skin temperature — Discomfort — Oedema — Barometric pressure

Introduction

Foot discomfort and swelling are common experiences during prolonged sitting. As the number of people occupied with sedentary work is growing steadily, more attention should be paid to these problems. Another situation with limited possibilities for leg movements is long-distance flying. Sitting in a tight seat-belt with the knees against the seat in front and the feet immobilized by cabin luggage implies that even healthy people often get swollen, aching feet and sometimes clinical oedema.

There are several insolved physiological problems concerning oedema-preventing mechanisms during orthostasis. A previous study showed that the small spontaneous movements while seated do not give any significant reduction in venous pressure in the superficial veins in the lower leg (Noddeland et al. 1983). This is remarkable since these small spontaneous movements are consistantly associated with a 50% reduction in foot swelling compared to immobilized sitting (Winkel 1985; Winkel and Jørgensen 1986a). However, Winkel's studies on foot swelling do not discriminate between the effects due to local leg/foot movements and those due to central haemodynamics and movements of the trunk. The latter may imply a significant effect on the muscle pump in the lower leg (Winkel and Bendix 1986). In addition, spontaneous foot movements in the sitting position reduce the fall in skin temperature (T_{sk}) (Winkel and Jørgensen 1986a), and thereby reduce the oedema-preventing effect of local foot haemoconcentration (Noddeland et al. 1981).

The aim of this investigation was to (1) create direct relationships between leg activity, foot swelling, T_{sk} and perceived discomfort during 8 h of sitting, and (2) study any marginal circulatory effects due to reduced barometric pressure which occurs in the cabin on intercontinental flights.

Materials and methods

Subjects. Six healthy women aged 21 to 31 years volunteered for the study. They were all familiar with the low pressure

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chamber. Their body weight ranged from 57 to 60 kg, and their body height ranged from 168 to 174 cm. None of the subjects suffered from clinical oedema, varicose veins or venous thrombosis.

Sitting position. The subjects were seated on a 5-legged office chair without wheels and without arm support (HÅG® MULTISIT no. 590). The seat was fixed in a horizontal position. The height of the seat was adjusted so that the ischial tuberosities were 1 cm lower than the level of the popliteal fossa when the tibia was vertical and the foot was resting on the floor. A desk was placed in front of the subjects.

Low-pressure chamber. Ambient temperature was set to 21°C and controlled by an air-conditioning system. Air flow and temperature was about the same at ground level pressure (750 mmHg) and at reduced barometric pressure (540 mmHg). Compression/decompression was completed within 2 min.

Foot volume. Foot volume was measured in a constant water level plethysmograph with a mean experimental error of 0.16% of the foot volume, i.e. about 1.6 ml (Winkel 1986).

Skin temperatur (T_{sk}). A thermocouple with low heat capacity (ELLAB Electric Universal Thermometer type TE 3, applicator type H1) was used. The thermocouple reached a stable temperature about 4 s after it was held against the skin. Repeated measurements of T_{sk} have been shown to cause a range of difference of 0.2°C (Winkel and Jørgensen 1986a). Nine different points on each lower limb and one on each arm were marked with ink. The exact location of each point is described in Table 1. All points were measured seven times during each experimental day (see Fig. 1).

Activity. Leg activity was measured by two motion sensors taped to the middle of the lateral sides of the lower legs. The sensors were connected to two battery-driven micro-computers carried in a waist belt (VITALOG® PMS-8, Palo Alto, California, USA). The micro-computers collected and stored data from the sensors throughout the day. Afterwards the data were transferred to a floppy disk by an APPLE II computer. The results were printed as a graphic display of activity on a time scale and as a list of the sums of activity registrations for each minute throughout the day. The activity data were processed in two different ways: (1) by calculating the average number of activity registrations per minute (reg/min), and (2) by counting the number of 1 min periods with one or more activity registrations (% time active).

Table 1. Definition of measuring points for T_{sk}

Point 1:	Dorsal side of the hallux, on the proximal joint
Point 2:	The ankle; 1 cm medial to the extensor hallucis longus tendon and 1 cm below the horizontal plane through the medial malleolus of the tibia
Point 3:	1 cm above the lateral malleolus
Point 4:	On the line from the lateral malleolus to the lateral epicondyle of the femur; one third from the distal end
Point 5:	As point 4 but at the middle of the line
Point 6:	As point 4 but two thirds from the distal end
Point 7:	On the centre of the patella
Point 8:	On the line from the lateral epicondyle of the femur to the greater trochanter; one third from the distal end
Point 9:	As point 8 but two thirds from the distal end
Point 10:	On the upper arm at the middle of the line from the lateral epicondyle of the humerus to the greater tuberocity

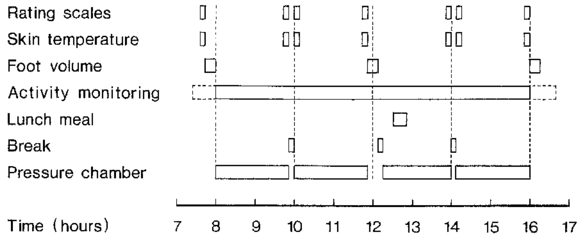

Fig. 1. Experimental design

Rating scales. The perception of discomfort (i.e. pain/tension/tiredness) right and left foot/lower leg was quantified by an analog-visual (AV) scale (cf. Winkel and Jørgensen 1986a). A 10 cm line was used, and the extremes were defined as "no discomfort" and "discomfort as bad as it can be". The subjects were asked to mark on the scale the point that best corresponded to their perceived discomfort. The distance between the mark and the "no discomfort"-end was then expressed as a percentage of the total scale length. The perception of right and left foot temperature was quantified separately on a seven-step scale: very cold/cold/somewhat cold/neutral/somewhat warm/warm/very warm.

Experimental design. The experiments were designed to be comparable both with a standard eight-hour working day and with long-distance flying. By having one leg inactive and the other spontaneously active, each subject served as their own control, and the effect of trunk movements could be disregarded. Each of the 6 subjects was studied on one day at ground level pressure (750 mmHg) and on one day at a barometric pressure of 540 mmHg corresponding to cabin pressure on intercontinental flights. This repetition had two reasons: a) to study any marginal circulatory effects due to reduced barometric pressure, and b) to study the reproducibility of foot swelling and discomfort.

The subjects came to the laboratory after a light breakfast at home. On both days they wore the same comfortable loose-fitting clothes and roomy wollen socks. At first they rested in a supine position for a least 30 min while the equipment was attached. Then the chairs were adjusted and the subjects were seated at the desk for 8 h. During 3 short breaks they walked to the lavatory (about 30 m). A light lunch was served at the desk after 4½ hours of sitting, and the food and drink was identical on the 2 experimental days. The subjects were instructed to keep one leg completely still (inactive leg). The other leg could be moved freely (active leg). In addition, they performed 10 plantar flexion movements with the active leg every 15 min (i.e. they raised the heel and kept the fore-foot on the floor). The right leg was chosen as the active leg in 3 of the subjects, and the left leg in the remaining 3. Foot volume, T_{sk} and foot discomfort were measured at the beginning, the middle and at the end of the experiments (Fig. 1). In addition, T_{sk}

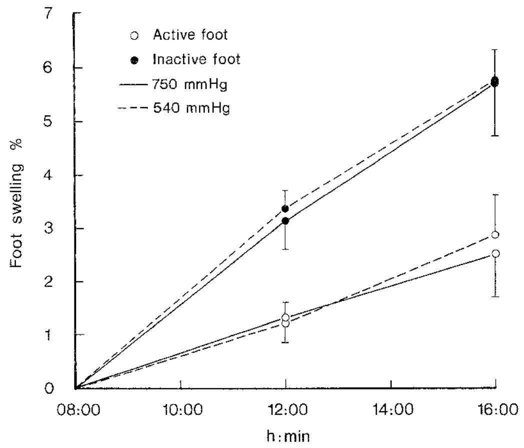

Fig. 2. Foot swelling in % of morning foot volume (mean ±SEM) during 8 h of sitting. ($n=6$)

and foot discomfort were measured before and after the morning and afternoon breaks.

Statistical methods. Foot swelling, leg activity, T_{sk} and ratings of discomfort were analysed by three- or four-way analysis of variance (ANOVA), the factors being barometric pressure, leg, time of day and subject. The ratings of discomfort were logarithmically (log) transformed to make the data appropriate for analysis. p values (two-tailed) about 0.05 or lower were considered as statistically significant.

Results

Foot volumes

At the beginning of the day the mean foot volume was 1022 ml (SD: 83) and 1013 ml (SD: 83) for the right and left foot respectively. The 8-h swelling averaged 5.7% in the inactive foot (Fig. 2). The swelling was significantly reduced by activity to 2.7% ($p<0.001$, SED: 0.2). In the inactive foot the rate of swelling was somewhat greater during the morning than in the afternoon; but the difference was not statistically significant as one of the subjects showed a pronounced increase in T_{sk} and therefore in the rate of foot swelling during the afternoon. For the remaining 5 subjects the rate of foot swelling during the morning (0.76%/h) was significantly higher than that in the afternoon (0.47%/h) ($p=0.05$, SED: 0.11). The swelling figures, as well as the other dependent variables, obtained in the reduced barometric pressure experiments were almost identical to those obtained at ground level.

Activity

An example of activity data distribution is shown in Fig. 3. Average activity during 8 h was 1.3 registrations per minute (reg · min^{-1}) in the active leg and 0.7 reg · min^{-1} in the inactive leg. This difference reached only borderline statistical significance ($p=0.06$, SED: 0.3). However, when calculated as % time active, the difference was highly significant: 30.9% time active in the active leg vs. 13.4% time active in the inactive leg ($0.001<p<0.005$, SED: 3.8). Neither of the two measures of activity showed any significant difference between morning and afternoon for either of the legs.

Skin temperature

The overall pattern showed that sitting was associated with a reduction in T_{sk} on both legs to-

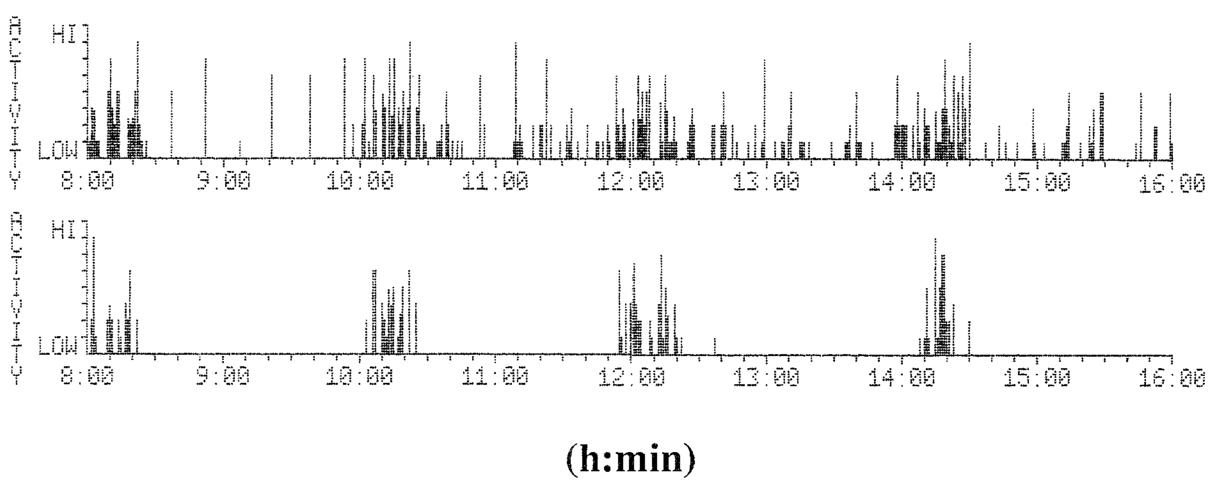

Fig. 3. Example of 8 h Vitalog recordings from the active leg *(upper panel)* and inactive leg *(lower panel)*

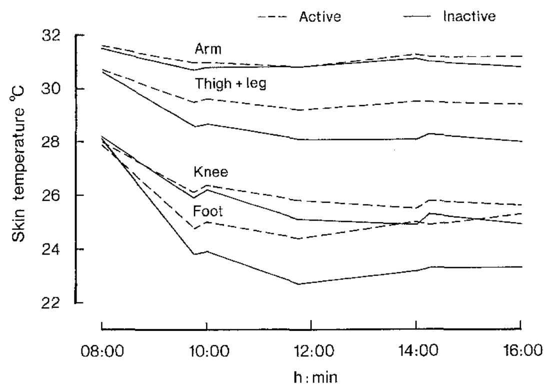

Fig. 4. Changes in T_{sk} during 8 hours of sitting (6 subjects × 2 experimental days). Arm: measuring point 10 (see Table 1). Thigh + leg: mean of points 4, 5, 6, 8 and 9. Knee: point 7. Foot: mean of points 1, 2 and 3

wards the environmental temperature (Fig. 4). The fall was most pronounced on the distal parts of the extremity and in skin areas overlying bone (Table 1, point 3 and 7). In general, the inactive leg became colder than the active; temperature differences between corresponding points ranged from 2—3° C on the foot ($p < 0.025$, SED: 0.4) to 0—1° C on the thigh (n.s.). The fall in T_{sk} levelled off before noon with the exception of the inactive calf (points 4,5 and 6), on which the cooling continued to decrease by 0.7° C on average during the afternoon ($p = 0.025$, SED: 0.3). The small increments in mean T_{sk} during the morning and afternoon breaks (see Fig. 4) were not statistically significant.

After lunch 1 subject differed markedly from this general pattern; both feet showed a sudden T_{sk}-increase for all 3 measuring points on both days (Fig. 5). The largest increase (from 20 to 32° C) was measured at point 1 (the hallux) on the inactive foot.

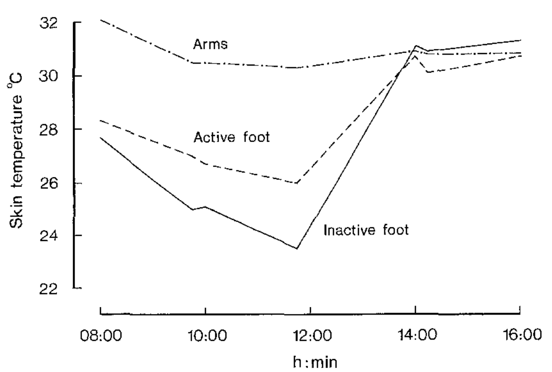

Fig. 5. Changes in T_{sk} during 8 h of sitting for one subject (mean of 2 experimental days). Arm: mean of right and left. Foot: mean of measuring points 1, 2 and 3 (see Table 1)

Ratings

In the inactive foot and calf the subjects experienced increasing discomfort during the day (Fig. 6) ($0.01 < p < 0.025$). The movements of the active leg significantly reduced this discomfort ($0.001 < p < 0.005$). The short breaks did not affect the succeeding rating of discomfort.

The temperature ratings are summarized in Table 2. The short periods of walking during the breaks and the activity performed while seated tended to reduce the perception of foot and calf cooling. One of the subjects rated an increase in perceived foot and calf temperature on both sides during the afternoon (noon: "somewhat cold", afternoon: "somewhat warm"). This corresponded to a pronounced increase in foot T_{sk} (see Fig. 5).

Relations between foot swelling, T_{sk} and activity

High foot T_{sk} is associated with a high rate of foot swelling in both the active and the inactive leg

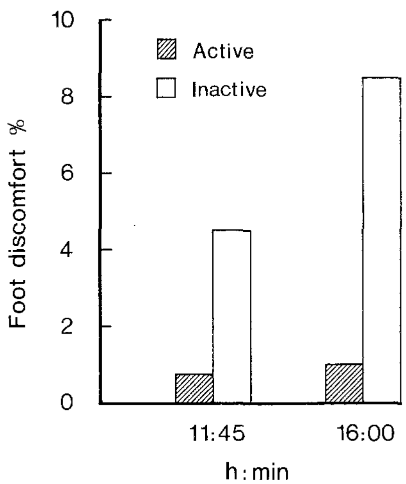

Fig. 6. Median foot/calf discomfort of active and inactive leg. At 08.00 the values were zero for both legs. ($n = 6$)

Table 2. Perception of foot and calf temperature for 6 subjects during 2 experimental days. See also "rating scales" in Fig. 1

	Start of experiments	Before breaks	After breaks
The inactive foot/calf colder than the active one	0%	52%	13%
Both feet/calves same temperature	100%	46%	83%
The inactive foot/calf warmer than the active one	0%	2%	4%
Number of ratings (~100%)	12	48	24

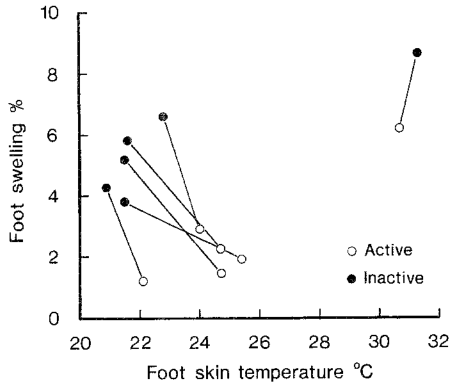

Fig. 7. Eight-hour foot swelling (% of morning foot volume) as a function of foot T_{sk} (mean of points 1, 2 and 3) at 16.00. Each circle shows the mean value of 2 experiments. Circles connected by a line are from the same subject

(Fig. 7). Spontaneous leg activity reduced foot swelling, but was also associated with a reduced fall in foot T_{sk} in 5 of the 6 subjects.

Discussion

Methodological considerations

The plethysmograph. Previous experiments have shown that 4 hours of inactive sitting is associated with a mean reduction in foot vascular volume corresponding to 0.5% of the total foot volume (Winkel and Jørgensen 1986b). This implies that the increase in interstitial fluid volume may be slightly underestimated (see Winkel 1985). The subjects went a few steps from the office chair to the plethysmograph, but vascular refilling was completed before the volume measurement (cf. Winkel 1985). Providing that the cells do not change volume (Sjøgaard and Bonde-Petersen 1981), one may conclude that the changes in foot volume mainly reflect volume changes in the interstitial fluid compartment.

The Vitalog. The discrimination between active and inactive foot was best when the activity data were expressed as % time active. This is reasonable as % time active is less influenced by the break periods with high activity in both feet than $reg \cdot min^{-1}$. % time active is also least vulnerable to differences in the sensitivity of the motion sensors.

Ratings. The AV scale has previously been used for the assessment of, for instance, pain and mood in patients. It has also been used in ergonomic studies to evaluate perceived work load and discomfort. In all these fields the AV scale has proved to be practical, reliable and valid (for references, see Winkel 1985).

Physiological considerations

As shown in this study, small spontaneous foot movements while seated clearly reduce foot swelling. The mechanisms that affect foot swelling rate in relation to leg activity are complicated by factors partly dependent on each other. For didactic purposes we have therefore split the mechanisms into two groups: those preventing and those promoting oedema formation.

Oedema-promoting factors. These are related to the small increase in skin blood flow accompanying spontaneous foot movements. Two observations indicate increased skin blood flow: (1) Even the few foot movements performed while moving to the plethysmograph were sufficient to eliminate the peripheral cyanosis observed in the cold inactive foot. (2) T_{sk} was consistently higher in the active leg compared to the inactive leg (Fig. 4). Small spontaneous foot movements do not cause a significant reduction in foot venous pressure (Noddeland et al. 1983). Still, transient venous pressure reductions may be sufficient to expel stagnant blood with high haematocrit and high plasma colloid osmotic pressure (Noddeland et al. 1981) and refill the capillaries with arterial blood. Thereby, the functional area available for capillary fluid filtration increases, and the effect seems to be that increased foot skin blood flow during orthostasis works as an oedema-promoting factor. This view is supported by the results shown in Fig. 7 where high T_{sk} is associated with high foot swelling. Oedema-promoting factors related to increase in skin blood flow are now the subject of further investigation.

Oedema-preventing factors. In addition to the above mentioned local foot haemoconcentration, three other factors have a potential to reduce capillary fluid filtration in the foot during orthostasis: a reduction in venous and capillary pressures, an increase in interstitial hydrostatic pressure and a decrease in interstitial fluid colloid osmotic pressure. Venous pressure reduction due to the spontaneous foot movements (Noddeland et al. 1983) seems to be too small to explain the large oedema-preventing effect. Also the subcutaneous interstitial fluid pressure in the foot and lower leg

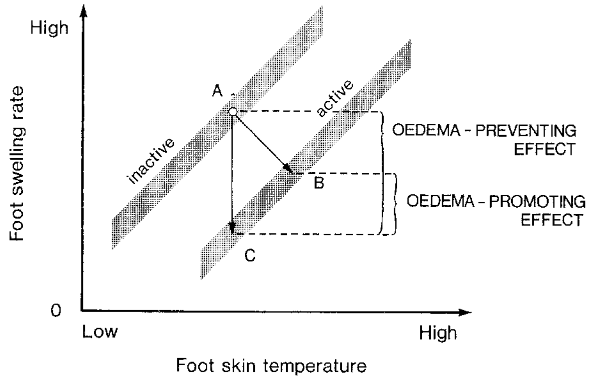

Fig. 8. Suggested interaction between leg activity and foot T_{sk} in regard to foot swelling rate during orthostasis. Units are arbitary, and the hatched areas are not necessarily parallel. The effect of small spontaneous leg movements is indicated by the arrow from *A* to *B*, i.e. reduced swelling and increased temperature. The anticipated oedema-preventing effect at constant foot T_{sk} (i.e. constant foot skin blood flow) is indicated by point *C*

is close to atmospheric pressure (Stranden et al. 1983; Noddeland, unpublished results) and may vary by only a few mmHg during foot movements. Thus, it seems unlikely that small foot movements can significantly reduce capillary fluid filtration and thereby increase interstitial fluid colloid osmotic pressure during orthostasis. The lymphatic system is able to drain interstitial fluid from dependent parts of the body against gravity (Aas et al. 1985). It is tempting to postulate that spontaneous foot movements stimulate lymphatic drainge.

To summarize, the oedema-preventing effect of the present modest leg activity seems to be modified by oedema-promoting factors (Fig. 7 and 8). The net result is, however, a reduction in oedema formation.

Conclusions

(1) Modest leg activity performed while seated reduces foot swelling, discomfort and fall in foot T_{sk} (a confirmation of previous results). In particular, it is shown that these changes occur even when the effect of trunk movements on leg muscle activity is eliminated.

(2) High foot T_{sk} seems to be associated with a high swelling rate in the foot.

(3) The fall in T_{sk} of the inactive foot levels off within 4 hours while T_{sk} of the inactive calf continues to decrease slightly during the following period.

(4) A reduced barometric pressure (540 mmHg) has no effect on foot swelling and T_{sk}.

(5) Leg movements should be encouraged during long-distance flying as well as during prolonged, constrained sitting in working life.

Acknowledgements. This investigation was supported by grants from the Swedish National Board of Occupational Safety and Health and the Royal Norwegian Air Force Institute of Aviation Medicine. We would like to thank Dr. H.T. Andersen for arranging excellent working facilities at the Royal Norwegian Air Force Institute of Aviation Medicine. Dr. G. Myhre introduced us to activity monitoring by VITALOG® microcomputers, and guided the trouble-shooting. HÅG® A/S, Oslo kindly provided new office chairs for the project.

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Accepted October 14, 1987