Effects of Mechanical Stimulation in Measurement of Thermal Pain Threshold

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Abstract. The improved thermal dolorimeter developed by Fukumoto has made it easy to measure thermal pain thresholds, but mechanical stimulations may be included as the probe is pressed into the skin. In order to evaluate these effects of mechanical stimulation on the improved thermal dolorimeter, the pain threshold temperatures were measured by a probe pressed to the human skin surface with weighting loads from 0.5 to 2.5 kgf. The loads of 2.0–2.5 kgf felt invasive to 8 of the 12 subjects, i.e., they experienced pain and numbness. The threshold temperature of one of these subjects, who developed water blisters around load-added area on the skin after the experiments, exceeded 50°C. The result that no significant difference could be found among the thresholds at the loads of over 2.0 kgf suggests the load of less than 2.0 kgf should be kept to execute proper experiments. In order to investigate other effects on thermal property by compressing, the blood flow was measured when the skin was compressed and three dimensional heat transfer simulations were conducted. The results of the simulations demonstrated that the temperatures of the heat source which were measurable in practice differed approximately 1 to 2°C from the true thresholds. The velocity of heating is also increased and subjects will be given stronger feelings of heating.


Keywords: thermal pain threshold, improved thermal dolorimeter, mechanical stimulation, subjective evaluation, heat transfer simulation

Introduction

Pain is a primitive sensation that, unlike the thermal and other sensations, has not evolved, and is essential to defending oneself. It is impossible to measure directly from outside at present, because it is a quantity of subjective feelings. The original attempt to measure pain was the thermal dolorimeter developed by Hardy in 1952. Since Hardy's dolorimeter up to this time, the threshold measuring method which has been used applies a certain stimulation to a subject and asks him whether pain exists or not, in order to determine the pain threshold.

Heat stimulation method is regarded as a suitable method in the view of the stability of stimulation, and is effective in monitoring and controlling the stimulations. Fukumoto (1982) developed an improved thermal dolorimeter so that traditional problems such as the size and the operational complexity of it were reduced. When using Hardy's thermal dolorimeter, the subject's forehead must be painted black and light of a 500W electric bulb was focused there as the heat source. Then the power of the light is increased step by step and the power which induces pain for the first time is determined as a threshold (Hardy et al., 1952).

The improved thermal dolorimeter has a probe which contains a heat-generating bulb at the top of it, and the probe is pressed to the test site on the skin. The current in the bulb starts to flow by the pressure of the probe on the skin, and the temperature rises as time progresses. Then the feelings of subject increase generally according to the skin temperature as is shown in Fig. 1. The time when the subject feels pricking pain and removes the probe from his skin is determined as the threshold. Thus, compared with the former method, experimental data can be obtained in one trial in this method (Fukumoto, 1982).

However, there is a considerable problem in the method using the improved thermal dolorimeter. The experimental results may contain the effects of mechanical stimulation and changes in heat conductivity due to changes in the strength of the pressure.

In recent years, we have tried to remove these effects by using a laser beam as a noncontact heat source (Satoh and Fukumoto, 1993, 1994), but the effects have not yet been clearly verified. In this paper, we present the results of the experiments executed to evaluate changes in threshold at various weighting loads.

Method

Definition of thermal pain threshold

Processes of subjective feeling during the measurement of the thermal pain threshold are generally
understood as a pricking pain that is generated after undergoing warm and burning sensations (Fukumoto, 1982). In this study, the thermal pain threshold was defined as the skin temperature measured at the time when a pricking pain was generated, so all of the subjects were trained to recognize this process.

Subjects

Twelve males aged 21–27 with no neurophysiological diseases were selected for this study. During the experiments each subject stood with his left forearm held perpendicular to the trunk and parallel to the ground and supported on a table. All tests were conducted between 3 and 5 o’clock in the afternoon in order to avoid post-meal changes in body temperature. Subjects were required to wear a T-shirt, jeans and a pair of socks (0.5 clo.).

Method of measurement

Threshold arrival time and threshold temperature were measured. Figure 2 shows the set-up used in the experiments. The set-up consisted of the improved thermal dolorimeter with its probe attached to the weighting load scales, a thermocouple thermometer with its detector attached to the top of the probe and a digital oscillo-recorder to record the signals from the thermometer.

For ease in measuring, the inside of the left forearm was chosen as the test site, avoiding sites with thick stratum corneum, mucous membranes or hair-rich sites. The weighting loads used were 0.5, 1.0, 1.5, 2.0 and 2.5 kgf (1 kgf=9.8 N). The load values were monitored, and if the variations of given load exceeded ± 10%, the test was repeated.

Five sites for measurement were specified, with the center point set at the point of 80 mm from the elbow joint along the midline and the other four points on a circle with a radius of 5 mm around the center point. In the same load, the measurements were performed five times at each of the five points, because the measurements of over five times in the same point often produced water blisters after the experiments. Then thresholds were derived as the average value of this data. The time interval was about 3 minutes, since Fukumoto (1982) showed that the effects of habituation could be avoided with intervals of over 2 minutes between tests.

The values of blood flow were measured using a laser-doppler blood flowmeter in the following cases and then were utilized in heat transfer simulations: (a) The probe of the blood flowmeter was placed with no weight and (b) the probe with a contact area of 85 mm² was attached to the experimental setup shown in Fig. 2 and the measurements were conducted with a load of 1.0 kgf. In each case the measurements of blood flow were performed in the same sites as those chosen in the measurements of pain threshold.

Subjective evaluation of mechanical stimulations

Pain threshold is generally said to change according to the environments surrounding the subject and his mental state. The weighting loads in this study were changed from values used customarily to ones which made the subjects feel strongly, so that the existence of effects of feelings generated by strong mechanical stimulations were considered in addition to the changes in conductivity of heat from the source.

The scales used to measure subjective evaluations for each load were prepared in Table 1. It is impossible to accurately define feelings generated by a certain load with one word or phrase. Thus the probe was pressed on...
the skin with the load of 1.5 kgf selected as the reference value at first, and subsequently the skin was pressed with a voluntary value of the five loads. One category of comparative feelings in Table 1 was then chosen by the subject. In order to evaluate only the subjective strength of mechanical stimulations, heat was not applied to work throughout these operations. If additional invasive feelings appeared, e.g. mechanical pain or numbness, there was the possibility that the feelings might affect the recognition of pain at the level of perception. Hence in this case, Table 1 (b) was also used to evaluate invasive feelings. These experiments were executed after the thermal threshold measurements.

Results and Discussion

Contact area and pressure between the probe and the skin

The geometry, contact area and pressure at the skin surface pressed by the probe are important factors in mechanical stimulation. The top of the probe of the improved thermal dolorimeter consists of a heat-generating bulb and a circle-shaped frame which supports the bulb as shown in Fig. 3, so these elements are brought into contact with the skin. Due to this particular three-dimensional geometry, the pressure within the contact area is not uniform. Moreover, the contact area is expected to vary with the weighting loads.

Figure 4 shows the results of the contacting areas and the pressure measured at each load in subject e. The average values were obtained from the three times of measurements at each point. It was difficult to maintain constant loads during contact due to the viscosity of tissue. In spite of these variations, the values of 0.5–2.5 kgf were representatively used in Fig. 4. Thus the curve of the area did not completely agree with the curve of pressure in shape.

Changes in thermal pain threshold by weighting load

The ambient temperature and humidity were 28.5 ± 0.2°C and 58 ± 4%, respectively. It has been reported that the thermal pain threshold varies with the primary skin temperature. Under these conditions, skin temperature is around 33°C.

Thermal pain thresholds were around 45°C using the measuring system and there was some difference between the true skin surface temperature and the thermocouple temperature. In the more strict sense of the word, the actual threshold is the temperature of the receptor, hence the data obtained in this study may have slight errors based on this principle.

Changes in thermal pain thresholds as a function of weighting load on the skin are shown in Fig. 5. Rises or falls could be observed in each subject. Thus the dispersion among the subjects increased as the load increased. One-factor ANOVA and multiple tests (Fisher's Protected Least Significant Difference) were performed on the threshold temperatures of each load to

<table>
<thead>
<tr>
<th>(a)</th>
<th>(b)</th>
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<tbody>
<tr>
<td>scale of evaluation</td>
<td>score</td>
</tr>
<tr>
<td>much stronger</td>
<td>7</td>
</tr>
<tr>
<td>stronger</td>
<td>6</td>
</tr>
<tr>
<td>little stronger</td>
<td>5</td>
</tr>
<tr>
<td>unchanged</td>
<td>4</td>
</tr>
<tr>
<td>little weaker</td>
<td>3</td>
</tr>
<tr>
<td>weaker</td>
<td>2</td>
</tr>
<tr>
<td>much weaker</td>
<td>1</td>
</tr>
</tbody>
</table>

(a) Comparative scales for each weighting load using the load of 1.5 kgf* as criteria. (b) Evaluation scale for additional feelings.

*: 1 kgf = 9.8 N.

Fig. 3 Constructions of the probe attached to the improved thermal dolorimeter. (a) Dimensions of the probe. (b) Geometry of contact end.

Fig. 4 Relationship between the stimulated area and the weighting load, and relationship between the pressure and the same load.
Fig. 5 Changes in thermal pain thresholds as a function of weighting loads on the heat-stimulated skin. The subjects were divided into group A (non-rising trend) and group B (rising trend).

Table 2 Results of multiple test executed for all combinations of loads

<table>
<thead>
<tr>
<th>Combinations</th>
<th>Group A</th>
<th>Group B</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5–1.0 [kgf]</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>0.5–1.5</td>
<td>*</td>
<td>*</td>
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<tr>
<td>0.5–2.0</td>
<td>–</td>
<td>*</td>
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<tr>
<td>0.5–2.5</td>
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<td>1.0–1.5</td>
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<td>–</td>
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<td>1.0–2.0</td>
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<td>–</td>
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<tr>
<td>2.0–2.5</td>
<td>–</td>
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</table>

The symbol * represents a significant difference with the significance level of 0.05.

threshold temperatures by each load could be found in the combinations of 0.5–1.5, 0.5–2.5, 1.0–1.5, 1.0–2.0, 1.0–2.5 and 2.0–2.5 kgf. In group B, thresholds rose as load increased and significant differences of the threshold temperatures of each load could be found in the combinations of 0.5–1.0, 0.5–2.0, 0.5–2.5, 1.0–2.0 and 1.0–2.5 kgf.

Significant differences with the level of 0.05 were obtained between light loads and heavy ones as shown in Table 2. This suggests that the existence of effects by the mechanical stimulations beyond certain loads can be observed. The boundary loads were also the limitation values to perform appropriate experiments using the improved thermal dolorimeter.

Relationship between threshold arrival time and threshold temperature

The improved thermal dolorimeter is a device which gives thresholds as threshold arrival time, but the temperature obtained at that time is considered to be a better indicator of the threshold. If the threshold arrival time and the density of dosed heat energy are used as thresholds, the values of threshold are affected by the primary skin temperature. The relationship between the threshold arrival time and the threshold temperature, which was examined only in subjects a-e, is represented in Fig. 6. The correlation coefficient was 0.903. The trend of each subject was different, which may be caused statistically significant differences. However, no difference with the significance level of 0.05 was found in any combination of loads.

Here the subjects were divided into two groups in which one had trends of rising and the other did not. If the average of thresholds of 0.5 kgf was smaller than those of the other loads, the subject was placed in the rising trend group. One-factor ANOVA and multiple tests were performed for both of the groups (Table 2).

In group A, thresholds did not have rising or falling trends as load increased, but significant differences of the
Fig. 6 Relationship between threshold arrival time and threshold temperature in subjects a-e.

by differences in heat conductivity between the heat source and the skin of each subject. In the same subject, for example in subject a, although the values of threshold arrival time were close to each other, the values of the threshold temperature were dispersed. Therefore it is necessary to measure the threshold temperature in parallel with the threshold arrival time.

Results of subjective evaluation of mechanical stimulations

Results of subjective evaluation in the subjects a-e are represented in Figs. 7 and 8. These suggest that the feelings closely corresponded to the load. It is considered that the linealities of experimental results were caused by the simplicity of paired tests between randomly given loads, namely 0.5, 1.0, 1.5, 2.0 and 2.5 kgf, and the load of 1.5 kgf as the center value. Invasive feelings were complained by two subjects in the case of 2.0 kgf and by four subjects in the case of 2.5 kgf. These loads corresponded to the pressure of about 2 kgf/cm² as referred in Fig. 4.

Feelings, such as mechanical pain and numbness, may also be induced in addition to the mechanical stimulations when the probe of the improved thermal dolorimeter is used with a weighting load beyond 2.0 kgf, so that these loads are not regarded as suitable conditions.

Although the conductivity between the heat source and the skin increased as the load increased, the threshold temperatures in the three subjects of group A fell. A cause of that is considered to be the effects by invasive feelings. In group B, contrary to group A, a rising trend was found as the load increased. The possibility was suggested that the trend of group B was induced by the suppression of neurotransmissions or that perceptions predominated the effects of the increase of heat conductivity due to the increase of load, and consequently thresholds rose. Erythema was observed in the experimental site of subject d after the experiments and this later developed into bullae, because the site was
heated by temperatures beyond 50°C as shown in Fig. 6.
The rising and non-rising trends require further investigation. Neurophysiological models would help to clarify this phenomenon.

*Effects of variations in blood flow upon the heat transfer in the tissue*

Blood flow is known as one of the main carriers of heat in a living body. When the skin is compressed, the blood flow will be obstructed and variations of thermal properties within the skin will occur. Thus there exists not only additional invasive feelings but also variations of thermal properties. In order to investigate the effects of obstructed blood flow and thermal property variation, the three-dimensional heat transfer simulations were conducted in the case of skin compressed. The simulations have been developed to make noninvasive and predictive studies.

Skin models used in the simulations are shown in Fig. 9. Free nerve endings, which act as the pain receptors, exist around the depth of 0.05 mm (Kruger et al., 1981). In these simulations, the depth of receptors were assumed to be 0.10 mm and 0.05 mm in the case of Fig. 9 (a) and (b), respectively from the surface (depth=0.00 mm). The idea behind these two models is to demonstrate that skin surface temperatures are affected by the decrease in the blood flow and the thickness of tissue. In Fig. 9 (a), it is assumed that the skin is heated with no pressure by the top of probe. In Fig. 9 (b), it is assumed that the skin is compressed to half in thickness and thus the blood flow is decreased. A temperature rising curve of time course was acquired by averaging the time course data obtained in the experiments of pain threshold.

The results of the blood flow measurement were 4.18 [ml/min/100 g] in the case of no-load and 0.81 [ml/min/100 g] in the case of 1.0 kgf loaded. The results of the heat transfer simulations including the obtained blood flows are represented in Fig. 10.

Temperatures at each depth of tissue rose as the temperature of the heat source rose. The results of these simulations demonstrated that the temperatures of the heat source which were measurable in practice differed by about 1 to 2°C from the true thresholds. Furthermore, temperatures in the case of 1.0 kgf loaded were about 0.8°C higher at the surface and 1.4°C higher at the depth of receptors than those in the case of no-load after 8 sec heating. This suggests that if pain threshold temperatures are constant independently of the load, the lower thresholds are measured when the tissue are compressed. However, the velocity of heating also increases with compression and subjects experience stronger feelings of heating. Such feelings indicate that there may be some psychological effect. Compression, by the speedy perception of heat, may contribute to the change in subject's threshold temperature. This indicates that a psychological effect may influence threshold temperatures.
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