The heating performance of prototype variable power control units attached to two domestic microwave ovens, 500 W and 700 W, was investigated. The units employed the phase control method where rated voltage was obtained by switching AC supply at a particular angular position on the sinusoidal voltage. In order to create experimental conditions employed in a previous study, Sydney tap water (50 mL) was heated at a 10% power level in the 500 W oven. Water boiled at 10 min in both experiments. However, the precision and control of the heating was greatly improved with addition of the control unit. A disinfecting solution (50 mL) and a tissue fixative (10 mL) were included for experiments with the 700 W oven. A power level of only 1% was sufficient to maintain the temperature of the fixative at low temperatures (30-40°C) where many biological reactions occur. The present results indicate that microwave heating power can be controlled by the variable power control method. This will make temperature control possible through the provision of an electronic feedback loop which links a thermocouple with the power control unit.

Key words: Microwave, Power control, Temperature control

INTRODUCTION

Thermocouple (TC) thermometry is susceptible to electrical noise as the signal voltage levels are very low, the order of microvolts. Therefore, TCs must be efficiently shielded when used in electromagnetic fields\(^1\). In addition, TCs must be grounded to avoid arcing in microwave ovens\(^2\). A previous study has demonstrated that these TC arrangements successfully record temperatures involved in microwave denture processing\(^3\). The various power levels available in conventional domestic ovens are produced by switching the magnetron on and off according to a duty cycle. For example, the 500 W oven used in the previous study had a 32 s duty cycle and the power was delivered for only 3 s or 10% of the cycle time when the lowest power option ("Low") was chosen\(^3\). During this short irradiation time the temperature of water increased rapidly as the oven was operating under its full power (500 W), although this situation is generally called 50 W. The same rapid temperature increase occurs in resin dough and its elimination is desirable\(^4,5\). Control of temperature is particularly critical for various biological applications of microwave technology\(^5,6\). The present study aimed at controlling microwave heating power.
MATERIALS AND METHODS

Experiment 1

The 500 W domestic microwave oven* used in the previous study3) was first used to recreate the same heating conditions. Details of the oven and the TC arrangement have already been given. A prototype power control unit@ was attached to the oven to supply variable power to the magnetron. The unit employed the phase control method where rated voltage was obtained by switching alternating current (AC) supply at a particular angular position on the sinusoidal voltage8). The unit allowed the output power to be set at 0-100% in 1% increment by touch buttons. Temperature of Sydney tap water (50mL) was measured by selecting a 10 per cent power level so that the heating performance could be compared with the result obtained in the previous study. Three measurements were carried out on the sample placed in the conical flask as before.

Experiment 2

A 700 W domestic microwave oven# with internal dimensions, 209(W) × 555(H) × 431 mm(D), was used in this experiment and a power control unit described above was attached to the oven. A hole was made in the top panel of the oven to accommodate a brass mounting block through which an Inconel sheathed chromel/alumel (type K) TC was vertically inserted. In view of wider application for the microwave heating technology in the future, a disinfecting solution$ and a tissue fixative&, as well as Sydney tap water, were tested in this experiment. Furthermore, the TC assembly provided a facility for locating the tip of the TC at a position suitable for different sample volumes, 50 mL (water and disinfecting solution) and 10 mL (fixative). Water samples were placed in a cylindrical 100 mL beaker and heated at power levels of 100, 10 and 1%. The disinfecting solution was diluted 1 : 8 with Sydney tap water and placed in a 50 mL Pyrex beaker and 100% power only was used to compare with the results from water. The fixative was placed in an open cylindrical vial and heated at 100, 10 and 1% power levels. A dummy water load of 50 mL was placed at a standardized position during heating of the fixative. At least three measurements were made for each material and each experimental condition.

All measurements of Experiments 1 and 2 were carried out after deactivating the turntable and placing the containers on a PTFE (Teflon) stand. Calibration and recording of temperature were followed using the methods described in the previous report3). A finite build-up time (about 1 s) was required for the microwave field to become active. Temperature was recorded continuously as in the previous study. All equipment was allowed to cool to room temperature between each test. Ambient conditions during the experiments were 22±1°C and 50±10% relative humidity.

* Carousel R-5980, Sharp Co., Osaka, Japan
@ IMA Pty. Ltd., St Ives, NSW, Australia
# Panasonic NN-6408, Matsushita Electric Industrial Co. Ltd., Osaka, Japan
$ Milton, Procter & Gamble Pty. Ltd., Villawood, NSW, Australia
& Kryofix, Merck, Darmstadt, Germany
RESULTS

Experiment 1
A representative temperature recording from this experiment is shown in Fig. 1. The starting temperature was between 19 and 20°C. Although temperature rises at the first 20 s were somewhat irregular, the rest of the curve was smooth and reproducible, reaching $37.3 \pm 0.7°C$ at 1 min, $74.5 \pm 1.3°C$ at 5 min and $100.3 \pm 1.4°C$ at 10 min. Before boiling point was recorded local bubble formation was visually noted and the heating curve became less smooth. The maximum temperature recorded was 102°C which was maintained until the oven was switched off.

Experiment 2
Temperature recordings of water and the disinfecting solution (DS) are summarized in Table 1. At the full power both fluids were heated at a similar rate and reached 100°C at

![Fig. 1 A representative curve obtained from water sample (50mL) in a 500W oven at a power level of 10%, The arrow marks the end of heating.](image)

<table>
<thead>
<tr>
<th>Time (s)</th>
<th>Water (°C)</th>
<th>100%</th>
<th>DS (°C)</th>
<th>10%</th>
<th>Water (°C)</th>
<th>1%</th>
<th>Water (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>18.5(0.5)</td>
<td></td>
<td>20.6(0.4)</td>
<td>17.9(0.5)</td>
<td></td>
<td>17.7(0.1)</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>47.5(3.9)</td>
<td></td>
<td>45.6(0.5)</td>
<td>25.5(0.2)</td>
<td></td>
<td>24.0(0.5)</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>66.9(1.0)</td>
<td></td>
<td>65.2(2.0)</td>
<td>26.2(0.4)</td>
<td></td>
<td>23.8(0.5)</td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>87.7(1.6)</td>
<td></td>
<td>84.4(2.3)</td>
<td>27.5(0.4)</td>
<td></td>
<td>23.9(0.5)</td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>101.8(1.3)</td>
<td></td>
<td>100.2(1.6)</td>
<td>28.8(0.3)</td>
<td></td>
<td>24.2(0.5)</td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>103.1(1.2)</td>
<td></td>
<td>102.4(0.6)</td>
<td>30.0(0.3)</td>
<td></td>
<td>24.4(0.5)</td>
<td></td>
</tr>
<tr>
<td>60</td>
<td>107.8(2.4)</td>
<td></td>
<td>104.0(0.4)</td>
<td>31.2(0.4)</td>
<td></td>
<td>24.5(0.5)</td>
<td></td>
</tr>
</tbody>
</table>
about 40 s. Figure 2 shows representative heating curves of water samples for the three power levels tested. The curves present initial sharp temperature rises for all power outputs. This continued with the full power but was soon controlled at about 10 s with the lower power levels. With the minimum power it was possible to maintain the temperature at around 24 °C. Figure 3 shows results from the fixative. The heating curves repeated a similar pattern as those obtained with water. At the maximum power, the fluid reached 95°C in 20 s which was followed by small rises and drops above this temperature until the oven was turned off. Both 10 and 1% power outputs increased temperature gradually. The latter provided an extremely slow rise above 38°C.

DISCUSSION

Most domestic microwave ovens have an output power in the range of 500 to 1000 W. These relatively high powers are commonly used for many histopathological procedures9). For denture processing an even wider range of 400–700 W has been reported10–13). Early model domestic microwave ovens were only capable of heating at a predetermined output, but various power levels are now available in modern ovens by means of a duty cycle14). This control method was used in the previous study3). For example the minimum power level was delivery of full power (500 W) for only 3 s during a 32 s duty cycle. Experiment 1 recreated this heating condition except for the addition of a prototype power control unit. Boiling point was reached at 10 min in both experiments. However, the heating curves were quite different, i.e., the step characteristic (peaks and troughs)9) inherent to the duty cycle method disappeared and was replaced by a smooth curve (Fig. 1).

It should be possible to adopt a short duty cycle so that peaks occurring under the full power are suppressed. This approach is found with a microwave processor dedicated to tissue fixation9). However, the step characteristic remains and the power reduction gained from the short cycle is offset by constant switching of the magnetron throughout the entire heating period. With the variable power control unit used in this study, switching of the magnetron occurs only once during the operation and at the beginning.

The effect of heating at full power for water and fixative are demonstrated in Figs. 2 and 3. A maximum of 107.8±2.4°C was reached after 60 s for water. The maximum for the same volume of water was 102°C in Experiment 1 and in the previous study3). It has been recently reported that microwave heating can cause superheating of water to about 110°C2). Extrapolation of the curve in Fig. 2 indicates that this temperature may have been attained if heating had continued. The disinfecting solution also reached a temperature above 100°C, apparently due to the high dilution with water. As discussed in the previous study3), superheating can occur when water vapour escapes into an existing air space and thus the pressure of the water builds up. Superheating will also occur when convection to the top surface of the solution and subsequent vaporization are insufficient due to the rapid heating2). Strong convection is generally indicated by the oscillation of temperature recording as depicted from the water sample (8–10 min) in Fig. 1. Convection is also probably dependent on the viscosity of a fluid. In the fixative this effect appears to be related to the complexity of the heating curve above 95°C (Fig. 3), as the apparent superheating is not as smooth as that observed in
POWER CONTROL FOR MICROWAVE HEATING

Fig. 2 Three representative curves obtained from water samples (50mL) in a 700W oven at three power levels (100, 10 and 1%). The arrows mark the end of heating.

the water sample.

Many histopathological techniques using microwave energy require small volumes of fluid to be heated. Even more stringent are the requirements for the heating of immunohistochemical reagents of extremely small volume. Many of these reactions have to be performed in the 30-40°C temperature range. It has been common practice to use a "dummy" water load to reduce the heating effect in these situations. This involves placing a large (100-200 mL) beaker of water in the oven cavity, along with the desired load. Many variables combine to make this technique unpredictable. The novel phase controlled power device described in this paper provides much better control under conditions of low temperatures and volume, and removes all the variables inherent in the extra water load technique. Fig. 3 illustrates this effect. Here a mere 1% of full power (7 W) is used to maintain the temperature of 10 mL of fixative in the range of 30-40°C.

Recent literature concerning the use of microwave ovens for tissue fixation in the laboratory stress adequate power control\(^9\) and the importance of precise temperature data\(^15\). Login et al.\(^16\) states the inadequacy of domestic ovens to produce reproducibly excellent fixation. They also make a plea for the development of precision microwave equipment for
Fig. 3 Three representative curves obtained from a tissue fixative (10mL) in a 700W oven at three power levels (100, 10 and 1%). The arrows mark the end of heating.

laboratory use. The present study demonstrates that adequate power control is possible by incorporating a variable power control unit into conventional domestic ovens. The phase control method has been employed in the past to control microwave power in industrial heating with large magnetrons using analogue electronics. The authors believe that the digital electronics adapted to small domestic magnetrons is unique. The present method also provided a smoother heating profile than that by the duty cycle method under the same or at least similar power output. Further investigation is required into the initial portion of the heating curve, which is heavily influenced by the need for the magnetron filament to be heated prior to the magnetron producing microwaves. This phenomena, however, occurs only once and the precision of the variable power source is utilized for the greater part of the heating period in contrast to the shortened duty cycle method. The TC thermometry is a cost effective method which provides precise continuous temperature data. Furthermore, the provision of a closed feedback loop between a TC and a power control unit will enable greater control of temperature. This makes selection of a predetermined time-temperature cycle for microwave denture processing possible. The results are promising and will be reported in a following paper.
CONCLUSIONS

Modification of a domestic microwave oven with a power control unit greatly improved the heating performance of 50 mL water sample compared to the same load in an unmodified domestic oven. This was due to elimination of the step characteristic (peaks and troughs) inherent to the duty cycle. It was indicated that biological applications of microwave technology such as denture disinfection and tissue fixation would require significant reduction in the output power of conventional ovens. Precise temperature control will be possible through the provision of an electronic feedback loop which links a TC with a variable power control unit. This will enable an operator to preset the temperature and control it automatically.

REFERENCES

光重合コンポジットレジンの残留モノマー量およびベンダント二重結合量

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コンポジットレジン硬化体から切り出した薄切片の微小部位におけるIRスペクトルを顕微赤外測定装置を組み込んだFTIRを用いて測定し、未反応二重結合量（UDB）を求めた。さらにこの薄切片から残留モノマーを溶出させた後の同一部位でのIRスペクトルをも測定し、ベンダント二重結合量（PDB）を求めた。また、この両二重結合量の差から溶出した二重結合量（EDB）を求める、残留モノマー量を推定した。

UDB, PDB, EDBをともに深さ方向に対して著しく変化した。PDBは光照射時間にかかわらず、得られた硬化深さの7～8割の深さまで、一定の値を示した。この部分におけるコンポジットはより密に架橋されていると推察される。モノマー組成によって異なるが、光重合された硬化体内には25～40％の二重結合がベンダント二重結合として存在することが示唆された。

ペースト・ペーストタイプ覆歯用セメントの熱的性質

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日本大学歯学部歯科理工学教室

4種市販品、ペースト・ペーストタイプ覆歯用セメントおよびヒト象牙質の熱的性質についての測定を行った。測定はセノンランプ・フラッシュ法による非定常法により行い検討した。全てのセメントにおいて熱伝導率および熱容、厚さの値によって熱物性が同等もしくは優れていることが判明した。

生物利用におけるマイクロ波加熱出力のコントロール

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*シドニー大学歯学部補綴学教室
**シドニー大学医学部婦人科学教室
***Industrial Microwave Applications (Australia)

マイクロ波による加熱を利用する際には、得られる温度を知るとともに温度調節のできることを望みたい。そ
のための第一歩として、マイクロ波の発振を行ううマグ
ネトロンの出力が一定で照射時間を変化させる従来の方
法と、マグネットロンの出力を変化させる方法を比較した。
32秒のサイクルを有する500Wの家庭用電子レンジを
用い、同様の照射エネルギーが発生していると考えられ
る条件（50 W, 10%）を設定した。50 mlの水道水を加
熱した場合、どちらの方法でも沸騰を要する時間は10分
であったが、後者の方法でなめらかな曲線が得られた。
これは、従来の方法では、短時間（3秒）のマイクロ波
照射中に500Wのエネルギーが放出され残りの29秒は
マグネットロンが停止しているのに対し、本方法では、低
いエネルギーが停止することなく照射されていることに
よる。
700Wの家庭用電子レンジによる消毒液及び組織固
定液の実験も追加したところ、一定の低出力を得ること
の必要性が示された。熱電対とマイクロ波発振回路を結
ぶことにより温度調節が可能となる。