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Accuracy of thermal microsensors embedded in orthodontic retainers of different material composition and thickness: An in vitro study

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Objectives: The present research aimed to assess the accuracy and precision of the TheraMon® microsensor embedded in different thicknesses of Hawley retainers (HR) for comparison with vacuum formed retainers (VFR).
Methods: Thirty microsensors contained within different thicknesses and composition of retainers were divided into three equal groups: Group A thick coverage HR (3 mm), Group B thin coverage HR (1 mm), and Group C VFR (1 mm). The microsensors were immersed in thermostatic water at a controlled temperature of 35°C, which corresponds to the average intra-oral temperature. After 1 week, data were gathered using the TheraMon® client software and analysed using ANOVA and Turkey's HSD tests.
Results: All TheraMon® microsensors were functional and produced uninterrupted recordings during the 1-week test period. Thermal detection differed between the three removable retainer groups. A near accurate thermostatic water detection was noticed with the thin HR with a mean temperature of 34.81 ± 0.04°C, followed by VFR 34.77 ± 0.09°C, and finally the thick HR 34.73 ± 0.05°C (ANOVA *p*-value = 0.025). A between-group comparison showed a significant mean difference (MD) between the thin and thick HR groups (MD: 0.08, *p*-value = 0.01). However, there were no significant differences between VFR and neither the thick Hawley (MD: 0.04, *p*-value = 0.27) nor the thin Hawley group (MD: -0.03, *p*-value = 0.39).
Conclusion: A removable retainer's variation in material thickness and composition could induce small but detectable changes in the precision of thermal detection by TheraMon® microsensors.
(Aust Orthod J 2023; 39: 42 - 48. DOI: 10.2478/aoj-2023-0005)

Received for publication: October, 2022
accepted: January, 2023.

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Introduction

The rapid continuing introduction of the digital world within the health sector after the spread of the COVID-19 pandemic in early 2020, has hastened a shift towards digitisation and further developments of dental applications, tele-dentistry, and many others.[1,2] These developments include the use of digital information and personal communication technologies and cloud computing to access and manage a variety of healthcare services.[3,4] This advance in technology facilitates offsite-based

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consultations, prescriptions, patient monitoring, the uploading of records, and audio/visual consultations with assigned healthcare professionals.[5]

Machine learning and artificial intelligence have been recently introduced in orthodontics to assist the collection and analysis of a large amount of data to learn about a patient's behaviour patterns.[6,7] The recent advancements build on previous systems and structures to advance orthodontic research and develop new models for orthodontic treatment.[8,9] Data are fuelling this progress in the healthcare sector and global researchers rely on it to provide services to patients.[10] However, collecting data remains a challenge primarily due to the limited capabilities of the monitoring-based systems.[11]

Rigid adherence to prescribed retention protocols ensures that post-orthodontic treatment goals for long-term stable outcomes are in place.[12] Monitoring a patient's compliance is considered essential to ensure optimal adherence to the prescribed appliance wear protocols.[13] Recently, individualised approaches have been developed to overcome the discrepancies between actual clinical progress, and subjective self-reported compliance to different removable retainer wear regimens. These modifications include systems such as microsensors, electronic reminder systems, and mobile device applications.[14,15]

The capabilities of these adjuncts have facilitated the use of artificial intelligence to digitally track data monitoring systems. However, the accuracy of current systems is often affected by challenges within the platform, the longevity of tracking, and the interaction between the monitoring systems and the experimental conditions (e.g., material composition, environmental conditions, and sustained long-term maintenance).[16,17]

Aims

New thermal monitoring microsensor systems have enhanced the clinical decision-making process and allowed future predictive algorithms to improve clinical practice. The current research group aimed, through this comparative *in vitro* study, to assess the accuracy and precision of the TheraMon® microsensor in different thicknesses of Hawley retainer (HR) in comparison with a vacuum formed retainer (VFR). It was expected that slight differences in material composition and thickness, could alter the thermal properties of the material, and cause different rates of conductive heat and temperature transfer, leading to inaccuracy and imprecision of the thermal detection microsensors.[18]

Materials and method

The microsensor

A commercially available TheraMon® microsensor (S version) was chosen as the most popular microsensor reported in the orthodontic literature.[19] The microsensor has relatively small dimensions (13 mm × 9 mm × 4 mm) and a light weight of approximately 0.4 grams. The physical properties allow the integration of the microsensor into different removable orthodontic retainers which would make them less prone to corrosion and less susceptible to recording failure. The microsensor uses an application-specific integrated circuit with 16 kilobytes of Electrically Erasable Programmable Read-Only Memory (EEPROM), which facilitates its multiple reprogramming.[20] The microsensor records appliance wear within the temperature range of 33.5°C to 38.5°C (attributable to changes in temperature caused by eating or drinking in the oral environment) at 15 min-intervals. Data may be stored for up to 100 days and then transferred to an associated software cloud in a process that could be repeated for a maximum of 15 months.

Procedure

An *in vitro* controlled laboratory study was carried out in the dental school of the First Affiliated Hospital of Zhengzhou University, Henan, China. Thirty TheraMon® microsensors (Handelsagentur Gschladt, Hargelsberg, Austria) were divided randomly and equally into three groups of 10 microsensors to comprise: Group A; HR with a thick coverage of acrylic material (3 mm), Group B; HR with a thin coverage of acrylic material (1 mm), and Group C; VFR (1 mm; Essix ACE® Plastic sheet) (Figure 1). The microsensors were supplied ready for use and standardised laboratory steps were carried out to embed the microsensors in the retainers by one experienced laboratory technician.

The retainer wires were adapted to the teeth and the microsensor was immersed in the acrylic when it was soft. A periodontal probe was used to assess the thickness of the covering acrylic layer from the mesial and occlusal surfaces while the material was

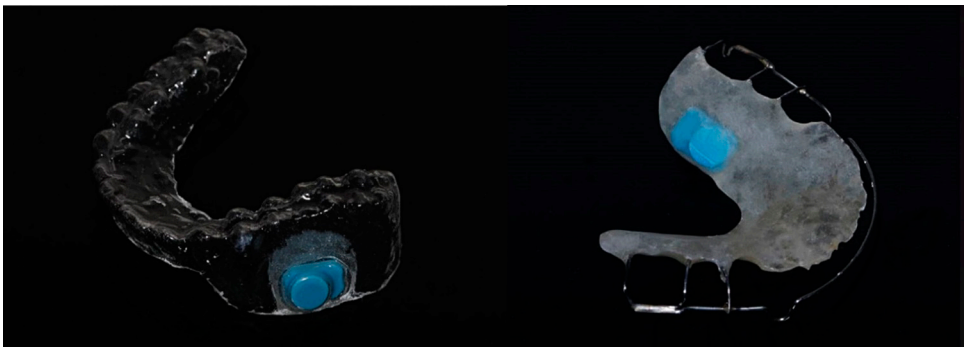


Figure 1. VFM and HR appliances with embedded thermal microsensor.

still soft. After the setting of the acrylic, the palatal surface was assessed and adjusted using an air driven low-speed handpiece (Dentsply® Sirona, Ballaigues, Switzerland). The microsensor was embedded in the 1 mm thickness Essix plastic sheet of the VFR using a MiniSTAR S® pressure forming machine. Subsequently, the VFR sheet was trimmed around the microsensor leaving a border of 1 to 2 mm. A thin layer of plaster was added on the posterior buccal area of the construction cast, to flatten the surface for easy placement of the microsensor. A second sheet of material was pressure-formed on the cast and trimmed. The microsensor sheet was then bonded to the cast model sheet using auto-polymerising dental acrylic resin (Palapress®; Kulzer GmbH, Mitsui Chemicals, Hanau, Germany).

Following the retainer fabrication steps, the microsensors were activated by the software reader after which all retainers were immersed in a thermostatic water bath (Zhejiang Jinbo Electronic Co® Ltd, China) filled with 8 litres of distilled water in a closed-box environment, at a controlled temperature of 35°C, which corresponds to the average intra-oral temperature.[21] Prior to data collection, the accuracy of the water bath was examined for two consecutive days by measuring water temperature (35°C) to ensure consistent and stable performance. The microsensors were left for 1 week without any intermittent pauses and the experimental conditions were designated to replicate the oral environment and full-time wear of the orthodontic retainers.[17] Water temperature and amount were checked twice daily. If volume decreased, water from a preheated water bath (35°C) was added to maintain constancy. The timestamp of the added water was recorded on a file sheet, to note any changes in temperature. The microsensor's data were evaluated at the end of the week (Figure 2).

The data were transferred from the microsensors to the TheraMon® client software (version 1.3.0.4, MC Technology GmbH, Hargelsberg, Austria) using a pen reader through an onboard antenna to a laptop running Windows 10 (64 bit). Data on the software was displayed as a graphical water bath time over a period of seven consecutive days. This totalled 168 hr representing full-time wear of the appliances for 1 week. Subsequently, data were displayed using the tracking graphical analyses, which were recorded by the microsensor every 15 min (Figure 3). The TheraMon® software has the capability to present a graph for short periods of time (days), which aligned with the 1-week trial. A generated analysis and temperature graphs presented precise information of the temperature changes during the experimental period.

Data analysis

Statistical analysis was conducted using the R statistical software (v4.1.2; R Core Team2021). A simple descriptive analysis was conducted to calculate time and temperature discrepancies between actual time in the water bath and microsensor-recorded time were calculated, to find the mean values. An ANOVA and Tukey's HSD test were applied to compare temperature means between the three groups and the results were deemed significant at $p < 0.05$. The microsensors were immersed in the water bath for a total of 10,080 min and at 35°C therefore, the recorded time did not pass this number.

Results

No technical errors occurred to any microsensor during the experimental period. The daily analysis

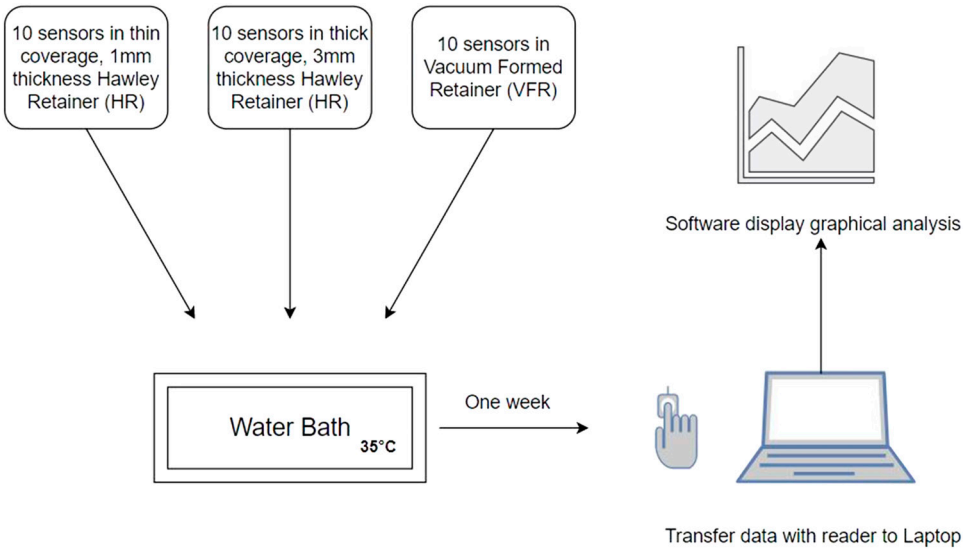


Figure 2. Characteristics of included groups and flowchart of steps.

revealed that all utilised microsensors were capable of providing a substantial performance function of 100% and able to record data for a continuous 1-week period. However, the detailed temperature graphs demonstrated small but significant differences in temperature recording between the groups.

The results revealed that the thin HR had a mean temperature reading of 34.81 + 0.04°C, followed by VFR at 34.77 + 0.09°C, and finally the thick HR with a mean of 34.73 + 0.05°C. The statistical analysis (ANOVA) yielded a *p*-value = 0.025, indicating a statistically significant difference between the groups. A between-group analysis was supplemented by Tukey's HSD test which showed a significant mean difference (MD) between the thin and thick HR groups (MD: 0.08, *p*-value = 0.01). However, there was no significant difference between the VFR and neither the thick HR (MD: 0.04, *p*-value = 0.27) nor the thin HR (MD: -0.03, *p*-value = 0.39) groups.

Discussion

Temperature microsensors are commonly used to monitor body temperature changes. They consist of thermistor-based temperature gauge which records heat pressure at consistent time intervals which are then saved to memory.[22] Fundamentally, the accuracy of a microsensor is determined by the closeness of the recorded readings to the actual value being monitored, taking into account all possible error sources.[23] The accuracy of the current study is defined by the proximity of the microsensor's readings to the true temperature of the water bath of 35°C. However, the precision of the readings is assessed by the

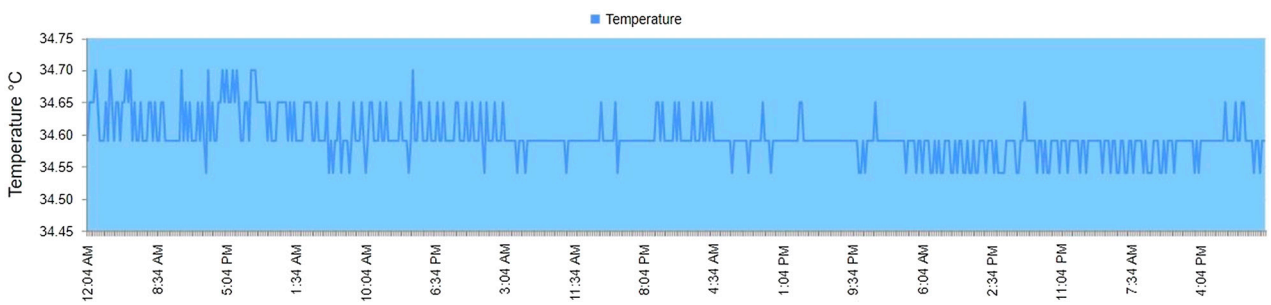


Figure 3. Detailed analysis of the temperature graph for one microsensor in the thick Hawley retainer group, with a temperature range between 34.54°C and 34.70°C.

distribution of readings per group, as measured by the standard deviation (SD). Therefore, the present aim was to assess the accuracy and precision of the TheraMon® microsensor in different thicknesses of HR (thin and thick) in comparison with a different material (VFR).

The overall results demonstrated that all microsensors were capable of detecting temperatures between 33.5°C and 38.5°C across the entire 1-week experimental period, thereby replicating the expected clinical conditions of retainer wear at an average intraoral temperature. This indicated excellent usefulness of the investigated microsensors despite the associated retainer material or thickness. Previous *in vitro* studies found a discrepancy in recording time from a few minutes to half an hour which are in contrast to the present findings.[17,24] This may be explained by a part-time recording period used in previous studies and by the recent progression in microsensor development which likely has improved the detection abilities and overall performance.

The detailed temperature graphs demonstrated differences in the mean temperature recordings across the groups. The differences were generally small related to accuracy and precision. A statistically significant difference was shown between the two HR acrylic thicknesses (thick and thin). However, the lack of significant difference between the VFR and both HR groups may indicate less influence of the type of assessed material. The findings could be also attributable to the overlapping distributions between the two material types, as the VFR group had approximately twice the SD as the HR groups (Figure 4). This varying precision, as evidenced by a wider distribution of readings, was evident despite the uniform thickness of the VFR material surrounding all microsensors in that group. The results illustrate a potential need to control the thickness of acrylic coverage so that it is minimised.

The detailed temperature results of each microsensor within the groups showed only small discrepancies, indicating a consistent utility for thermosensor use

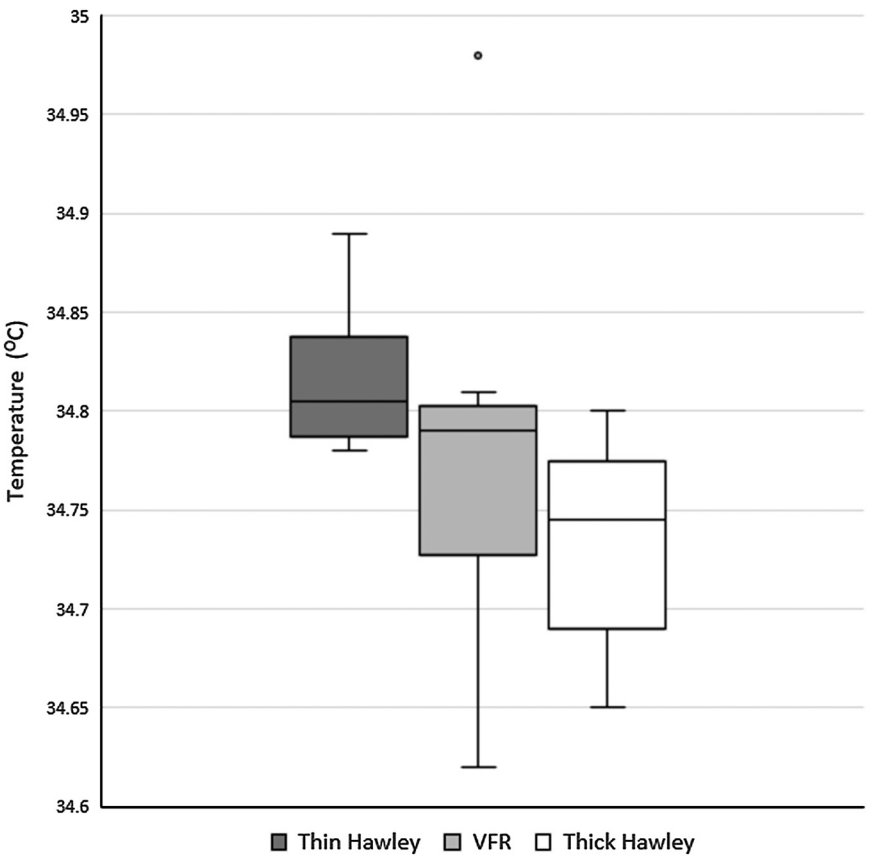


Figure 4. Distribution of microsensor temperature readings within each group.

within different retainers. The water bath was an acceptable replica of the oral environment; however, continuous monitoring across the experiment period was mandatory to ensure temperature stability. However, recent advancements in microsensor-based technology have enabled the microsensors to be covered by a thin layer of polyurethane which has been shown to often be insufficient to protect the microsensors from the possibility of corrosion.[14] Therefore, caution should be taken to ensure complete coverage of the microsensors during laboratory manufacture. The successful placement of the microsensors proved to be easier within the HR group, in comparison to the VFR group which is likely prone to breakage at the attachment area between the joined sheets.

Clinically, these differences could alter the detailed temperature detection, and subsequently affect the comprehensive recording of mean temperature. It would be advisable to control the acrylic thickness to 1 mm and attention given to full coverage of the microsensors to prevent corrosion from oral fluids. The laboratory manufacture and placement of the microsensor in the HR group was easier and less prone to failure in comparison to VFR. Nonetheless, patient preferences may require clear retainers, and so caution is advised in fabrication.

In recent years, modifications in microsensor technology have significantly improved accuracy. In turn, accurate monitoring of orthodontic patients in clinical settings is now possible to determine patient compliance with removable appliances over the short- and long-term. Sub-optimal adherence to retainer wear may be easily identified.[19] Understanding the factors that affect the detection and performance abilities of microsensors would provide areas for further improvement. Such understanding should not only be confined to the laboratory steps but should also extend to the physiological and environmental factors that may influence the performance of thermal microsensors. Consequently, proper consideration of the thermal properties of retainer material could enhance accuracy and precision of detailed thermal detection in future applications of microsensors.

Limitations

Although this *in vitro* study followed strict laboratory and experimental conditions, there are some plausible limitations for consideration. An extension of this experimental setup to include a control group without material coverage was not feasible because of the likelihood of corrosion upon direct exposure of the microsensors to water.[17] An additional potential limitation was the ability to maintain water volume; however, precautionary measures were taken by using a large water bath container within a closed and controlled environment to control for evaporation, which assisted in maintaining acceptable water volume levels. The microsensors demonstrated stable performance across the three groups; however, there was no assessment of the reliability of thermal detection over longer periods which is an area for future research.

Conclusion

The accuracy of temperature detection of the TheraMon® microsensors was affected by the material thickness and composition of different removable retention appliances. However, the differences were small and did not appreciably impact on their clinical utility. For detailed temperature monitoring, it may be advisable to apply a thin layer of acrylic coverage in HRs within limits to control the thermal detection properties of the intra-oral device.

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Conflict of interest

The authors declare that there is no conflict of interest.

Funding

This study was funded by the Health commission of Henan province, with number: SBGJ202002074.

References

1. Rahman N, Nathwani S, Kandiah T. Teledentistry from a patient perspective during the coronavirus pandemic. Br Dent J 2020;14:1–4.

2. Wafaie K, Mohammed H, Mohamed AMA, Zhou J, Daniel B, Yiqiang Q. A qualitative study of orthodontic patients' experiences in quarantine during the COVID-19 pandemic outbreak. Am J Orthod 2022;161:498–506.
3. McCall B. COVID-19 and artificial intelligence: protecting health-care workers and curbing the spread. Lancet Digit Health 2020;2:166–e7.
4. Torous J, Jän Myrick K. Digital mental health and COVID-19: using technology today to accelerate the curve on access and quality tomorrow. JMIR Ment Health 2020;7:18848.
5. Whitelaw S, Mamas MA, Topol E, Van, Spall HGC. Applications of digital technology in COVID-19 pandemic planning and response. Lancet Digit Health 2020;2:435–40.
6. Yamashiro T, Ko CC. Artificial intelligence and machine learning in orthodontics. Orthod Craniofac Res 2021;24 2:3–5.
7. Mohammad-Rahimi H, Nadimi M, Rohban MH, Shamsoddin E, Lee VY, Motamedian SR. Machine learning and orthodontics, current trends and the future opportunities: a scoping review. Am J Orthod Dentofacial Orthop 2021;160:170–9.e4.
8. Steels S, Van der Zande M, van Staa TP. The role of real-world data in the development of treatment guidelines: a case study on guideline developers' opinions about using observational data on antibiotic prescribing in primary care. BMC Health Serv Res 2019;19:942.
9. Bichu YM, Hansa I. Applications of artificial intelligence and machine learning in orthodontics: a scoping review. Prog Orthod 2021;22:18.
10. Sousa MJ, Pesqueira AM, Lemos C, Sousa M, Rocha Á. Decision-making based on big data analytics for people management in healthcare organizations. J Med Syst 2019;43:290.
11. Pastorino R, De Vito C, Migliara G, Glocker K, Binenbaum I, Ricciardi W. Benefits and challenges of Big Data in healthcare: an overview of the European initiatives. Eur J Public Health 2019;29:23–7.
12. Johnston CD, Littlewood SJ. Retention in orthodontics. Br Dent J 2015;218:119–22.
13. Tsomos G, Ludwig B, Grossen J, Pazera P, Gkantidis N. Objective assessment of patient compliance with removable orthodontic appliances: a cross-sectional cohort study. Angle Orthod 2014;84:56–61.
14. Schott TC, Göz G. Wearing times of orthodontic devices as measured by the TheraMon® microsensor. J Orofac Orthop 2011;72:103–10.
15. Mohammed H, Rizk MZ, Wafaie K, Ulhaq A, Almuzian M. Reminders improve oral hygiene and adherence to appointments in orthodontic patients: a systematic review and meta-analysis. Eur J Orthod 2019;41:204–13.
16. Charavet C, Le Gall M, Albert A, Bruwier A, Leroy S. Patient compliance and orthodontic treatment efficacy of Planas functional appliances with TheraMon microsensors. Angle Orthod 2019;89:117–22.
17. Schott TC, Göz G. Applicative characteristics of new microelectronic sensors Smart Retainer® and TheraMon® for measuring wear time. J Orofac Orthop 2010;71:339–47.
18. Kaya E, Kurt A, Er M. Thermal degradation behavior of methyl methacrylate derived copolymer. J Nanosci 2012;12:8502–12.
19. Moreno-Fernández A, Iranzo-Cortés JE, Paredes-Gallardo V. Effectiveness of removable appliances with temperature sensors in orthodontic patients: a systematic review and meta-analysis. Eur J Orthod 2022;44:134–45.
20. Schott TC, Ludwig B, Glasl BA, Lisson JA. A microsensor for monitoring removable-appliance wear. JCO 2011;45:518–20.
21. Moore RJ, Watts JT, Hood JA, Burritt DJ. Intra-oral temperature variation over 24 hours. Eur J Orthod 1999;21:249–61.
22. Iden T, Horn EP, Bein B, Böhm R, Beese J, Höcker J. Intraoperative temperature monitoring with zero heat flux technology (3M SpotOn sensor) in comparison with sublingual and nasopharyngeal temperature: an observational study. Eur J Anaesth 2015;32:387–91.
23. Aggarwal N, Garg M, Dwarakanathan V, Gautam N, Kumar SS, Jadon RS. Diagnostic accuracy of non-contact infrared thermometers and thermal scanners: a systematic review and meta-analysis. J Travel Med 2020;27:taaa193.
24. Kirshenblatt S, Chen H, Dieltjens M, Pliska B, Almeida FR. Accuracy of thermosensitive microsensors intended to monitor patient use of removable oral appliances. JCDA.ca 2018;84:i2.