Research Paper

Hong Kong Physiotherapy Journal
Vol. 42, No. 1 (2022) 15–22
DOI: 10.1142/S1013702522500020

Hong Kong Physiotherapy Journal
https://www.worldscientific.com/worldscinet/hkpj

Immediate effects of manual hyperinflation on cardiorespiratory function and sputum clearance in mechanically ventilated pediatric patients: A randomized crossover trial

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Received 3 March 2021; Accepted 24 August 2021; Published 29 September 2021

Background: In developing countries, lower respiratory tract infection is a major cause of death in children, with severely ill patients being admitted to the critical-care unit. While physical therapists commonly use the manual hyperinflation (MHI) technique for secretion mass clearance in critical-care patients, its efficacy has not been determined in pediatric patients.
Objective: This study investigated the effects of MHI on secretion mass clearance and cardiorespiratory responses in pediatric patients undergoing mechanical ventilation.

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Methods: A total of 12 intubated and mechanically ventilated pediatric patients were included in this study. At the same time of the day, the patients received two randomly ordered physical therapy treatments (MHI with suction and suction alone) from a trained physical therapist, with a washout period of 4 h provided between interventions.
Results: The MHI treatment increased the tidal volume [V_t; 1.2 mL/kg (95% CI, 0.8–1.5)] and static lung compliance [C_{stat}; 3.7 mL/cmH$_2$O (95% CI, 2.6–4.8)] immediately post-intervention compared with the baseline ($p < 0.05$). Moreover, the MHI with suction induced higher V_t [1.4 mL/kg (95% CI, 0.8–2.1)] and C_{stat} [3.4 mL/cmH$_2$O (95% CI, 2.1–4.7)] compared with the suction-alone intervention. In addition, the secretion mass [0.7 g (95% CI, 0.6–0.8)] was greater in MHI with suction compared with suction alone ($p < 0.05$). However, there was no difference in peak inspiratory pressure, mean airway pressure, respiratory rate, heart rate, blood pressure, mean arterial blood pressure or oxygen saturation ($p > 0.05$) between interventions.
Conclusions: MHI can improve V_t, C_{stat} and secretion mass without inducing adverse hemodynamic effects upon the pediatric patients requiring mechanical ventilation.

Keywords: Manual hyperinflation; suction; physical therapy; secretion clearance; pediatric; mechanical ventilation.

Introduction

Lower respiratory tract infection is a leading cause of mortality in children under the age of 5 years. In particular, pneumonia, one of the most common lower respiratory tract infections, is a major cause of death in Thailand and other developing countries.[1] During lower respiratory tract infection, muco-ciliary clearance can become overloaded by excessive mucus production, or be impaired by heightened inflammation, with an associated loss of ciliary function.[2] The resultant impairment of airway clearance predisposes these patients to secondary complications, such as acute lobar atelectasis.[3]

Children admitted to pediatric intensive-care units (PICUs) who receive mechanical ventilation for severe pneumonia, often have physical therapy administered as a standard therapy.[2,3] The aim of chest physical therapy is to improve airway clearance, breathing mechanics, gas exchange and ultimately, the rate of patient recovery.[2] Typically, chest physical therapy comprises postural drainage, percussions, vibrations, suction and manual hyperinflation (MHI).[3] Some manual techniques, including manual chest percussion, are stressful procedures in mechanically ventilated patients.[2] This can negatively impact upon the implementation of this treatment in patients receiving mechanical ventilation, especially the pediatric patients.[4,5] However, recent systematic reviews.[3,6] suggest that MHI can be useful for airway clearance in ventilated pediatric patients due to enhanced removal of secretion and reopening of collapsed airways.[6,7] Nevertheless, while the majority of studies have investigated the efficacy of MHI in adult patients,[8] the efficacy of MHI on pediatric lung physiology remains less well understood.[9,10] This is important to address, since secretion retention can be higher in pediatric patients due to smaller airways.[11]

Therefore, the aim of this study was to investigate the immediate effects of MHI on cardiorespiratory function and secretion mass in mechanically ventilated pediatric patients. It was hypothesized that MHI with suction would improve the tidal volume (V_t), static lung compliance (C_{stat}) and secretion mass compared to suction alone.

Methods

Study design

This study employed a randomized treatment sequence and a crossover clinical trial. On the day of treatment, the MHI with suction or suction-alone protocol was randomized to be given as the first treatment protocol, with the other protocol applied (at 1.00 pm) 4 h (washout period) later on the same day. The randomization order was determined by a computer-generated random sequence (Microsoft Excel 2012). Sample size calculation was based upon the study of Choi and Jones,[12] with 12 patients required based upon an α of 0.05 and a power of 80%. The study protocol was approved by the Lampang Hospital and Naresuan University Ethics Committees. The protocol was registered in the Thai Clinical Trials Registry database

(TCTR20160418001). Written informed consent was obtained from all patients via their parents before commencing the study.

Participants

All patients recruited for this study had been admitted to the PICU at Lampang Hospital and were diagnosed with pneumonia and secretion retention according to the British Thoracic Society guidelines[13] for the management of community-acquired pneumonia in children. Patients had subsequently been referred to the PICU physical therapist for physical therapy management.[13] The patients met the inclusion criteria of being aged < 15 years, receiving mechanical ventilation via an endotracheal tube for at least 24 h and presenting with vital signs in the normal range.[11] Patients with cerebral palsy, history of thoracic surgery, pneumothorax, acute respiratory distress syndrome, severe acute head injury, the usage of inotropes and vasopressors drugs, severe bronchopleural fistula, rib fracture, emphysema bullae, lung abscess, history of preterm birth, heart disease or requiring mechanical ventilation with a peak inspiratory pressure (PIP) higher than 40 cmH_2O, an $FiO_2 > 0.6$ and a positive end expiratory pressure (PEEP)$>$ 10 cmH_2O, were excluded from the study. Sixteen patients were initially enrolled and screened, with only 12 patients meeting the inclusion criteria and taking part in the study.

Interventions

All subjects were positioned into a supine position for 15 min to achieve baseline stability prior to the intervention. The same supine position was maintained until the end of the treatment. The procedures were performed following the clinical practice guidelines of the Infectious Diseases Society of America and the American Thoracic Society.[14,15]

MHI intervention

Manual hyperinflation was performed by single physical therapist using a silicone resuscitator bag (Laerdal Medical Corp., USA) via two-handed technique. The resuscitator bag (maximum volume of 500 mL) was connected to a pressure manometer (NIF-KIT, Smiths Medical, USA) with an oxygen flow of $10\,L \cdot min^{-1}$. A reservoir bag was included in the circuit. The MHI was performed with slow and deep inspirations (2 s) to a peak inflation pressure of 30 cmH_2O followed by a 2-s inspiratory pause (2 s) and a quick pressure release (1 s). Rest intervals of 1 s interspersed the MHI maneuvers.[16–18] The total duration of the MHI treatment was 3 min 36 s (six times per set$\times$ six sets).

Suction intervention

Endotracheal closed suction with pressure control ventilation (PCV) was performed by the same experienced registered nurses who were blinded to the treatment sequence. The duration of suction was 10 s with 5-s rest for each set. Three sets of suction with a closed suction system (Pacific Hospital Supply, Taiwan) were used for all patients. The size of the suction catheters was a maximum of 10 French gauge. The catheter was inserted into the carina and withdrawn about 1 cm prior to the application of a continuous negative pressure of 100 mmHg, with the total duration of 45 s per suction treatment. No suction sessions involved instillation of normal saline in the endotracheal tube. For each treatment, the secretion was collected in a secretion collection tube (Pacific Hospital Supply, Taiwan) attached to the closed suction system. Vital signs were monitored throughout. The interventions were to be terminated if the vital signs deviated from the normal range.[11]

Outcome measures

Cardiorespiratory variables were measured before treatment (baseline), immediately after treatment and subsequently, every 5 min up to 30 min post-treatment. All data were recorded at a single time point by an independent nurse, blinded to the intervention. The V_t, C_{stat}, PIP and mean airway pressure (MAP) were recorded from the display of a mechanical ventilator (SERVO-i and Bennett 840 machine). Respiratory rate (RR), heart rate (HR), systolic blood pressure (SBP), diastolic blood pressure (DBP), mean arterial blood pressure (MABP) and oxygen saturation (SpO_2) were recorded from the non-invasive monitoring equipment (Philips IntelliVue MP30, Germany).

The secretion mass was measured to the nearest 0.01 g using a digital scale (Tanita Model 1579, Japan). The secretion wet weight was calculated by the sputum cannister weight with secretions from suction minus the sputum cannister weight.

Statistical methods

Two-way repeated-measures analysis of variance (ANOVA) was used to compare the results of the study. Significant interaction effects were analyzed using post-hoc t-tests with a Bonferroni adjustment. The secretion mass was analyzed using a paired t-test. The Statistical Package for the Social Sciences was used for all statistical analysis (SPSS, version 23; SPSS Inc., Chicago, IL, USA). Statistical significance was accepted at $p < 0.05$. Data are reported as mean ± SD or 95% confidence intervals.

Results

Twelve pediatric patients (six boys and six girls) were enrolled and completed both interventions. The characteristics of the patients are summarized in Table 1. The age of the patients ranged from 3 months to 43 months. All patients were diagnosed with pneumonia and ventilated in PCV mode. Seven patients were ventilated via the SERVO-i (MAQUET Holding B.V. & Co. KG, Rastatt, Germany) machine and five patients were ventilated via the Puritan Bennett 840 (Medtronic, Minneapolis, USA) machine. The sedative agents (choral hydrate and dormicum) were used in all patients. A consort diagram of the study protocol is illustrated in Fig. 1.

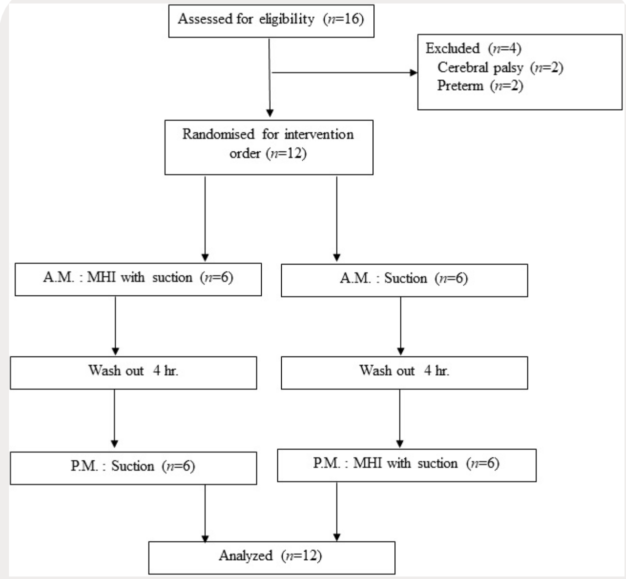

Fig. 1. CONSORT diagram of the trial.

Effect of interventions on cardiorespiratory function

There were no significant differences between the baseline parameters of the MHI with suction and suction-alone conditions. The MHI with suction increased V_t by an average of 1.2 mL/kg (95% CI, 0.8–1.5) and increased C_{stat} by 3.7 mL/cmH_2O (95% CI, 2.6–4.8) immediately post-intervention when compared with the baseline ($p < 0.05$). At 15- and 30-min post-MHI with suction, V_t and C_{stat} were similar to the baseline values ($p > 0.05$). Twelve patients demonstrated a clinically relevant improvement in C_{stat} (between 31% and 118%) and seven patients demonstrated a clinically relevant improvement in V_t (between 10% and 21%) immediately after MHI with suction when compared to the baseline.

Table 1. Characteristics of the patients studied ($n = 12$).

Variable	Mean (SD)
Age (years)	2 (1.8)
Body weight (kg)	9.7 (3.7)
Height (cm)	79.5 (15.3)
Ventilation setting PIP (cmH_2O)	15.6 (1.6)
PEEP (cmH_2O)	4.2 (0.6)
FiO_2	0.4 (0.1)
Duration of intubation at the time of study (days)	5 (3)

Notes: PIP = peak inspiratory pressure, PEEP = positive end expiratory pressure, FiO2 = fraction of inspired oxygen.

The effects of MHI with suction and suction-alone conditions on cardiorespiratory function are presented in Tables 2 and 3, respectively. There were significant differences in V_t and C_{stat} between the conditions, with the MHI with suction having higher V_t [1.4 mL/kg (95% CI, 0.8–2.1)] and C_{stat} [3.4 mL/cmH_2O (95% CI, 2.1–4.7)] compared with the suction-alone condition immediately post-intervention ($p < 0.05$).

There was no change in PIP, MAP, RR, HR, SBP, DBP, MABP or SpO_2 after MHI with suction. Moreover, the cardiorespiratory function variables were not significantly changed after suction alone (Tables 2 and 3).

Effect of interventions on secretion mass

The secretion mass in the MHI with suction intervention (1.1 ± 0.4 g) was higher compared to the secretion mass with suction alone (0.5 ± 0.3 g,

Table 2. The effects of MHI with suction and suction-alone interventions on cardiorespiratory parameters and secretion mass.

Parameter	MHI with suction				Suction alone			
	Pre-treatment	Post-treatment	15-Min post-treatment	30-Min post-treatment	Pre-treatment	Post-treatment	15-Min post-treatment	30-Min post-treatment
TV (mL/kg)	11.82 (2.8)	12.98#,* (3)	11.67 (3.1)	11.97 (2.9)	12.04 (2.8)	11.76 (2.9)	11.78 (2.9)	12.14 (3.3)
C_{stat} (mL/cmH_2O)	6.4 (2.6)	10.1#,* (3.6)	7.9 (3.4)	7.9 (3.5)	7.1 (3.5)	7.4 (3.5)	7.5 (3.6)	7.3 (3.1)
PIP (cmH_2O)	15.6 (1.6)	16.2 (1.2)	16 (1.4)	16 (1.3)	16.5 (1.1)	16.4 (1.2)	16.4 (1.6)	16.4 (1.8)
MAP (cmH_2O)	8.3 (1.1)	8.1 (0.9)	8 (1)	7.8 (0.9)	8.2 (0.9)	8.3 (1)	8.5 (1)	8.1 (0.9)
HR (bpm)	129.6 (21.5)	132.7 (18.8)	129.5 (19.6)	130.9 (19.9)	128.8 (21.2)	128.3 (19.9)	126.3 (19.3)	127.3 (19.9)
RR (bpm)	32.8 (5.9)	33.6 (5.9)	31.9 (4.7)	32.5 (5.6)	31.8 (7.5)	32.8 (7.7)	33.5 (7.3)	32.8 (7.2)
SBP (mmHg)	96.8 (8.5)	97.8 (7.3)	97.5 (10.5)	98.3 (7.9)	96 (9.5)	97.2 (7.7)	99.8 (10.9)	97.6 (9.5)
DBP (mmHg)	55.1 (5.5)	52.8 (3.6)	58 (4.9)	55.3 (4.3)	56.5 (5.8)	53.1 (4.5)	53.3 (5.8)	53.3 (4.5)
MABP (mmHg)	69.1 (4.5)	67.8 (2.8)	71.3 (5.4)	69.6 (4.3)	69.6 (3.7)	67.7 (4.5)	68.7 (5.7)	68.2 (4.8)
SpO_2 (%)	99.4 (0.9)	99.6 (0.5)	99.3 (0.9)	99.6 (0.5)	99.3 (0.9)	99.3 (0.9)	99.3 (1)	99.5 (0.8)
Secretion (g)		1.1* (0.4)				0.5 (0.3)		

Notes: The data are represented as mean (SD). TV: Tidal volume, C_{stat}: Static lung compliance, PIP: Peak inspiratory pressure, MAP: Mean airway pressure, HR: Heart rate, RR: Respiratory rate, SBP: Systolic blood pressure, DBP: Diastolic blood pressure, MABP: Mean arterial blood pressure and SpO_2: Oxygen saturation. #Significant difference between the pre- and post-treatment interventions ($p < 0.05$). *Significant difference between the two treatment interventions ($p < 0.05$).

Table 3. Mean differences (95% CI) for the outcome measures between MHI with suction and suction-alone interventions.

Parameter	Mean differences between MHI with suction versus suction alone (lower upper limits)			
	Pre-treatment	Post-treatment	15-Min post-treatment	30-Min post-treatment
TV (mL/kg)	−0.2 (−0.7 − 0.2)	1.4 (0.8 − 2.1)*	0.1 (−0.8 − 1.1)	0.1 (−1.1 − 1.2)
C_{stat} (mL/cmH_2O)	−0.7 (−1.9 − 0.6)	3.4 (2.1 − 4.7)*	1.1 (0 − 2.3)	1.3 (−0.5 − 3)
PIP (cmH_2O)	−0.4 (−1 − 0.2)	0.2 (−0.4 − 0.8)	0.2 (−0.4 − 0.8)	−0.1 (−0.7 − 0.5)
MAP (cmH_2O)	0.1 (−0.5 − 0.7)	−0.3 (−1.2 − 0.7)	−0.6 (−1.5 − 0.3)	−0.3 (−0.8 − 0.2)
HR (bpm)	0.8 (−3.9 − 5.4)	3.6 (−0.9 − 8.1)	2.5 (−2.5 − 7.5)	2.8 (−0.1 − 5.8)
RR (bpm)	1 (−2.4 − 4.4)	−0.3 (−2.9 − 2.4)	−2.5 (−5.5 − 0.4)	−1.3 (−3.5 − 1)
SBP (mmHg)	0.9 (−6.1 − 7.9)	−0.3 (−4.8 − 4.3)	−3.2 (−10.8 − 4.5)	−0.3 (−5.4 − 4.9)
DBP (mmHg)	−1.4 (−7.1 − 4.2)	1.1 (−4.2 − 6.4)	6.2 (−1 − 13.3)	3.5 (−4 − 11)
MABP (mmHg)	−0.5 (−4.6 − 3.7)	0.7 (−3.5 − 4.8)	3.2 (−2.1 − 8.4)	1.9 (−2.5 − 6.4)
SpO_2 (%)	0.1 (−0.8 − 0.9)	0.5 (0 − 0.8)	0 (−0.4 − 0.2)	0 (−0.8 − 0.8)
Secretion mass (g)		(0.7 − 0.8)*		

Notes: *Significant between group differences ($p < 0.05$).

$p < 0.05$; see Fig. 2). A mean difference of 0.7 g (95% CI, 0.6–0.8) was observed between the MHI with suction and suction-alone treatments.

Discussion

This is the first randomized crossover trial study, which has assessed the effects of MHI on secretion production and cardiorespiratory responses in mechanically ventilated pediatric patients. The main finding of this investigation was that MHI with suction increased V_t, C_{stat} and secretion mass compared to suction alone. Moreover, there were no differences observed in PIP, MAP, RR, HR, BP or SpO_2 in pediatric patients receiving mechanical ventilation due to pneumonia. There were no adverse effects of MHI on cardiodynamics in the mechanically ventilated pediatric patients assessed in this study. Therefore, our findings suggest that MHI may improve secretion removal in pediatric patients.

Pediatric lung physiology has lower lung compliance and functional residual capacity compared with adults, leading to premature airway closure. In pediatric patients with pulmonary diseases, reduced pulmonary compliance can increase bronchial-wall edema and the risk of airway collapse.

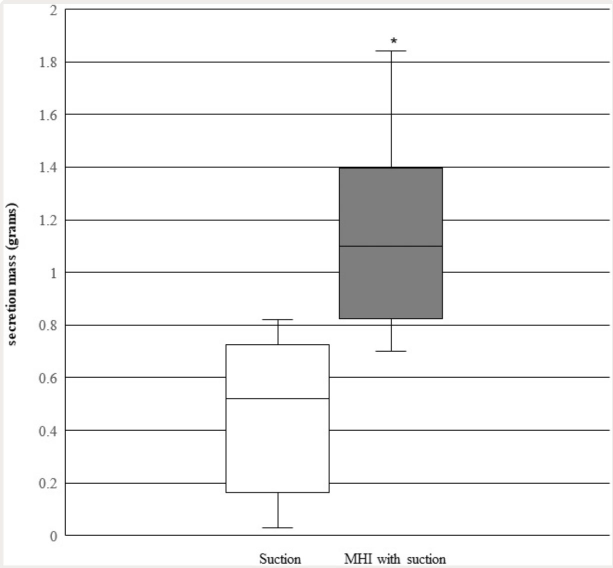

Fig. 2. The effects of MHI with suction and suction alone on secretion mass (mean ± SD).

This can often be corrected by chest physical therapy or a bronchodilator.[9,10] It is the variance in lung physiology between children and adults which has led to limitations in translating the existing MHI literature to the current study cohort. It has previously been suggested that the aim of chest physical therapy during acute infection is to enhance airway clearance, assisting in improving breathing mechanics and gas exchange to promote patient recovery.[2,18] Manual hyperinflation, a technique commonly used in adult and pediatric intensive-care units,[3,19] is used by up to 96% of physiotherapists in Canada.[20] Gregson *et al.*[21,22] showed that MHI can increase both peak expiratory flow and peak expiratory flow to peak inspiratory flow ratio in pediatric patients, enhancing the removal of secretion from peripheral to proximal airways. In agreement with previous works, Soundararajan and Thankappan.[23] demonstrated that arterial oxygenation can be improved in pediatric patients with upper lobe collapse after cardiac surgery. Moreover, Viana *et al.*[24] found that lung volumes could be improved by MHI with and without PEEP in preterm newborns. Nevertheless, previous studies have combined treatments with MHI, making it difficult to distinguish between the techniques utilized to enhance airway clearance. In our work, we studied pediatric patients with pneumonia and secretion retention, therefore, our results add to the existing knowledge base related to MHI in pediatric cohorts with respiratory failure that require invasive mechanical ventilation.

Cardiorespiratory functions

In this study, the MHI with suction increased V_t and C_{stat}, with C_{stat} immediately improved by 58% after the MHI with suction. These changes in volume and compliance are consistent with previous studies, and may be linked to increased airway diameter and secretion removal.[12] The airway diameter in children is smaller compared to adults and might be an important consideration for high airway resistance with pulmonary disease in children.[9,10] Although airway resistance was not measured in this study, peak inspiratory pressure and mean airway pressure were not different and, as such, it can be assumed that airway resistance was not different. Moreover, physiotherapists and medical staff assessed lung sounds after MHI and there was no evidence of wheezing sounds, which can indicate increased airway resistance.[10,12] In line with the previous observations of Cunha *et al.*[25] who reported that MHI had no adverse effects on HR, BP and SpO_2 in pediatric patients receiving invasive mechanical ventilation, we observed MHI does not adversely affect hemodynamics. The use of MHI with a low V_t (6–8 mL/kg) is a protective strategy for hemodynamic stability during mechanical ventilation in pediatric patients.[6,16] In this study, we performed MHI at a PIP of 30 cmH_2O in accordance with previous guidelines.[16] Our results suggest that MHI is a beneficial and safe technique for airway clearance in pediatric patients requiring mechanical ventilation.

Secretion mass

Application of MHI with suction increased the secretion mass compared to the suction-alone condition. Since increased peak expiratory flow can aid secretion to the larger airway, the increase in secretion mass reported in this study might be a function of an increase in peak expiratory flow. Despite not assessing the peak expiratory flow, previous investigations have revealed that MHI can enhance secretion removal via a higher peak expiratory flow.[26] It is possible that the sputum dry weight may directly indicate the actual amount of sputum; for example, there is a linear relationship between sputum dry weight and wet weight (i.e., the higher the sputum wet weight, the higher the sputum dry weight).[27] In this study, we chose sputum wet weight due to costing.

The limitations of this study included the severity of the disease not being classified and the lack of a long-term follow-up. These limitations mean that the application of MHI could not be related to both of these outcomes. Therefore, future research is warranted to determine the repeated interventions of the MHI on long-term effect in specific disease and different ventilator modes on time to extubating and length of hospital stay. The relationship between peak expiratory flow and secretion mass should also be investigated.

In conclusion, this study indicated that the MHI technique can improve lung volume, compliance and secretion mass than suction alone. There were no adverse effects on hemodynamics in pediatric patients requiring mechanical ventilation.

Acknowledgments

We would like to thank all the patients and their families and the nurses and medical staff of PICU, Lampang Hospital, Thailand for taking part in this study.

Conflict of Interest

No potential conflicts of interest are reported.

Funding/Support

This study was supported by Grants from the Graduate Program of the Faculty of Allied Health Sciences, Naresuan University and the Naresuan University Research Fund, Thailand.

Author Contributions

Tawatchai Luadsri conceptualized and designed the study, data collection and analysis, and also prepared the draft of the manuscript. Weerapong Chidnok conceptualized and designed the study, prepared the draft of the manuscript and reviewed the manuscript. Jaturon Boonpitak, Kultida Pongdech-Udom and Patnuch Sukpom participated in data collection. Tawatchai Luadsri, Jaturon Boonpitak, Kultida Pongdech-Udom, Patnuch Sukpom and Weerapong Chidnok have made substantial intellectual contributions to the study. All authors have read and approved the final manuscript.

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