Immediate autonomic nervous system activity in skin microcirculation during osteopathic cranial vault hold intervention

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Abstract

Effects of osteopathy in the cranial field (OCF) frequently involve changes in skin blood flow (SBF) and autonomic nervous system (ANS) functioning. ANS related frequency markers fell short to adequately explain physiological reactions in general as well as during OCF. An intermediate (IM) frequency band generated by a brainstem pacemaker expanded ANS research in SBF. Studying IM frequencies during OCF may provide new insights on treatment relevant ANS responses. Data from forehead SBF measurements in twenty-five healthy participants were recorded in a blocked design before, during, and following an osteopathic cranial vault hold (CVH) intervention. Analyses included momentary frequencies of highest amplitude (MFHA) from wavelet time-frequency distributions and amplitudes in low (0.05 – 0.12 Hz), intermediate (0.12 – 0.18 Hz), and high (0.18 – 0.4 Hz) frequency bands. During CVH, LF averaged interval durations significantly increased, while IM and HF band durations decreased. Amplitudes significantly increased in LF, IM and HF bands. A cluster analysis found individual response patterns where 77% of the participants exhibited a highly stable, slowed LF oscillation (0.07 Hz) while another group remained in an IM dominated mode. Further explorative analyses suggested that the increase of LF activity duration during CVH may be related to higher self-regulation ability. Rhythmic patterns due to sensory input reduction and CVH in SBF matched previous findings on a central pacemaker induced ‘0.15 Hz rhythm’/IM activity, which may explain physiological reactions during CVH. These findings suggest further investigations of the role of OCF interventions in ANS mediated disorders.

Introduction

The study of physiological rhythms in science in general and in osteopathic manipulative therapy (OMT) has been marked by controversies and setbacks. To some authors, rhythmic activity merely represented “clanking of the cogs” while others proposed their vital purpose such as reflecting autonomic nervous system (ANS) activity (Laborde et al., 2017; Malpas, 2002; Park & Thayer, 2014; Pomeranz et al., 1985). The concepts of cranial-sacral treatment (CST) or osteopathy of the cranial field (OCF) and the cranial rhythmic impulse (CRI) of William Sutherland have been burdened by controversy, viewed for decades even as esoteric tool in CST (McPartland & Mein, 1997; Nelson et al., 2006). Yet, this should not surprise as physiological and psychophysiological research supplied confounding or contradictory concepts or models of physiological rhythms, and this precipitated also in scientific efforts in OCF. Recently, it has been suggested to reformulate the relevance of osteopathic practice and principles (e.g., Esteves et al., 2020; Smith, 2019). Furthermore, the hypothesis that Sutherland’s models may be based on abandoned eighteenth century physiological studies by Emanuel Swedenborg (Jordan, 2009) underscores the need not only for reflecting current osteopathic theories but calls also for further scrutinizing physiological underpinnings of OMT techniques.

OMT is focused on enhancing the body’s self-regulation putatively by stabilizing sympathetic and parasympathetic branches of the ANS. This is frequently operationalized by either time- or frequency-domain measures of heart rate variability (HRV; Rechberger et al., 2019). Frequency-domain measures often investigate a low frequency (LF) band, proposed to mark a combination of sympathetic and
parasympathetic effects, as well as a high frequency (HF) band, commonly agreed as a surrogate of the cardiac vagal function (Camm et al., 1996; Laborde et al., 2017). It has been proposed that an optimal level of vagally mediated HRV denotes health and self-regulatory capacities while low vagal HRV is related to poor cardiovascular health outcomes (Thayer et al., 2012). Over the past century, several studies have investigated the immediate and long-term physiological effects of OMT on ANS functioning and several studies found an increase of HF-HRV parameters during and directly following OMT treatment in healthy non-symptomatic adults, suggesting a modulation of the parasympathetic branch (Arienti et al., 2020; Carnevali et al., 2020; Cerritelli et al., 2020; Henley et al., 2008; Rechberger et al., 2019; Ruffini et al., 2015). However, the interpretation of previous studies is often limited, e.g., by use of the LF/HF ratio, which has been criticized for long for the physiological ambiguity of LF composition (Berntson et al., 1997). Therefore, a ‘second generation model’ for HRV research is direly needed which considers also its non-stationary and non-linear features (Billman, 2013; Goldstein et al., 2011; Heathers, 2012; Malpas, 2002; Perlitz, Cotuk, Lambertz, et al., 2004; Reyes del Paso et al., 2013; Schwerdtfeger et al., 2020). Another problem pertains to the existence of additional rhythms possibly indexing the CRI, which cannot be explained using conventional frequency domain measures such as the LF/HF ratio (McPartland & Mein, 1997; Rasmussen & Meulengracht, 2021). In summary, this necessitates the application of a different methodology to allow inferences on ANS adaptation processes during OMT.

Recently, the possibility of a central pacemaker of autonomic regulation has been reiterated in the literature, and the stationary frequency boundaries, especially in the much-disputed LF range, have been challenged (Pfurtscheller et al., 2020; Schwerdtfeger et al., 2020). This was preceded by comprehensive studies establishing a dynamic physiological model linking cardiac, vascular, and respiratory rhythms to rhythmic activity in unspecific reticular neurons in the common brainstem system of dogs (Langhorst, 1984), which confirmed activity in these neurons at approximately 0.15 Hz (Lambertz et al., 2000; Lambertz & Langhorst, 1998). Interestingly, McPartland and Mein (1997) already linked this approach to OCF since those frequencies appeared identical with those reported for the CRI. Since these studies rested solely on animal models, this approach was not pursued.

Regarding OMT, the significance of 0.15 Hz physiology was further discussed by Pelz (2015) in the light of a comparable frequency band in human skin microcirculation between 0.12–0.18 Hz. This frequency band was identified to coincide with subjective feelings of profound naïve or triggered relaxation (Ziege, 1992; Perlitz et al., 2004). Further, demonstrated to prevail also in arterial blood pressure, respiration, and HRV in individuals experienced in practicing autogenic training (AT), this rhythm was shown to be coordinated at integer number ratios. This so-called n:m coordination may appear in lower or upper harmonics with the “0.15 Hz rhythm band” at its center (Perlitz, Cotuk, Lambertz, et al., 2004). A recent functional magnetic resonance imaging (fMRI) study found evidence on activity of a central pacemaker within the left brainstem in humans (Pfurtscheller et al., 2020), which confirmed the findings in animals of previous studies (Lambertz et al., 2000). Furthermore, activity in the intermediate (IM) band (previously also labelled as ‘0.15 Hz rhythm band’) was associated with activation in core interoceptive areas of the central autonomic network (Keller et al., 2020). In summary, this suggests that the IM band physiology in
skin microcirculation indexes central autonomic functioning, and the possibility of harmonic couplings offers a more dynamic account of ANS functioning compared to the standard LF/HF model.

In the current study, we examined physiological ANS responses in healthy individuals before, during, and following a specific OCF intervention, i.e., cranial vault hold (CVH). Using semi-linear algorithms, LF, IM and HF bands in photoplethysmography (PPG) skin blood flow (SBF) were computed as combined time-frequency parameters. It is the purpose of this communication to interpret findings in forehead skin PPG recordings during CVH on the background of IM band physiology to account for effects of OMT (Pelz, 2015). We hypothesize that the physiological reactions in SBF observed during CVH may be explained by a dynamic model of ANS functioning including changes in IM band activity. Furthermore, we wanted to explore similarities of IM band dynamics associated with CVH with those described during hypnoid states (Perlitz, Cotuk, Lambertz, et al., 2004).

Materials And Methods

Experimental protocol and participants

Twenty-five healthy adults (14 female, 11 male, aged 42.4 ± 13.1 years) participated in this study. As four participants completed two measurements at an interval of 1 week, analyses were performed with a total of 31 measurements. All participants were non-smokers without osteopathic treatments during the preceding three months. Exclusion criteria were mental health symptomatology assessed with the ICD-10 symptom rating (ISR) questionnaire (Tritt et al., 2010), a history of or acute neurological or cardiovascular disorders, current use of psychoactive medication as well as high-performance sport, and smoking. Furthermore, to ensure spontaneous ANS activity, participants were instructed and formally agreed to abstain from caffeine for 4 hours and from alcohol consumption for 48 hours prior to testing. Recruitment was conducted through personal contact. Experimental sessions were held in private practice rooms of two osteopathic practitioners (examiner 1: n = 20 measurements; examiner 2: n = 11 measurements). The experiment was conducted according to the Code of Ethics of the World Medical Association (Declaration of Helsinki, 2008). All participants provided written, informed consent, and all protocols were approved by the Institutional Review Board of the state of lower-saxony (EK vote from 04/03/2017).

Procedure

All participants underwent cranial vault hold (CVH) as an osteopathic intervention commonly employed to stimulate ANS activity, and sections with open and closed eyes serving as within-subject control conditions. Examiners and participants were blind to the data recording, and off-line data analysis. As standard osteopathic hands-on technique, CVH touches standardized cranial regions and cranial bones at very low pressure on the scalp. For the current communication only PPG-data of participants was used to study physiological rhythms in skin microcirculation before, during, and following OCF specific CVH intervention. During testing, the examiner was seated behind the head of the participant who remained in a supine position. Each experimental session was performed at comfortable room temperature and
consisted of five consecutive sections (300 seconds each; following the first measurements of the study, 30 seconds were added between sections to account for motion artifacts produced during section transitions). These sections consisted of two different “hands-off” resting states during which the participant was encouraged by an automated female voice to either keep the eyes open (EO) or eyes closed (EC) bracketing the “hands-on” CVH phase during which eyes were closed as well (see Fig. 1).

Psychometry - Questionnaires

Since IM band physiology was previously found to be associated with activation of CNS interoceptive networks (Keller et al., 2020), we assessed self-rated levels of self-regulation using the self-regulation scale of the Multidimensional Assessment of Interoceptive Awareness (Version 2; MAIA-2; Mehling et al., 2018). The MAIA-2 assesses the interoceptive awareness defined as the conscious level of interoception accessible to self-report. Furthermore, participants completed a short version of the Spielberger State-Trait Anxiety Inventory (STAI-5; Zsido et al., 2020).

Photoplethysmography data acquisition and processing

Forehead SBF was recorded using PPG and respective data was analyzed for activity in previously published defined frequency bands (LF: 0.05–0.12 Hz; IM: 0.12–0.18 Hz; HF: 0.18–0.4 Hz; Perlitz, Lambertz, et al., 2004). PPG and ECG-derived HRV measures have been shown to correlate highly during rest (Schäfer & Vagedes, 2013). The momentary frequencies of highest amplitude (MFHA), namely the frequency with the highest amplitude for each time step, was extracted for the above frequency bands. Frequency band averaged interval durations (total of 300 s for each section) were computed from MFHA values and were comprised of a single dominating frequency for each time bin. Furthermore, signal amplitudes for defined frequency bands were computed for each section. For technical details of recording, preprocessing and signal analyses see Appendix 1.

Statistical analysis

Statistical analyses were performed with the Statistical Package for the Social Sciences (SPSS), version 27 (SPSS Inc., Chicago, IL, USA). A p-value of < .05 was considered statistically significant. Frequency band averaged interval durations (total of 300 s for each section) were computed from MFHA values and were comprised of a single dominating frequency for each time bin. MFHA derived frequency band durations were imported to SPSS. Separate one-way analyses of variance (ANOVAs) investigated differences in averaged interval durations as well as amplitudes between each of the five consecutive sections for LF, IM and HF bands. In case of significant F-test, post-hoc tests (Tukey's correction) probed differences between individual sections.

LF, IM and HF durations were submitted to K-means cluster analysis (Hartigan, 1975) to explore whether participants could be clustered into two groups showing different physiological responses during CVH. Furthermore, averaged MFHA time courses in absolute normalization were plotted for all participants as well as separately for the two groups. Spearman's correlations were computed for STAI-5 values and
frequency durations. To further investigate the psychophysiological relevance of frequency adaptation during CVH, LF changes were correlated with self-regulation ability (subscale from MAIA-2). As this was an exploratory analysis, correlations were not corrected for multiple testing.

**Results**

MFHA derived frequency band averaged activity durations

The dominating frequency in skin microcirculation, i.e., that of highest amplitude was probed for each experimental section. Frequency band averaged interval durations computed from MFHA values displayed a single dominating frequency for each time bin. Therefore, the sum of durations for LF, IM, and HF amounted to 300 s per section. One-way ANOVAs probed differences of duration of averaged frequency band interval durations between each of the consecutive five sections (Fig. 2). We observed an overall significant difference between sections for durations of the LF band ($F(4,150) = 8.17, p < .001$), for IM band ($F(4,150) = 4.09, p = .004$), but not for the HF band ($F(4,150) = 2.25, p = .07$). Post-hoc tests using Tukey correction showed that the averaged interval duration of LF activity was significantly longer in section 3 (CVH) compared to all other control sections (all $p < .001$). The averaged interval duration of IM activity during CVH, however, was significantly shorter compared to sections 1, 2 and 5 ($p < .05$) but not compared to section 4. The ANS changes induced immediately by CVH did not prevail in the sections following this intervention in any frequency band (all $p > .2$).

Signal amplitudes

Amplitude dynamics reflect ANS activity on the cardiac level and on the level of the vasculature. We therefore compared changes in SBF amplitude along the boundaries of LF, IM, and HF bands computing one-way ANOVAs between consecutive sections (Fig. 3). There was an overall significant difference between sections for the LF band ($F(4,150) = 27.04, p < .001$), for IM band ($F(4,150) = 5.45, p < .001$) as well as the HF band ($F(4,150) = 11.41, p < .001$). Post-hoc Tukey corrected pairwise comparisons showed a significant increase of amplitudes during CVH compared to all other sections in the LF and HF band (LF all $p < .001$; HF all $p < .05$) as well as a significant increase during CVH compared to sections 1, 2 and 4 (all $p < .05$) in the IM band. A significant increase from section 2 to 4 in the HF band suggests that the immediate increase of amplitudes during CVH persisted within this frequency range.

Psychophysiological reactions during Vault Hold intervention

Mean MFHA of all participants showed a decrease from 0.12–0.13 Hz at baseline to 0.088 Hz during CVH. An explorative K-means clustering analysis based on LF, IM and HF durations showed two distinct responses to CVH (‘LF-responders’: $N = 24$; means: LF = 292.2, IM = 18.7, HF = 4.1; ‘IM-responders’: $N = 7$; means: LF = 120.0, IM = 114.2, HF = 78.6). Averaged MFHA time courses for all participants as well as for separate groups showed that ‘IM-responders’ stabilized in IM mode suggested by decreased variability, while ‘LF-responders’ showed a decrease to a stable oscillation around 0.07 Hz during CVH. See Fig. 4 for group time-courses and descriptive statistics.
Psychometric data was only completed in a subsample of 20 participants and due to the limited sample size, Spearman's correlations were computed. In line with the relation of anxiety processing in LF and IM bands (Pfurtscheller et al., 2018), STAI-5 state, and trait values were correlated with baseline LF and IM frequency durations and amplitudes. There was a significant correlation between IM Band frequency durations at baseline (section 1) and state anxiety ($r = -0.50$, $p = 0.01$). To further investigate the psychophysiological meaning of frequency duration and amplitude increases during CVH, physiological measures were correlated with self-rated self-regulation ability (MAIA-2; Fig. 5). In line with previous research on the emergence of the IM band during autogenic relaxation, the duration of IM band frequency and self-regulation were positively correlated during baseline ($r = 0.55$, $p = 0.006$; section 1: eyes open). Furthermore, self-regulation was positively associated with the increase of averaged interval duration of the LF band from baseline to CVH ($r = 0.60$, $p = 0.003$). Correlations with amplitudes in both frequency bands yielded no significant findings. Results were not corrected for multiple testing.

**Discussion**

The aim of the present study was to investigate immediate physiological responses in forehead skin microcirculation in 25 healthy non-symptomatic adults recorded continuously before, during and following a single cranial technique, i.e., cranial vault hold (CVH). Applying time-frequency analysis to PPG recordings allowed relating outcomes to a theoretical dynamic model of systemic ANS variability in LF (0.05–0.12 Hz, 3–7.2 cpm), IM (0.12–0.18 Hz, 7.2–10.8 cpm) and HF (0.18–0.4 Hz, 10.8–24 cpm) bands (Keller et al., 2020; Perlitz, Cotuk, Lambertz, et al., 2004). This approach displayed time series of instantaneous adaptive ANS activity, which responded to calls for more in-depth studies on the effects of OMT on self-regulatory processes voiced recently (Esteves et al., 2020). Using time-frequency analyses of laser doppler flowmetry or PPG data, clinical outcomes in OMT studies attributed changes in SBF mostly to altered peripheral sympathetic nervous system (PSNS) output on segmental or suprasegmental reflexes (p. 914; Zegarra-Parodi et al., 2015).

In our study, the momentary frequency of highest amplitude (MFHA) computed from high temporal resolution wavelet analysis revealed significant changes of ANS activity for averaged frequency interval durations within the LF ($\uparrow$) and IM ($\downarrow$) band in response to CVH. Furthermore, and most compelling, amplitudes increased significantly in the LF band, in IM band, and in HF bands compared to sections 1, 2, 4 and 5. This strongly suggests systemic physiological responses on a suprasegmental level above deeper tissues (e.g., Edfeldt & Lundvall, 1994). Effects of CVH are unlikely attributable solely to sympathetic activity since microneurography recordings in non-symptomatic participants have confirmed that frequencies only up to 0.1 Hz can be sympathetically modulated (Stauss et al., 1998, 1999; Zegarra-Parodi et al., 2014). Those studies also found isolated stimulation of the median nerve trigger contralateral reactions in SBF. This underscores difficulties of observing isolated responses of physiological systems in an organism without ‘spill over effects’ between organ systems. The effects of amplitudes most likely take place at the level of arteriovenous shunts because vasoconstrictors and vasodilators are under sympathetic control. Systemic responses have been documented for activity in the skin at 0.15 Hz (Ernst & Petzold, 2012; Keller et al., 2020; Perlitz, Lambertz, et al., 2004; Ziege et al., 1997).
Contrary to explaining the observed rhythms during CVH as TH waves (e.g., Nelson et al., 2006), we propose our current data and previously reported findings in the literature support a dynamic model of IM physiology. Essential for the physiology of the IM band is central pacemaker activity in the brainstem at 0.15 Hz (± 0.03 Hz) as well lower and upper harmonic frequencies emerging in peripheral signals with integer number couplings in blood pressure, HRV, respiration, and PPG upon a decline of arousal (Lambertz & Langhorst, 1998; Perlitz, Cotuk, Lambertz, et al., 2004; Perlitz, Lambertz, et al., 2004).

Recent findings in fMRI studies confirmed pacemaker activity in the human brainstem with activities at 0.1 and 0.15 Hz. Both pacemaker activities were observed separately in various individuals, but also within a single subject (Schwerdtfeger et al., 2020). Invasive investigations by Langhorst and Lambertz demonstrated central pacemaker activity in small non-specific neurons in the range of 0.15 Hz in several hundred extracellular measurements (Lambertz & Langhorst, 1998; Langhorst et al., 1984; Perlitz, Lambertz, et al., 2004). Here, findings on a reticular rhythm (retR) generated in unspecific neurons in the reticular network in the lower brainstem of dogs provided crucial insights into frequency interactions of ANS frequency generation between 0.05 and 0.5 Hz (Lambertz & Langhorst, 1998). Moreover, these authors demonstrated the retR and the rhythm of respiration be different from one another in spite of a close linkage between them (Langhorst, 1984). Later, this concept was complemented with findings in humans during autogenic training, which mainly showed the formation of phase synchronizations in a ratio of 1:1 and 1:2 (n:m coordination) in respiration, blood pressure, HRV, and skin blood flow (Perlitz, Cotuk, Lambertz, et al., 2004). This concept gained further support by findings during general anesthesia showing continued ‘0.15 Hz rhythm activity’ despite of cessation of physiological respiration (Podgoreanu et al. 2002; Ziege et al., 1997).

Recently, Pfurtscheller and colleagues (2020) demonstrated peripheral IM band activity and concomitant activity of a central neural pacemaker located in the left brainstem confirming the 0.15 Hz rhythm in R-to-R intervals and respiration. Using a different methodological approach of lower spatial resolution, this still corroborates invasive findings on the cellular level by Lambertz and colleagues (2000). Such physiological pathways reflect the power of ANS mediated adaptation, which aims at economizing the modes of operation of physiological systems (Bethe, 1940; McCraty et al., 2009; Mirollo & Strogatz, 1990; von Holst, 1939).

Previous studies have observed the presence of multiple principal components in spontaneous fluctuations within the standard LF range (0.04–0.15 Hz), appearing at 0.08 and 0.12 Hz (Kuusela et al., 2003). We used MFHA to investigate the primary principal component of SBF as we considered this the best approximation to palpation performed by osteopathic practitioners. Overall, average MFHA during baseline sections 1, 2, 4, and 5 at 0.12 Hz was different from MFHA during CVH at 0.088 Hz. However, averaging across our groups (means: 0.07 and 0.14 Hz) would thus have falsely implied 0.1 Hz activity, which is commonly attributed to baroreceptor activity, and which may not at all have been present in recordings. Therefore, we exploratively inspected individual data for physiological fit and observed two different modes of operation. A K-means clustering analysis of physiological responses during CVH confirmed a group of LF-responders (N = 24; 77%) and a group of IM-responders (N = 7; 23%). This
confirmed our initial hypothesis of IM band stabilization during CVH with decreased variance of mean MFHA in 23% of recordings. Changes in IM-responders during CVH were strikingly similar to the mode described in SBF for naïve and trained relaxation using autogenic training (AT) (Fig. 3; Perlitz, Cotuk, Schiepek, et al., 2004). These analyses showed 0.15 Hz rhythms in SBF (PPG) with sensory input reduction by closing the eyes, and enhanced stability of 0.15 Hz rhythms with the onset of AT. This suggests IM-responders might have been under control of brainstem pacemakers (Pfurtscheller et al., 2020).

LF-responders exhibited a significant immediate decline of MFHA (0.115 Hz in section 2 to 0.071 Hz in section 3) and a distinct loss of rhythmic modulation during CVH. ANS activity in LF-responders might have been under tonic sympathetic control, which has been often reported in earlier studies (Zegarra-Parodi et al., 2014, 2015). This 0.07 Hz activity was associated with distinct increases in amplitudes presenting as spindle shaped oscillations in the raw PPG signals. Early studies already described spindle-shaped oscillations in SBF (Deutsch, 1952), which were referred to as psychomotor waves. These phenomena are also known as beat oscillations which may result from interference of closely coupled rhythmic sources (Perlitz, 2021). Such oscillators or pacemakers have been identified in the brain stem and they are hallmarks of IM band activity (Rassler et al., 2018).

Another possible source accounting for the loss of rhythmic modulation might come from 1:1 phase coordination or phase-locking between SBF and, e.g., respiration. Extended periods of 1:1 phase coordination have been reported as another central feature of the IM band physiology during AT (Perlitz, Cotuk, Lambertz, et al., 2004; Perlitz, Cotuk, Schiepek, et al., 2004; Perlitz, Lambertz, et al., 2004). This phenomenon has been known for long to originate in central nervous sources (Bethe, 1940). Prolonged episodes of phase-locking, on the contrary, may also index a pathological condition such as in sleep apnea (Riedl et al., 2014). For that reason, von Bonin and colleagues (2014) suggested to include at least two physiological signal sources when probing cardiovascular physiology. Therefore, these pathways mandate further study.

Recent investigations suggested that the LF range at 0.05–0.1 Hz indexes successful anxiety processing (Rassler et al., 2022; Schwerdtfeger et al., 2020). Our current findings suggest that most ANS adaptation occurred within the LF and IM band. In 20 participants, we observed a significant negative relation between IM band duration at baseline and state anxiety values, i.e., longer IM episodes were related to lower anxiety levels. This appears to support involvement of sympathetic nervous system since attenuated vagal tone and elevated levels of sympathetic activity were found in states of anxiety (Friedman, 2007). Yet, states of anxiety and processing of anxiety differ from one another. Baseline IM band durations as well as the increase of LF frequency duration (compared to baseline section 1) during CVH were related to a higher level of self-reported self-regulation ability. This supports findings on activation of an interoceptive central network with presence of IM band activity in HRV and respiration (Keller et al., 2020) and it is also in support of our notion of 0.07 Hz activity representing subharmonics of IM band activity. These findings certainly warrant further studies including repetitive psychometry.
Hopefully, these findings may help overcome the 'lack of information available to describe the potential link between changes in SBF and similar changes in the blood circulation in deeper tissues' stated for OMT research (p. 914; Zegarra-Parodi et al., 2014) since the IM band activity has been found to encompass and take effect on all stages of the entire organism.

Limitations

There are several limitations to generalization of our findings. First, though our sample includes numerous repetitions of each experimental condition, the overall sample was relatively small. Second, backed by experimental evidence from previous studies we deem it justifiable to limit our current findings to skin perfusion data. However, further analyses should include other physiological systems and their dynamic interactions. This should also include physiology of the osteopathic examiner to fully understand the biodynamic interplay within and between osteopath and patient. Third, a sham condition should be included to be able to compare effects of CVH as to its specificity. Fourth, adding another frequency band (IM band) still does not resolve the problem of rigid frequency bands. However, it offers a better fit within the much-disputed LF range (Schwerdtfeger et al., 2020). Lastly, our analyses are based on MFHA and TFD which have inherent limitations such as suppressing frequencies of minor amplitude and some frequency uncertainty particularly in lower frequencies.

Conclusions

A cranial osteopathic intervention (CVH), executed in the supine position, was associated with immediate changes in autonomic output to the SBF in 25 healthy adults. We report rhythmic IM band responses to CVH in forehead SBF in a smaller group, which was comparable with dynamics reported for IM activity in response to autogenic relaxation. These frequency responses are in keeping with former and recent reports on central pacemaker activity located in the brainstem. A larger group of participants responded to CVH with distinct LF activation, which may contain sympathetic activity, but which appears more likely to represent subharmonics of the primary IM band. Further studies of all variables interacting with the ANS, including pre-post psychometry should be warranted. These activation scenarios appear to support open questions for the still controversial concept of the CRI or PRM.

List Of Acronyms

osteopathic manipulative therapy (OMT), primary respiratory mechanism (PRM), osteopathy in the cranial field (OCF), cranial rhythmic impulse (CRI), autonomic nervous system (ANS), cranial vault hold (CVH), intermediate rhythm (IM), photoplethysmography (PPG), skin blood flow (SBF), multi-scaled time frequency distribution (mTFD), heart rate variability (HRV), sympathetic neuron activity (SNA), eyes open (EO), eyes closed (EC), reticular rhythm (retR)

Declarations
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Competing interests

The authors declare no competing interests.

Data availability

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Author contributions

H.P. and V.P. conceived the idea for the study. H.P., V.P., M.K., G.M., and K.M. contributed to the design and planning of the research. H.P. and J.M. were involved in data collection. V.P., G.M. and M.K. analysed the data. H.P. coordinated funding of the project. All authors edited and approved the final version of the manuscript.

References


**Figures**
Figure 1

Experimental paradigm. Each session was comprised of five sections, lasting 300 seconds each. Section 1 and 5 (eyes open) as well as section 2 and 4 (eyes closed) were performed “hands-off”. Section 3 was “hands-on” during which the Vault Hold was applied and participants’ eyes were closed. During each session, forehead skin blood oscillations were recorded.
Figure 2

Durations of MFHA derived averaged frequency band duration intervals (in [s]), showing significant increase of LF- and significant decrease of IM-band duration during Vault Hold. Sections: 1. Eyes open (EO); 2. Eyes closed (EC); 3. EC + CVHI; 4. ES'; 5. EO'. Abbreviations: LF: low frequency, IM: intermediate frequency; HF: high frequency.
Figure 3

Averaged amplitudes within LF, IM and HF frequency bands for each consecutive section, showing a significant increase of amplitudes during Vault Hold. Sections: 1. Eyes open (EO); 2. Eyes closed (EC); 3. EC + CVHI; 4. ES’; 5. EO’. Abbreviations: LF: low frequency, IM: intermediate frequency; HF: high frequency.
Figure 4

Averaged momentary frequency of highest amplitude (MFHA) derived from Morlet Wavelet time frequency distribution in absolute normalization of recordings of forehead skin PPG (blue center graph), and positive and negative standard deviation (light blue sectors). (A) Averaged MFHA of the entire study sample; (B) Averaged MFHA of ‘LF-responders’; (C) Averaged MFHA of ‘IM-responders’; (D) Descriptive statistics of mean frequencies for all sections showing ample oscillating activity in all section with

<table>
<thead>
<tr>
<th>Section</th>
<th>All ((N = 31))</th>
<th>LF-responders ((N = 24))</th>
<th>IM-responders ((N = 7))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>.119 (± .04)</td>
<td>.111 (± .03)</td>
<td>.146 (± .06)</td>
</tr>
<tr>
<td>2</td>
<td>.124 (± .04)</td>
<td>.115 (± .03)</td>
<td>.156 (± .05)</td>
</tr>
<tr>
<td>3</td>
<td>.088 (± .04)</td>
<td>.071 (± .02)</td>
<td>.147 (± .04)</td>
</tr>
<tr>
<td>4</td>
<td>.132 (± .05)</td>
<td>.123 (± .04)</td>
<td>.162 (± .07)</td>
</tr>
<tr>
<td>5</td>
<td>.128 (± .04)</td>
<td>.120 (± .03)</td>
<td>.155 (± .06)</td>
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exception of section 3 in LF-responders where oscillations in the first half of section 3 seem distinctly slower than in the second half.

**Figure 5**

(A) Significant correlation \( r = .55 \) of self-regulation (MAIA-2) and IM band duration during baseline (B) as well as self-regulation and LF change from baseline to CVH \( r = .60 \). Findings suggest that not only the appearance of IM frequency but also a response in LF band induced by CVH is related to interoceptive processes.
Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- Appendix1.docx