Noninvasive myocardial contractility monitoring with seismocardiography during simulated dives

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30(1): 19-27 - Objective: To determine if bradycardia during hyperbaric exposure is accompanied by a negative influence on myocardial contractility. Methods: Accelerometer-based registration of myocardial compression waves with Seismocardiography (SCG) for noninvasive contractility monitoring. Comparative pulmonary artery (PA) catheter study (9 ICU-patients, mean = 67ys) with ejection-fraction (EF) equivalent versus sum of g-values of contraction phase in SCG, and Preload (leg-positioning). Test with monitoring of changes in Contractility Index (ContrI) derived from the SCG-power spectrum (contraction phases, area under curve). Hyperbaric chamber study (0.6MPa dive-simulation) in 14 healthy divers. Quantitative SCG-(ContrI, power spectra) and ECG-recording. Results: Correlation between changes in EF (PA catheter) and in the g-values (SCG) was rSP=0.87 (p<0.0001). ContrI increased in the leg-positioning test parallel to preload increase, heart rate remained stable. During hyperbaric exposure (0.6MPa) heart rate decrease was highly significant (68 to 58 min\(^{-1}\); p<0.001), ContrI and power spectra remained nearly unchanged, SCG registration was noise free. Conclusions: Hyperoxic bradycardia during simulated dives is not accompanied by impaired contractility measured with SCG, which is concordant to findings with invasive methods in current literature. SCG is suitable for noninvasive and stress free contractility monitoring and patient surveillance in a hyperbaric chamber.

bradycardia, hyperoxia, diving, seismocardiography, contractility measurement, hyperbaric chamber

INTRODUCTION

Exposure to hyperbaria leads to bradycardia, which is assumed to be caused by a reaction of the autonomic nervous system to the elevated pO\(_2\) (1) in the breathing gas and might not only have a negative influence on heart rate, but on overall cardiac performance. Although hyperoxic bradycardia is well known, there is still discussion about parallel changes in left ventricular function (2,3). Recent studies with pulmonary artery (PA) catheter measurements under hyperbaric and hyperoxic conditions showed variations in cardiac output (CO) (4), a 10% reduction of CO during 3 atm O\(_2\) in an animal model (5) or even an unchanged cardiac index (6). However, beside the use of echocardiography and the invasive thermodilution method (Swan-Ganz catheter) or even more invasive techniques in animal studies (5), a focus on noninvasive monitoring of myocardial function during hyperbaric exposure might help to augment
knowledge about changes in cardiac contractility during simulated dives. Therefore, one possible approach is Seismocardiography (SCG).

SCG allows for the registration of compression waves produced during myocardial contraction by detecting them with a pressure-proof low frequency accelerometer placed on the lower third of the sternum. The compression waves of the heart have been investigated with emphasis on left ventricular dysfunction and hyperfunction (7), systolic time intervals (8) and on CO measurement (9), but the method reached only limited clinical use. In 1990, Salerno and Zanetti (10) began to reuse SCG in single accelerometer technique to improve the precision of myocardial ischemia detection during exercise testing (11,12) and balloon angioplasty (13). Besides registration of ischemic changes in heart function, analysis of the SCG amplitudes gives information about global contractility, similar to a geophone. Recently, Bongiorni and co-workers showed that a micro-accelerometer fixed on a temporary endocardial pacing lead registered so-called peak endocardial accelerations, close related to the contractility of the whole heart (14). In 1983, an animal study using a surface low-frequency accelerometer and intracardiac contractility measurement (dp/dt) showed the same close relationship (15), and the accelerometer signal was used to calculate cardiac output before (9) and in a recent study by McKay et al. (16).

Before the monitoring changes in contractility during hyperbaric exposure, two pilot studies were performed to test the accuracy of SCG against the Ejection-Fraction (EF)-equivalent calculated from standard PA catheter in ICU patients on one hand, and to document the suitability of the Contractility Index (ContrI, derived from the SCG curve) for contractility monitoring in a physiologic testing with changing preload (leg-elevation) on the other hand. Contractility monitoring during hyperbaric exposure to 50m depths (0.6 MPa) was done with a modified pressure-proof SCG system and ContrI calculation from digitally stored data.

METHODS

The first pilot study took place on the ICU of the Medical Clinic of the Christian-Albrechts University in Kiel, the second pilot study as well as the hyperbaric chamber study in the German Naval Medical Institute in Kiel, Germany. Informed consent was obtained from each participant, and the ethics committee of the University Kiel approved the chamber exposures to 50m (0.6MPa). Because of legal restrictions (medical, hygienic and technical safety) on an ICU, only the original commercial available SCG device (SCG 2000, Seismed® Inc., Minnesota, USA) was allowed in the SCG-PA catheter study with no ability for digital raw data export for specific computer analysis. The modification for hyperbaric environment used the original accelerometer of the SCG 2000, but connected to a specific pre-amplifier in a pressure-proof box. With this modification the technique of SCG signal measurement, which only depends on the accelerometer type and a compatible charge-amplifier, was not different from the original device, but allowed signal amplification inside the hyperbaric chamber to reach an acceptable signal-to-noise ratio, and additionally digital storage of the data for mathematical analysis outside.

**Quantitative analysis of the SCG signal**

The piezo-electric sensor of the SCG system, which was placed on the lower third of the sternum, produces an electric charge as a result of sensor displacement due to movement of the heart in the thorax. A two-step differentiation of the displacement data results via a velocity curve in the final acceleration-curve with amplitudes proportional to the amount of detected
vibrations, measured in g-values (1g=9.81m/s²; earth gravity force) like in a typical seismometer. Changes in myocardial contractility were calculated from the contraction-phase, beginning with the R-Wave in ECG and of 360ms duration (90 data points). In this time frame the g-values from the accelerometer curve were summed up for the contractility calculation.

**PA catheter study**

Summations of peak accelerations were derived from the printouts of the SCG-2000-device, beginning with the MC point (mitral valve closure) to IM (isovolumetric movement phase), IM to AO (aortic valve opening), AO to IC (isotonic contraction phase), IC to RE (rapid ejection phase) (10,11) (Figure 1). The resulting "sum of g-values" was tested as an indicator for cardiac contractility against the Ejection-Fraction equivalent from the PA catheter.

**Figure 1**: Original SCG recordings and SCG power spectra. The analyzed SCG part of the cardiac contraction phases is marked bold (MC: Mitral Valve Closure; IM: Isovolumetric Contraction; AO: Aortic Valve Opening; IC: Isotonic Contraction; RE: Rapid Ejection Phase) and shown in the lower part as power spectra of 20 consecutive contraction phase-recordings (90 data points = 360ms from R-Wave in ECG). Main frequency domain at 10 Hz.

**Simulated dives and preload test**

The digitally stored SCG data allowed a mathematically more accurate approach for the summation of the measured accelerations. A frequency-analysis (Fourier Transformation) (Figure 1) was calculated from the contraction phase-data (again 360ms duration from R-wave), and the integral (area under curve) of the resulting amplitudes went into the formula for the dimensionless Contractility-Index (ContrI) calculation:

\[
\text{ContrI} = \frac{(\text{sum of amplitudes})^2}{\text{signal}_{\text{max}} - \text{signal}_{\text{min}}}
\]
DFT (Discrete Fourier Transformation) and automatic R-wave detection in the ECG were programmed in Turbo Pascal (Borland, USA). Before DFT, the SCG-data were preprocessed, which included the subtraction of the linear trend from each data point and a Hanning weighting of the DFT-window (90 data points).

**SCG-PA-catheter study**

From 9 patients on an ICU in Internal Medicine (mean age 67yr; University Hospital Kiel) with PA catheters already inserted for cardiac output monitoring (5 cases of resuscitation after myocardial infarction, 2 cases of cardiomyopathy with severe heart failure, and 2 cases of sepsis), repeated SCG measurements of 60 sec duration on following days were taken to register spontaneous changes in myocardial function due to the underlying disease. All patients were in sinus rhythm and ventilation controlled. The PA catheter (IntelliCath®, Edwards) allowed for the calculation of the ejection fraction (EF) equivalent from stroke volume (SV) measurement using the thermodilution method and the directly taken pulmonary artery wedge pressure (PAWP) according to the formula: \[ EF = \frac{SV}{PAWP} \]. The formula is based on the general equation for EF calculation: \[ EF = \frac{SV}{EDV} \] where changes in PAWP represent changes in EDV (end-diastolic volume) according to the Frank-Starling mechanism (17,18). Thus, the EF-equivalent is close related to myocardial contractility.

Because of inter-individual differences in thorax anatomy and other individual parameters in the patients, the absolute values of the SCG-curves tended to differ widely between individuals, and therefore SCG contractility as well as the EF-equivalent results from the PA catheter are presented as relative changes from 100% baseline due to the spontaneous changes in myocardial function of the patients.

**Preload test**

In 12 young and healthy volunteers (27.4±7.1ys.; 180±9.5cm; 79.5±11.9kg) a physiologic test based on the Frank-Starling mechanism (17,18) was done to test the accuracy of the parameter "ContrI" from SCG in measuring actual changes in contractility. The volunteers legs were lifted stepwise from 0° to 20°, 45°, 80°, and back to 0° with registration of heart rate and SCG in all leg positions. An increase in ContrI corresponding to the increase in myocardial contractility due to the increased preload was awaited.

**SCG-Hyperbaric chamber study**

14 experienced and healthy professional and sports divers (29.8±6.7yr) were exposed to 0.6MPa (according to 50m depth) ambient pressure for 3 minutes in compressed air followed by a decompression phase with stops (5min) at 0.16MPa (6m), and 0.13MPa (3m) in the HYDRA 2000 hyperbaric chamber (Haux, Germany). SCG was recorded together with ECG, while the volunteers were resting in supine position, and the sampling time was one minute on each pressure level. SCG was recorded with the pressure-proof steel-covered original accelerometer from the SCG-2000 device, connected to a battery-driven and pressure-proof covered charge preamplifier (Type 2635, Brüel & Kjær, Denmark) inside the chamber. The amplified SCG signal was transported via shielded cables and a special plug in the chamber-hull to a computer outside the hyperbaric chamber and recorded digitally (12-bit analog-to-digital converter dt2814, Data Translation, USA) with a sampling frequency of 256 Hz for ECG and SCG (binary data format). ContrI was calculated according to the mentioned above computerized SCG signal analysis for myocardial contractility monitoring during dive simulation. Additionally, the Power-spectra of
the DFTs were visually checked for changes in the myocardial contraction pattern during the different diving phases (surface-50m-6m-3m-surface).

Statistics
In the PA-catheter study the correlation coefficient $r_{SP}$ (Spearman) was calculated from the results and tested for significance. Significance testing from the hyperbaric chamber study as well as the preload test was done with t-tests for dependent samples. Significance was assumed for $p < 0.05$.

RESULTS

SCG-PA catheter study
Repeated measurements were done in all patients, and during the observation time the patients showed spontaneous changes in myocardial function due to the underlying severe diseases. The changes in EF-equivalent, calculated from the PA catheter data, ranged mainly from -20% to +50% in relation to the first measurement. The percent changes in the g-value summation of the SCG contraction phase covered nearly the same range, and the Spearman correlation coefficient yielded $r_{SP}=0.87$ ($p<0.0001$) (Figure 2).

Preload test
In the tested group of young and healthy men, increasing the preload by leg elevation from 0° to 80° did not have any significant influence on heart rate, which remained stable between 60 and 70 bpm throughout the testing. On the other hand, ContrI increased highly significant from $22.5\pm2$ (0° flat leg-position) to $25.9\pm1.9$ (20°; $p<0.001$), to $26.4\pm1.7$ (45°; $p<0.001$), to $27.3\pm1.7$ (80°; $p<0.01$), and went back to $23.5\pm1.7$ (0° at the end of the test; no significant difference to 0° at the beginning). The linear regression revealed an $r=0.89$ (Figure 3). All reported values are mean ± SEM.

SCG - hyperbaric chamber study
Heart rate behavior: The resting heart rate under normobaric conditions (0m) was $67.9\pm2.2$bpm. At 50m (0.6MPa) the divers showed a significantly reduced heart rate of $57.9\pm1.9$bpm ($p<0.001$). During the decompression stops at 6m ($59.8\pm2.2$bpm; $p<0.001$) as well as 3m ($60.6\pm1.8$bpm; $p<0.001$), heart rate increased again but remained significantly reduced compared to initial surface conditions. After surfacing heart rate again went up to $63.3\pm2$bpm, which was still slightly but not significantly reduced compared to test beginning (Figure 4).

ContrI: Despite the significant heart rate reduction during hyperbaric exposure ContrI did not show significant changes during the simulated dive. Coming from an initial ContrI of $22.1\pm2.3$ (0.1MPa), the ContrI at 50m (0.6MPa) was still $21.7\pm1.6$, when heart rate reached its minimum. During decompression ContrI tended to decrease slightly (6m: $20.2\pm1.7$; 3m: $20.1\pm1.7$) but not significant in opposite to the increasing heart rate, and went back to $20.9\pm2$ after surfacing again (Figure 4).

The visual examination of the SCG power spectra (contraction phases) showed a main frequency domain round 10Hz and a second one round 20 Hz, and neither major changes in overall morphology nor a decrease in the main frequency domain was found during hyperbaric exposure.
Figure 2: Changes in the Ejection Fraction- (EF) Equivalent derived from Pulmonary Artery- (PA) Catheter plotted against changes in SCG (sum of g-values MC-IM; IM-AO; AO-IC; IC-RE during contraction). Data are presented in percent from baseline recording (100%; first measurement in each patient). Linear regression of the data is plotted (straight line). rSP=0.87 (p<0.0001).

Figure 3: Heart rate- and Contrl-response to changes in leg-position in healthy volunteers. Abscisse: Degree of leg-elevation from resting position (supine; 0°) stepwise to 80° and back to 0°. Left Ordinate: Heart rate (HR; triangles). Right Ordinate: Contrl from SCG (filled circles; arbitrary values). Values are means±SEM (*:p<0.05; **:p<0.01; ***:p<0.001)
DISCUSSION

Hyperoxia in hyperbaric environments induces a drop in heart rate, which has become known as hyperbaric bradycardia (1). However, knowledge about possible parallel changes in myocardial contractility is limited. In the presented study myocardial contractility was monitored during exposure to hyperoxic ambient conditions (0.6 MPa) using the accelerometer-based Seismocardiography and a quantitative approach for compression wave analysis. With respect to the results of Bongiorni, Ozawa and McKay (14,15,16), who had demonstrated the close relationship between the magnitude of the detectable SCG-signal and the underlying actual myocardial contractility, accuracy of the actual quantitative method was tested in two preceding pilot studies, a clinical setting with calculation of the EF-equivalent from PA catheter values as an established clinical standard, and a Preload-Test with its well known influence on preload based on the Frank-Starling principle.

The high significant correlation ($r_{SP} = 0.87$) between the percent changes of the g-values in SCG and the EF-equivalent derived by PA catheter indicates that Seismocardiography is suitable for noninvasive contractility-monitoring even in critically ill patients with an appropriate accuracy, particularly when it is considered that the PA catheter itself has an error range of about 15% (19). Leg elevation ($0^\circ$, $20^\circ$, $45^\circ$, $80^\circ$) increases cardiac contractility due to its positive effect on preload, which can be documented with the dimensionless ContrI derived from SCG. Moreover, even the absolute ContrI-values were similar in young and healthy test persons, and allowed for the comparison of the absolute values in the hyperbaric chamber study too, where healthy divers were examined. During the hyperbaric exposures the tested subjects on one hand showed the awaited drop in heart rate at "depth" and its normalization during decompression, but both, heart rate and ContrI, remained lower at the end of the test, which might be due to an initial
pre-start situation with an increased sympathetic tone. On the other hand, ContrI showed no significant decrease when heart rate reached its minimum at 0.6MPa ambient pressure, but in contrast tended to decrease slightly during decompression. The main frequency domain round 10Hz even slightly increased during maximal compression, maybe due to better cardiac filling conditions and a consecutive higher contractility during longer R-R-intervals. Salerno and Zanetti (11,13) had shown that impairment of myocardial systolic movement is detectable with SCG, but the overall characteristics of the SCG-power spectra remained unchanged and indicated nearly undisturbed cardiac function during hyperbaric exposure, which supports Lafay (3), who also found no evidence of left ventricular dysfunction in echocardiography in deep dives. Moreover, these findings are in agreement with Mak et al. (20), who reported reduced cardiac output and an increase in LVEDP (left ventricular end diastolic pressure) but no impairment in dp/dt under hyperoxic conditions. Comparable results were also found by Abel (5) in anesthetized dogs: air at 3 atmospheres absolute had nearly no negative effect on LV-dp/dt, and even the administration of 100% O\textsubscript{2} at 0.1 MPa led to a LV-dp/dt reduction of only 10.8 % compared to the controls. Thus, with the completely noninvasive and stress free method of Seismocardiography previous results of uninfluenced cardiac contractility under hyperoxic conditions could be confirmed without the risk of false-positive results because of stress-reactions (positive inotropic influence) from invasive Swan-Ganz-catheterization (4,6).

SCG recording, signal amplification and transport to the outside registration system was possible with a full acceptable signal-to-noise ratio and suggests that SCG may be a qualified method for myocardial contractility-surveillance during hyperbaric therapy.

CONCLUSION

In conclusion, there is no evidence from the seismocardiographic data that the hyperoxic bradycardia is accompanied by a reduced myocardial contractility, which is in concordance to current literature. Seismocardiography allows for an easy-to-use noninvasive monitoring of myocardial contractility with accurate and reproducible results compared to an invasive "gold-standard" even under hyperbaric conditions.

REFERENCES

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