Baroreflex Buffering of Sympathetic Activation During Sleep
Evidence From Autonomic Assessment of Sleep Macroarchitecture and Microarchitecture

Ferdinando Iellamo, Fabio Placidi, Maria Grazia Marciani, Andrea Romigi, Mario Tombini, Stefano Aquilani, Michele Massaro, Alberto Galante, Jacopo M. Legramante

Abstract—We examined the effects of sleep microstructure, ie, the cyclic alternating pattern (CAP), on heart rate (HR)- and blood pressure (BP)-regulating mechanisms and on baroreflex control of HR in healthy humans and tested the hypothesis that sympathetic activation occurring in CAP epochs during non-rapid eye movement (non-REM) sleep periods is buffered by the arterial baroreflex. Ten healthy males underwent polysomnography and simultaneous recording of BP, ECG, and respiration. Baroreflex sensitivity (BRS) was calculated by the sequences method. Autoregressive power spectral analysis was used to investigate R-R interval (RRI) and BP variabilities. During overall non-REM sleep, BP decreased and RRI increased in comparison to wakefulness, with concomitant decreases in low-frequency RRI and BP oscillations and increases in high-frequency RRI oscillations. These changes were reversed during REM to wakefulness levels, with the exception of RRI. During CAP, BP increased significantly in comparison to non-CAP and did not differ from REM and wakefulness. The low-frequency component of BP variability was significantly higher during CAP than non-CAP. RRI and its low-frequency spectral component did not differ between CAP and non-CAP. BRS significantly increased during CAP in comparison to non-CAP. BRS was not different during CAP and REM and was greater during both in comparison with the awake state. Even during sleep stages, like non-REM sleep, characterized by an overall vagal predominance, phases of sustained sympathetic activation do occur that resemble that occurring during REM. Throughout the overnight sleep period, the arterial baroreflex acts to buffer surges of sympathetic activation by means of rapid changes in cardiac vagal circuits. (Hypertension. 2004;43:814-819.)

Key Words: sympathetic nervous system ■ baroreflex ■ heart rate ■ blood pressure

Growing evidence indicates that sleep is not devoid of cardiovascular risk.1,2 The mechanisms linking sleep to cardiovascular events are not clearly defined, yet the most likely contributor appears to be the autonomic nervous system.1,2 Specifically, the increase in sympathetic activity occurring during rapid eye movement (REM) sleep has been invoked as a potential trigger for nocturnal arrhythmias in this period and for the higher-than-expected incidence of cardiovascular events in the early morning hours after awakening.1-5 However, Lavery et al have clearly shown that a considerable rate of cardiovascular events occur throughout the overnight period. It thus appears that the adverse consequences of sleep may not be limited to the REM phase.

Concerning the autonomic modulation of the cardiovascular system, the general view is that compared with wakefulness, light and deep sleep (non-REM) is characterized by a vagal predominance, as opposed to the sympathetic predominance of REM.5-7 Studies investigating sleep structure have led to the identification of a natural electroencephalographic arousal rhythm within the non-REM sleep stages, related to transient lightening of sleep depth, known as the cyclic alternating pattern (CAP).8,9 CAP corresponds to a prolonged oscillation of the arousal level, whereas the complementary condition, non-CAP (NCAP), is closely related to a degree of stability in sleep depth.8,9 Functionally, CAP translates a condition of sustained arousal instability; however, the arousal swings that characterize CAP sequences are not driven by any motor or respiratory disturbances and are associated with variations of autonomic activity.8,9 Spectral analysis studies reported an increase in the low-frequency (LF) and a decrease in the high-frequency (HF) component of heart rate variability (HRV) during CAP compared with non-CAP sequences,10,11 suggesting the occurrence of nighttime periods of relative sympathetic activation even during

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phases, like non-REM sleep, characterized by an increase in the background level of parasympathetic activity. These findings would indicate that surges of sympathetic activity may occur not only during REM. They also suggest the need to take into consideration sleep microstructure when evaluating the effect of sleep on cardiovascular autonomic regulation. Studies performed so far on sleep microstructure dealt with HRV only. However, neural cardiovascular regulation is rather complex and made of several intertwined mechanisms that involve the control of HR and blood pressure (BP) and the relationship between changes in BP and HR through the arterial baroreflexes. No one study has addressed the influences of sleep microstructure on the arterial baroreflex control of HR, which is a key component of cardiovascular homeostasis and carries relevant pathophysiological and prognostic information. A more thorough understanding of sleep microarchitecture-related neural regulation has important clinical implications, because it may help to clarify why some cardiovascular events often occur at night.

Accordingly, in this study, we examined the effects of sleep macrostructure and microstructure on HR- and BP-regulating mechanisms and on baroreflex control of HR in healthy humans and tested the hypothesis that the arterial baroreflex acts to buffer sympathetic activations occurring during the overnight period.

Methods

Subjects

The study was conducted on 10 healthy men subjects (aged 26.5±4.2 years). All subjects were nonsmokers and were using no medications. Subjects were asked to avoid caffeine, alcohol, and physical exertion for 24 hours before the study. No one had history of sleep disorders. At the time of admission to the study, all subjects underwent a physical examination and routine laboratory test. All gave informed consent. The study has been approved by the Institutional Ethical Committee.

Recorded Variables

Subjects were connected to an analogical multichannel signal conditioner and amplifier/filter (Marazza, Monza, Italy). The electrocardiographic signal was recorded from a precordial chest lead. BP was continuously and noninvasively measured by Finapres (Ohmeda 2300). The cuffed finger was maintained at heart level with the aid of sandbags and an arm board. Respiratory signal was recorded by means of a piezoelectric thoracic belt. The analogical signals were sampled at 300 Hz per channel and stored on the hard disk for subsequent analyses.

Sleep Recordings

Polysomnographic recordings were performed with a computerized EEG system (Stellate System; Westmount, Quebec, Canada). Montage included 2 EEG (C3-A2, O2-A1), 2 electrooculographic (ROC-A1, LOC-A1), and 3 EMG channels (mylohyoideus and anterior tibialis muscles). Electrodes were positioned according to the International 10 to 20 System.

Experimental Protocol

All-night polysomnographic studies were performed after 1 night of habituation to the laboratory environment. The instrumentation started, on average, at 11:00 PM. Analyses were performed on the signals recorded during the awake state in the immediate pre-sleep period with the subjects resting supine (10 minutes) and on data segments recorded during light sleep (stage II [S2]), deep sleep (stage III-IV, slow-wave sleep [SWS]), and REM sleep. Sleep was staged according to the criteria of Rechtschaffen and Kales. Subsequently, CAP and NCAP sequences were detected in each recording during S2 and SWS, according to the rules defined by Terrazano et al. We studied 3 different epochs of at least 5 minutes from CAP and 3 different epochs from NCAP periods during both S2 and SWS. For each subject, 12 epochs were selected (3 from S2-CAP, 3 from S2-NCAP, 3 from SWS-CAP, and 3 from SWS-NCAP). To avoid gross effects on R-R interval (RRI) and BP variability, only CAP and NCAP periods without arousals were selected.

Spontaneous Baroreflex Analysis

Details of this analysis have been previously described. Briefly, the mean slope of spontaneous sequences of consecutive beats characterized by systolic blood pressure (SBP) and RRI changing in the same direction (either increasing, ie, up-sequences or decreasing, ie, down-sequences) was calculated and taken as a measure of the integrated baroreflex sensitivity (BRS).

Power Spectral Analysis

The methodology for autoregressive power spectral analysis of RRI and finger SBP variabilities has been described previously. Spectral analysis of respiratory activity was performed only to assess the main respiratory frequency. Two main components were considered in the RRI and SBP variability signals: that in the frequency band from 0.04 to 0.15 Hz (low-frequency [LF]) and that in the range from 0.15 to 0.4 Hz (high-frequency [HF]). The power density of each spectral component was calculated in absolute values and normalized units (nu). The normalized LF component of RRI (LF_{RRI}) and the absolute LF component of BP (LF_{BP}) variability are considered markers of sympathetic cardiac and vascular modulation, respectively, whereas the normalized HF component of RRI variability would reflect respiratory-driven vagal modulation to the sinoatrial node. Accordingly, spectral power of RRI variability will be presented only in normalized units.

Statistical Analysis

Comparisons among the awake state and the different sleep stages were performed by the Friedman ANOVA on ranks. Pairwise multiple comparison procedures were performed by the Student-Newman-Keuls test. Differences were considered statistically significant at P<0.05.

Results

Sleep characteristics are reported in Table 1. A normal sleep macrostructure was observed in all subjects. SBP decreased during S2 and SWS as compared with during wakefulness, whereas it recovered back to wakefulness during REM (Figure 1). Diastolic BP did not show significant changes during the different sleep stages. As compared with wakefulness, RRI increased significantly during sleep without differences among S2, SWS, and REM (Figure 1).

The relative bradycardia was accompanied by a progressive increase in the normalized HF_{RRI} with increasing sleep depth from wakefulness to SWS followed by a decrease to the

<table>
<thead>
<tr>
<th>TABLE 1. Sleep Characteristics (means±SD)</th>
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<tr>
<td>Total Sleep Time (min)</td>
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<td>Stage I, %</td>
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<td>Stage II, %</td>
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<tr>
<td>Stage III-IV, %</td>
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<td>REM, %</td>
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<td>Awakening, %</td>
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REM indicates rapid eye movement.
wakening level during REM. Normalized LF_RR showed a
significant decrease from wakefulness as sleep deepened,
followed by a significant increase during REM to the level
observed during the awake state (Figure 2). LF_SBP decreased
significantly during SWS compared with the awake state, and
then it markedly and significantly increased to the wakening
level during REM (Figure 2). Respiratory frequency de-
creased slightly, albeit significantly, during sleep, without
differences between the different sleep stages (Figure 2).
BRS, as estimated by pooling together both up-sequences
and down-sequences, we found that baroreflex gain increased
significantly in response to loading stimuli, ie, increasing BP
ramps, during all sleep stages as compared with wakefulness,
attaining the maximum value during REM, whereas it did not
differ significantly in response to unloading stimuli, ie,
decreasing BP ramps, during sleep as compared with wake-
fulness (Figure 3).

The results of the comparison of the cardiovascular vari-
ables and autonomic indexes according to sleep microstruc-
ture analysis are shown in Table 2 and Figure 4. RRI was not
significantly different between CAP and non-CAP condi-
tions, whereas SBP was significantly higher during CAP
SWS than non-CAP SWS. BP values during CAP conditions
were not significantly different from those recorded during

![Figure 1. Systolic (SAP, hatched bars) and diastolic (DAP, open
bars) blood pressure (upper panel) and R-R interval (bottom
panel) during sleep. S2 indicates light sleep; SWS, slow-wave
sleep; REM, rapid eye movement sleep. *P<0.05 among sleep
stages by ANOVA on ranks.](image1)

![Figure 2. High-frequency (HF_RR, left
upper panel) and low-frequency (LF_RR,
right upper panel) components of R-R
interval variability, low-frequency compo-
nent of SBP variability (LF_SBP, left bot-
tom panel), and breathing frequency
(right, bottom panel) during the different
sleep stages. *P<0.05 among sleep stages
by ANOVA on ranks.](image2)

![Figure 3. Baroreflex sensitivity (BRS) for up-sequences and
down-sequences pooled together (upper panel) and for down-
sequences (middle panel) and up-sequences, (bottom panels)
during the different sleep stages. *P<0.05 among sleep stages
by ANOVA on ranks.](image3)

![Figure 4. Breathing frequency (left upper panel) and R-R interval (bottom panel) during sleep. S2 indicates light sleep; SWS, slow-wave
sleep; REM, rapid eye movement sleep. *P<0.05 among sleep
stages by ANOVA on ranks.](image4)
REM. LF SBP was significantly higher during CAP than non-CAP conditions during both S2 and SWS, although it was less than during REM. LF RR (nu) was not significantly different between CAP and non-CAP epochs during both S2 and SWS. HF was significantly higher and LF significantly lower in both non-CAP and CAP than in REM. BRS showed a trend toward an increase from awake to non-CAP, CAP, and REM sleep. When up-sequences and down-sequences were analyzed separately, BRS in response to increasing BP ramps was significantly greater during CAP than non-CAP during both S2 and SWS, and not different between CAP and REM. Again, no significant differences were detected in BRS in response to decreasing BP ramps during sleep as compared with wakefulness and among the different sleep epochs (Table 2).

**Discussion**

The novel findings ensued from the analysis of sleep microstructure and macrostructure are: (1) that even during sleep stages characterized by an overall vagal predominance, phases of sustained sympathetic activation do occur that resemble that occurring during REM; (2) that throughout the overnight asleep period, the arterial baroreflex acts to buffer surges of sympathetic activation by means of rapid changes in cardiac vagal circuits.

Previous studies dealing with sleep-related neural cardiovascular regulation have focused on the conventional scoring defining the sleep macrostructure. As in these studies, we observed a decrease in BP during S2 and SWS, with a recovery to the awake level during REM associated with parallel changes in LF SBP. HR decreased throughout the sleep period in comparison with wakefulness, and this decrease was associated with increases in the HF and decreases in the LF component of HRV during S2 and SWS, which were reversed during REM. This overall picture points to a cardiac parasympathetic predominance during non-REM and to a peripheral sympathetic activation during REM, in agreement with studies that directly recorded peripheral sympathetic nerve traffic. The lack of a tachycardic effect, despite the simultaneous increase sympathetic activation, frequently reported during REM could be explained through a vagally mediated baroreflex mechanism offsetting cardiac sympathetic activation, as suggested by the increase in BRS in response to hypertensive stimuli.

As to the lack of significant changes in BRS down-sequences, a different buffering effect of arterial baroreflex in response to increases and decreases in BP during sleep has
already been reported by our group\textsuperscript{25} and is tentatively explained by the nonlinear properties of the baroreceptor reflex.\textsuperscript{26,27} Specifically targeted additional studies are required for a finer definition of this issue. However, within the framework of the present investigation, it could be argued that the lack of changes in BRS in response to BP decrease could indicate that arterial baroreflexes act more to defend the lower HR of sleep rather than to oppose it.\textsuperscript{5,26,28}

The analysis of sleep microstructure allowed us to make evident, for the first time to our knowledge, the occurrence of phases of sustained peripheral sympathetic activation, cleansed of arousal, similar to those of REM outlasting the transient sympathetic activation and BP increase induced by arousal stimuli ("K" complex\textsuperscript{5–7}) and spread throughout the overnight asleep period. As in REM, sympathetic activation of CAP epochs was associated to buffering influences from arterial baroreflexes. In fact, during CAP, LF$_{SBP}$ was significantly higher than during non-CAP, although to a lesser extent than during REM, and was associated with a significant increase in BRS up-sequences (Figure 4), with no significant difference in RRI, similarly to what emerged from the analysis of sleep macrostructure. A relevant difference between REM and CAP conditions was detected in the autonomic modulation of the sinoatrial node. In fact, whereas the HF component (nu) of HRV decreased and the LF component (nu) increased during REM in comparison to the global non-REM sleep, LF (nu) did not change significantly during CAP as compared with non-CAP conditions, and HF (nu) showed a slight increase. The finding of an increase in LF$_{SBP}$ without a concomitant change in the LF component of HRV would implicate a differential control of cardiac and peripheral sympathetic outflow during CAP, in line with the emerging concept of selectivity of autonomic regulation.\textsuperscript{28–30}

Clearly, the brain neurophysiological patterns of CAP are different from REM.\textsuperscript{31} CAP epochs occur during sleep stages (that is, non-REM) characterized by an already heightened level of background cardiac vagal activity that may dampen cardiac sympathetic activation, as indicated by the significantly greater and lower mean values of the HF nu and LF nu components of HRV, respectively, during non-REM sleep stages as a whole in comparison with the corresponding CAP epochs (Table 2).

Our finding of no significant changes in cardiac autonomic modulation between CAP and non-CAP conditions are at variance with the limited previous studies, which reported increases in LF and decreases in HF RRI oscillations during CAP.\textsuperscript{10,11} The reasons for these discrepant findings are not readily apparent but may relate, in part, to the much younger age of subjects included in one study,\textsuperscript{11} because aging significantly affects structural organization of sleep.\textsuperscript{31} Unfortunately, in both these studies, autonomic vascular modulation and baroreflex control of HR have not been assessed, making a comparison with our results difficult.

Clearly, regulation of sinoatrial node during sleep cannot be simply equated to an increase in sympathetic predominance in REM and an increase in parasympathetic predominance in non-REM sleep. Generalization of autonomic output from a single autonomic parameter should be performed with caution.

A potential limitation of this study includes the indirect method used to assess changes in autonomic function. The issue of the validity of this approach was recently addressed by experiments in humans\textsuperscript{22} in whom direct recordings of muscle sympathetic nerve activity were performed during various states of autonomic regulation, as produced by graded infusions of vasodilators and vasoconstrictors. The presence of similar, coherent, oscillations at low- and high-frequency in nerve activity, RRI, and SBP variabilities at various levels of induced pressure changes provides support to the use of LF$_{HR}$ and HF$_{HR}$ to infer the changing state of, respectively, sympathetic and vagal modulation of the sinoatrial node and of LF$_{SBP}$ as an index of efferent sympathetic vascular modulation.\textsuperscript{22}

**Perspectives**

The findings of the present investigation could provide some clues into neural mechanisms for cardiac events during night. It has been shown that a great percentage of cardiac events, including myocardial infarction and sudden deaths, occur throughout the nocturnal period.\textsuperscript{1,2,32} It has also been reported that myocardial ischemia occurring during sleep is not limited to REM, but may occur to a greater extent during SW sleep;\textsuperscript{33} however, the underlying mechanisms have not been elucidated. A body of evidence indicates a link between increases in sympathetic activity and the increased risk for life-threatening arrhythmias, whereas increases in parasympathetic activity would reduce the risk for ventricular arrhythmias\textsuperscript{34,35} and cardiovascular events.\textsuperscript{12} Within the framework of studies with sleep staging, disappearance of nocturnal vagal predominance during non-REM sleep has been reported after myocardial infarction\textsuperscript{36} and proposed as a significant factor in the nocturnal occurrence of fatal events. By converse, the increase in BRS by conferring protection against the surges of sympathetic activation might result in a condition less favorable for cardiac events. Because BRS increases during CAP times in combination with an increase in sympathetic activation, we speculate that disruption of this increased baroreflex gain during CAP, and in REM as well\textsuperscript{25} (as may occur, for example, in ischemic and heart failure patients and in subjects with obstructive sleep apnea), might conceivably predispose to an increased likelihood of arrhythmic–ischemic events occurring throughout the sleep period and that this mechanism might contribute, in addition to others, to explain the nonuniform nighttime distribution of acute cardiac events.\textsuperscript{2}

It is noteworthy that autonomic differences between CAP and non-CAP are present in stage 2 and in SWS, which generally occupy \(\approx 70\%\) of the total sleep time. Hence, microstructural phenomenon may impact extensively on neural cardiovascular regulation throughout sleep.

Limitations of the study include the small sample size and the lack of breathing pattern monitoring. Anyway, the differences observed across the different sleep stages were remarkably consistent and highly significant. As to the effect of respiration, we do not know to what extent changes in respiratory pattern that may occur during sleep could have affected HRV and BRS, inasmuch as we did not measure tidal volume. However, changes in breathing frequency at least should have not signif-
icantly influenced BRS and HRV parameters, because they did not differ among the different sleep stages.

In conclusion, our study dealing with sleep microstructure showed that sustained sympathetic activation, resembling that occurring during REM, does occur during non-REM sleep phases characterized by EEG-defined cycling alternating pattern and are associated to an increased BRS, eluding the reciprocal balance that conversely seems to characterize wakefulness. Simultaneous assessment of BRS and HRV according to sleep microstructure could prove helpful in identifying patients at increased risk for nocturnal events (eg, early postmyocardial infarction, impaired left ventricular function, obstructive sleep apnea syndrome)\(^3^7\) and in guiding therapy effectively during the nighttime.\(^!\) This would be possible with a complete, noninvasive, minimally disturbing approach.

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