

# Automatic sleep staging using only two electrodes on the forehead

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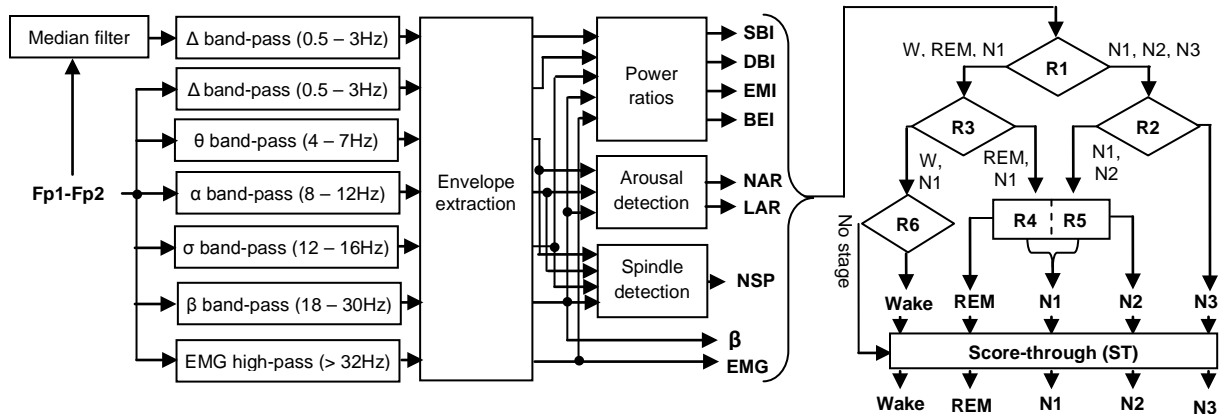
**Introduction:** Multichannel polysomnography (PSG) is ill-suited for applications such as epidemiological studies, large-scale clinical trials, or sleep monitoring in domiciliary environments. An ideal alternative should be an unobtrusive, inexpensive and self-applicable device accompanied with validated algorithms for rapid processing of high volumes of data. We have developed an algorithm for automatic sleep staging that operates on a single EEG channel (F<sub>p1</sub> - F<sub>p2</sub>). An advantage of such an approach is that adhesive disposable electrodes can be easily applied to the forehead by patients after minimal training.

**Methods:** The algorithm was developed on sleep recordings of 10 healthy sleep-deprived subjects, and validated on 11 sleep-deprived and 18 well-rested subjects (**Table 1**). Sleep disorders in participants were ruled out by a combination of questionnaires, activity monitoring and sleep study. All polysomnograms were scored manually by two independent experts who adhered to the AASM rules. Automatic staging combined spectral decomposition of the Fp1-Fp2 signal and a decision tree that classified 30-second epochs into one of the 5 stages (W, R, N1, N2 or N3) on the basis of 9 descriptors of sleep micro- and macro-structure (**Fig. 1**). Automatic and manual hypnograms were compared on an epoch-by-epoch basis for each validation group, and sensitivity, PPV, percentage agreement and Cohen's kappa were calculated from the resultant agreement tables. Total sleep time (TST), sleep latency (SL), wake after sleep onset (WASO) and time spent in REM were calculated for each subject using both the reference and algorithm-generated hypnograms and analyzed on Bland-Altman plots.

**Table 1:** Demographic, clinical and sleep data in the training and validation groups (means, with ranges in brackets)

	Training group (sleep-deprived)	Validation group 1 (sleep-deprived)	Validation group 2 (well-rested)
Number of subjects	10	11	18
Age [years]	27 (20 – 63)	25 (18 - 40)	27 (18 – 45)
Recording time (RT) [min]	160 (120 – 197)	175 (112 – 260)	450 (314 - 502) <sup>1)</sup>
RDI [h <sup>-1</sup> ]	1.5 (0 – 3)	1.8 (0 – 4)	1.9 (0 – 4)
Arousal Index [h <sup>-1</sup> ]	11 (1 – 30)	12 (2 – 25)	10 (1 – 20)
Wake [% of RT]	10 (3 – 21)	11 (2 – 26)	9 (2 - 18)
REM [% of RT]	15 (2 – 29)	14 (1 – 26)	19 (8 - 26)
N1 [% of RT]	9 (4 – 24)	10 (1 – 23)	11 (5 – 21)
N2 [% of RT]	36 (22 – 45)	35 (10 – 53)	41 (34 – 50)
N3 [% of RT]	30 (2 – 45)	30 (3 - 53)	20 (14 - 41) <sup>2)</sup>

1) p < 0.0001 2) p < 0.1, marginally significant



**Figure 1:** Block diagram of the algorithm for sleep staging based on the Fp1-Fp2 EEG (SBI, DBI, EMI, BEI -ratios of sigma and beta, delta and beta, EMG and beta, and delta power before and after media filtering, respectively; NAR, LAR – number and total length of arousals; NSP – number of spindles; β, EMG – average beta and EMG power)

**Results:** Epoch-by-epoch agreement between the automatic and reference scoring was substantial in both validation groups (**Table 2**). Inter-rater agreement for the same data was 83% ( $\kappa = 0.78$ ). Most misclassifications occurred during uneventful wake/sleep transitions, whereas cortical arousals and consolidated sleep were detected with high accuracy. The algorithm provided unbiased and accurate estimates of total sleep time (TST) and sleep latency (SL), but slightly overestimated WASO (**Figure 2**).

**Table 2:** Reference vs. automatic scoring in sleep-deprived (left) and well-rested validation group (right)

	W	N1	N2	N3	R	Sum
Wake	274	31	19	3	20	347
NREM1	57	183	49	25	43	357
NREM2	36	64	891	97	18	1106
NREM3	4	21	94	1021	0	1140
REM	0	19	36	1	491	547
<b>Sum</b>	<b>371</b>	<b>318</b>	<b>1089</b>	<b>1147</b>	<b>572</b>	<b>3497</b>
Se (%)	79.0	51.3	80.6	89.5	89.1	
PPV(%)	74.0	57.6	81.8	89.1	85.9	
Agreement (%)	81.8	Cohen's Kappa			0.76	

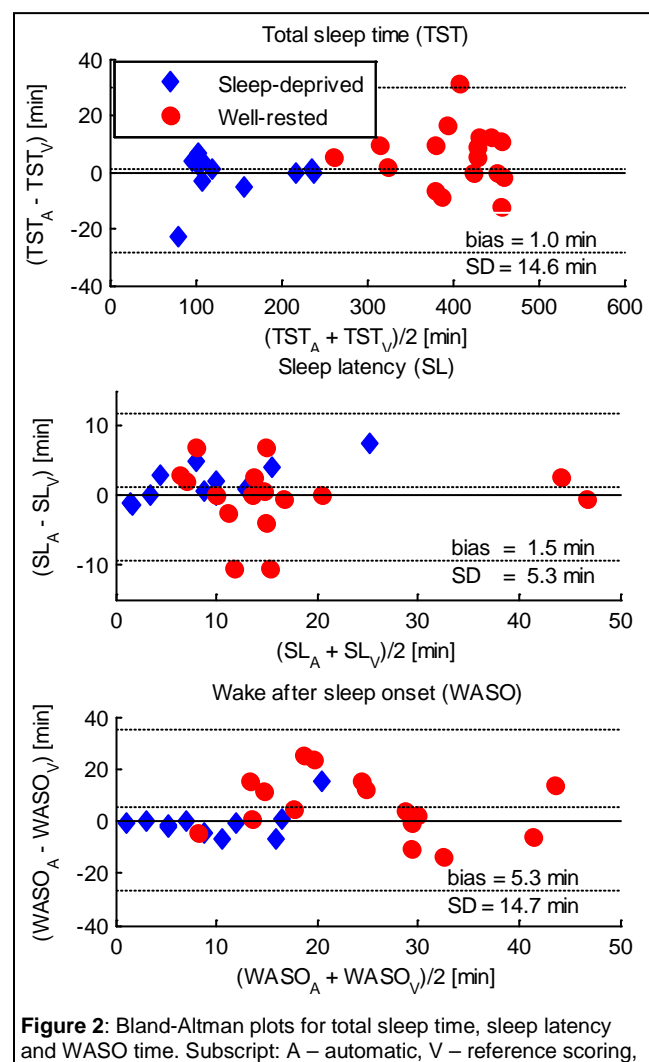
	W	N1	N2	N3	R	Sum
Wake	1051	151	46	4	113	1365
NREM1	266	836	227	22	280	1631
NREM2	21	563	5219	261	119	6183
NREM3	15	55	402	2808	0	3280
REM	129	253	85	25	2861	3353
<b>Sum</b>	<b>1482</b>	<b>1858</b>	<b>5979</b>	<b>3210</b>	<b>3373</b>	<b>15812</b>
Se (%)	77.0	51.2	84.4	85.6	85.3	
PPV(%)	71.0	45.0	85.8	90.0	84.8	
Agreement (%)	80.8	Cohen's Kappa			0.74	

**Discussion:** The agreement between the automatic and reference scoring was similar to the inter-rater agreement reported for healthy subjects<sup>1-4)</sup> and comparable to the performance of other algorithms for automated sleep staging validated in healthy subjects<sup>2-5)</sup>. Accuracy of the automatic staging was dependent on the morphology of the  $F_{p1}$ - $F_{p2}$  signal. Differentiation of wakefulness from light NREM sleep was difficult because of a complete lack of the alpha rhythm in the  $F_{p1}$ - $F_{p2}$  signal during wakefulness with eyes closed. On the contrary, REM, solid NREM and disturbed sleep were detected with high sensitivity and precision because spindles, K-complexes, delta waves, cortical arousals and rapid eye movements are easily observed in the frontopolar EEG during respective sleep stages.

**Conclusions:** The results confirm feasibility of automatic sleep scoring from a single EEG/EOG channel recorded with only two forehead electrodes. Additional studies on elderly subjects and clinical populations are warranted before the algorithm is introduced into clinical practice.

### References

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