Breathing Rate Estimation from the Electrocardiogram and Photoplethysmogram: A Review - Supplementary Material

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This supplementary material contains several items which were either omitted from the main text, or only described in brief.

S1. Search Strategy

An overview of the search methodology was provided in Section II. Further details are provided here, allowing the search reported in this publication to be reproduced, and the methodology to be used to conduct updated searches in the future.

A. Inclusion and Exclusion Criteria

Publications were eligible for inclusion in the review if they described an algorithm which used the ECG or PPG as an input signal, and estimated BR or breath-to-breath intervals. Publications were excluded if: (i) they were written in a language other than English; (ii) no full text was available (after contacting authors where possible); or, (iii) they were patents.

B. Designing a Search Strategy

An initial manual search was performed yielding 90 qualifying publications. These publications were used to design a search strategy to be determined as follows. Inspection of the publication titles revealed three common themes: (i) the process of respiration; (ii) a mathematical process; and, (iii) description of the input signal. Words which occurred in at least 5% of the publication titles were sorted into one of these three categories, or deemed to be irrelevant. This yielded 27 keywords: three in the respiration category; 15 in the mathematical process category; and nine in the input signal category. A total of 76.7% of the titles contained at least one of the keywords from each category. Therefore, a search strategy was devised consisting of three search terms were used (one for each category), and publication titles had to contain at least one keyword from each search term to be included. The next step was to eliminate keywords which did not add value to the search strategy, to increase the specificity of the search. A total of 10 keywords did not add value to the search strategy, as demonstrated by there being no reduction in the sensitivity of the search strategy (from 76.7%) when each was individually omitted. Omission of all 10 only slightly reduced the sensitivity of the search strategy to 75.6%. Therefore, this was chosen as the search strategy. The final keywords are listed in Table S1.

TABLE S1
SYSTEMATIC REVIEW SEARCH TERMS

Search term	Theme	Keywords
S1	Respiration	breathing, respiration, respiratory
S2	Mathematical process	derivation, derived, estimation, extraction, methods, rate, rates
S3	Input signal	ECG, electrocardiogram, photoplethysmogram, photoplethysmographic, photoplethysmography, PPG, pulse

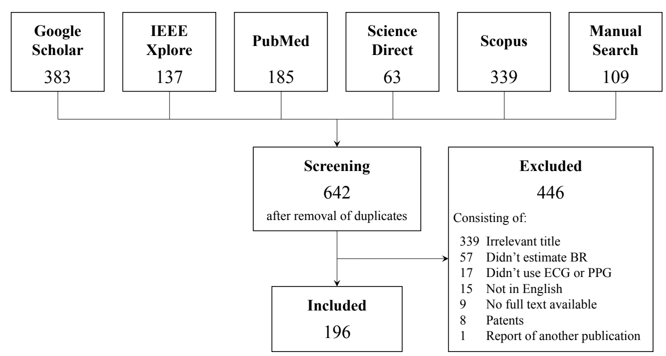

Fig. S1. Identification and screening of publications describing BR algorithms showing: the number of publications identified by the searches, screened, excluded and included in the final analysis.

C. Conducting the Search

The electronic search was conducted on 15^{th} March 2017. The identified publications were screened as follows. Firstly, any publications with irrelevant titles were discarded. Secondly, remaining publications were screened against the inclusion and exclusion criteria. The results of this screening process are summarised in Fig. S1 and provided in full in the supplementary file *BRReviewScreeningResults.xls*. The electronic search yielded 87 additional qualifying publications. In addition, a further manual search was undertaken prior, yielding a further 19 publications.

D. Reproducing the Search

Here we provide instructions on how to repeat the search, for the purposes of updating it in the future.

- **Google Scholar**: Use the following search criteria at http://scholar.google.co.uk/ :
  allintitle: respiratory OR respiration OR breathing AND rate OR estimation OR derived OR extraction OR rates OR methods OR derivation AND ecg OR pulse OR photoplethysmogram OR photoplethysmographic OR ppg OR electrocardiogram OR photoplethysmography
  In this review the results of the search were copied by hand since there was no method available for exporting the results.
- **IEEE Xplore ®**: Use the following search criteria in the IEEE Xplore ® Command Search at http://ieeexplore.ieee.org/search/advsearch.jsp?expression-builder :
  ("Document Title":breathing OR "Document Title":respiratory OR "Document Title":respiration) AND ("Document Title":derivation OR "Document Title":derived OR "Document Title":estimation OR "Document Title":extraction OR "Document Title":methods OR "Document Title":rate OR "Document Title":rates) AND ("Document Title":ECG OR "Document Title":electrocardiogram OR "Document Title":photoplethysmogram OR "Document Title":photoplethysmographic OR "Document Title":photoplethysmography OR "Document Title":PPG OR "Document Title":pulse)
  The results can be downloaded in comma-separated value format.
- **PubMed**: Use the following search criteria at http://www.ncbi.nlm.nih.gov/pubmed :
  (((respiratory[Title] OR respiration[Title] OR breathing[Title])) AND (rate[Title] OR estimation[Title] OR derived[Title] OR extraction[Title] OR rates[Title] OR methods[Title] OR derivation[Title])) AND (ecg[Title] OR pulse[Title] OR photoplethysmogram[Title] OR photoplethysmographic[Title] OR ppg[Title] OR electrocardiogram[Title] OR photoplethysmography[Title])
  The results can be downloaded in comma-separated value format. Note that the results file contains an additional header row every 51 rows which will need to be deleted prior to analysis.
- **Science Direct**: Use the following search criteria at the Science Direct Expert Search:
  TITLE((breathing OR respiration OR respiratory) AND (derivation OR derived OR estimation OR extraction OR methods OR rate OR rates) AND (ECG OR electrocardiogram OR photoplethysmogram OR photoplethysmographic OR photoplethysmography OR PPG OR pulse))
  The results can be downloaded in BibTex format.
- **Scopus**: Use the following search criteria at http://www.scopus.com/ , selecting the Article Title search field:
  (respiratory OR respiration OR breathing) AND (rate OR estimation OR derived OR extraction OR rates OR methods OR derivation) AND (ecg OR pulse OR photoplethysmogram OR photoplethysmographic OR ppg OR electrocardiogram OR photoplethysmography)
  The results can be exported in comma-separated value format.

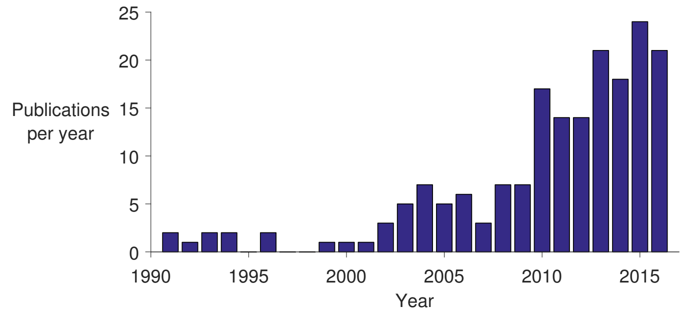

Fig. S2. The number of publications describing breathing rate (BR) algorithms published each year since 1990. The rate of publication has risen steadily since 1999. One further publication dates from 1971 (not shown).

The analyses performed in this review can be reproduced using the *BRReviewAnalyses.m* Matlab ® script.

E. Rate of Publication

The number of publications describing BR algorithms each year has risen steadily since 1999, as shown in Fig. S2.

S2. BR Algorithms

A. Beat Detection Techniques

Feature-based techniques for extraction of respiratory signals require detection of inidividual beats, as noted in Section III-A3.

ECG beat detection is typically performed by identifying QRS complexes, from which the R-waves can be identified. Approaches for identifying QRS complexes include: threshold beat detection [1]; adaptive threshold beat detection using the first derivative of the ECG [2], [3]; a combination of methods using adaptive threshold detection and the curve length transform [4]; and, wavelet transform methods [5]. The adaptive threshold, curve length and wavelet methods have all been evaluated on the benchmark MIT/BIH arrhythmia database, achieving sensitivities and PPVs for beat detection of over 99.5 %, as described in [2], [3], [6] and [5], [7], [8] respectively. Once QRSs have been detected, R-waves can be identified. They have been identified as the maximum ECG value between consecutive QRS onsets [9], or more specifically, as the maximum value within a certain time of the detected QRS (*e.g.* within 20 ms [10]).

PPG beat detection is similarly performed by identifying cardiac pulses, from which pulse peaks can be identified. Methods of identifying cardiac pulses include: band-pass filtering to eliminate non-cardiac frequencies (*e.g.* 0.5-2.0 Hz), followed by peak detection [11]; threshold beat detection using the first derivative of the PPG [12]; the Incremental-Merge Segmentation (IMS) algorithm [13], [14]; and, identifying regions for pulse peaks using a simultaneous ECG signal [15]–[19]. Pulse peaks are then identified as the maximum PPG value between consecutive cardiac pulse onsets [9], [11].

B. Selection of Auto-Regressive Model Order

Techniques for estimation of BR which use autoregressive modelling require a specified model order, as noted in Section

III-C. Pre-specified model orders have been used, such as 8, or 11 [20], [21]. The model order has also been determined by analysis of the respiratory signal using: (i) Rissanen's minimum description length method [22]; (ii) the Akiake criteria [4]; or (iii) the optimal parameter search (OPS) criterion [23]–[25], which can be time-invariant or time-varying to improve accuracy of BR estimation from non-stationary respiratory signals [26]. In addition, Shah *et al.* fused the spectra obtained using a range of model orders (2 - 20) [27], and Pimentel *et al.* fused spectra obtained both by using multiple model orders and from multiple respiratory signals [28].

S3. Methodologies used to Assess BR Algorithms

The results of an analysis of the methodologies used to assess BR algorithms were provided in Section IV-A. The data on the methodologies are provided in *BRReviewMethodologiesData.xls*. The analysis of the data reported in Section IV-A can be reproduced using the *BRReviewAnalyses.m* Matlab ® script.

Note the following aspects of the data and analysis:

- The analysis of window durations was conducted in seconds. Two articles which reported the duration in beats were not included in the analysis.
- Subjects in the CapnoBase dataset were denoted as being critically-ill (signals were collected during elective surgery and routine anaesthesia [14].

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