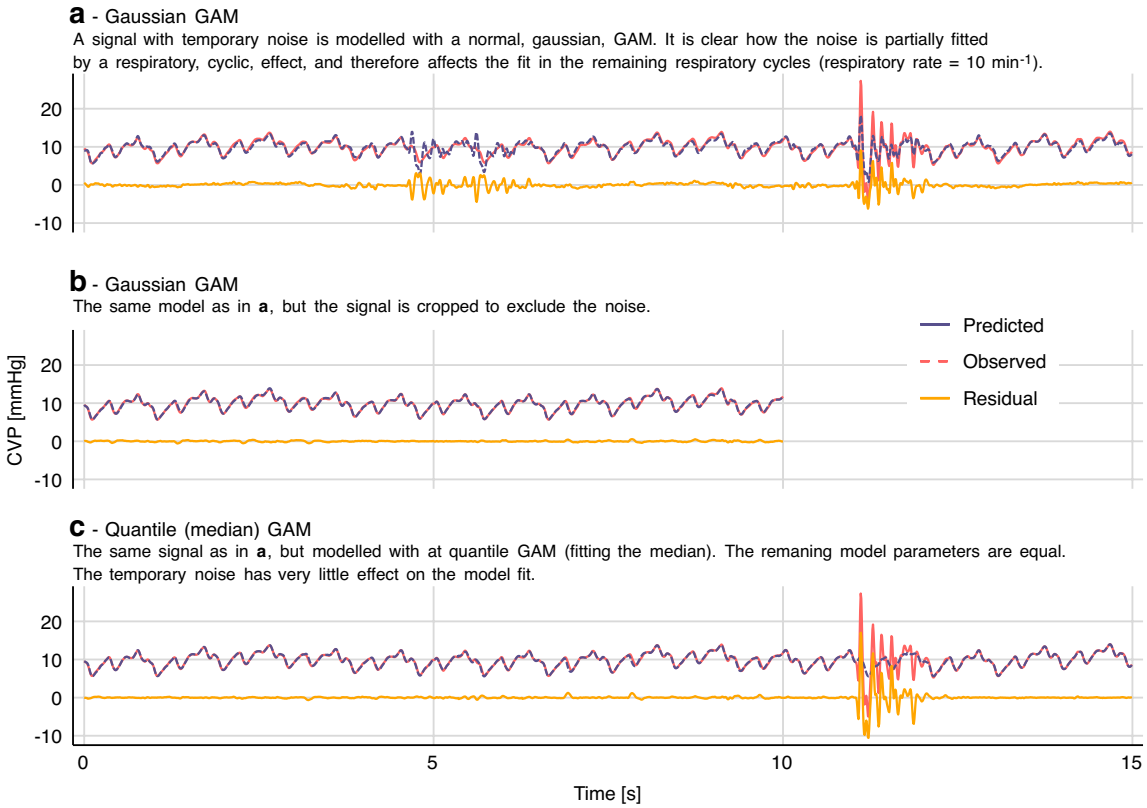

Fig. 7 Quantile generalized additive models (QGAM) robustly fit medical signals with non-normal errors. The models correspond to the model shown in Fig. 5

2.3.3 Dealing with signal noise

In the examples above, we have fitted data on the assumption that errors (residuals) are normally distributed. In practice, extreme outliers are much more common than expected from a normal distribution. Most of the time, the measured signal (e.g. CVP) will reflect the true state with very little noise. However, temporary large deflections of the waveform are common (e.g. due to manipulation of transducer or tubing). Together, these two sources of noise give rise to errors that are both non-normal and heteroscedastic (with non-constant spread). If we try to fit this data with a model that assumes homoscedastic, normally distributed errors, we will likely encounter overfitting. This is illustrated in Fig. 7a, where the noise at 12 s is also predicted one respiratory cycle earlier—a least squares regression will prioritise being a little wrong twice over being doubly wrong once (since the errors are squared).

To remedy the problem with noise having a high impact on the fit, an effective approach is to fit the median of the signal with a *quantile* GAM. When fitting the median, there is no assumption about the conditional distribution of the dependent variable, and outliers (e.g. from noise) have a much lower impact on the model fit (see Fig. 7c). The *qgam* package by Fasiolo et al. extends *mgcv* to allow fitting quantile models [22].

3 Discussion

In this methodological paper, we demonstrate how GAMs can be used as a flexible tool for modelling cyclic medical time series and waveforms. We give two heart–lung interaction examples: The first is a specific use-case: a robust calculation of pulse pressure variation from a time series of pulse pressure measurements. The second is a demonstration of how we can use a relatively simple model to fit the CVP waveform, with very little preconception of the shape of the waveform.