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RESAMPLING METHODS FOR SIGNALS RECORDED AT VARIABLE SAMPLE-TIME INTERVALS DURING GENERAL ANESTHESIA

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ABSTRACT

This work provides an overview upon the problems posed by the variable sampling times of the data recorded during general anesthesia. The time instant at which the data were saved into the database is not following a fixed interval; i.e. the real signals were recorded at variable sample-time intervals. This situation can produce numerical errors and erroneous results when the signals are employed for identification or control tasks. In this contribution, real data measured from the patients are pre-processed and the methods for a fixed resampling procedure are analyzed with respect to effort-result trade-off. The result is a useful database with suitable signals to be used for identification and control purposes.

Keywords: anesthesia control, resampling data, variable sampling time.

INTRODUCTION

Adequate anesthesia can be defined as a reversible pharmacological state where the patient's muscle relaxation, analgesia and hypnosis are guaranteed. Anesthesiologists administer drugs and adjust several medical devices to achieve such goals and to compensate for the effect of surgical manipulation while maintaining the vital functions of the patient.

Figure-1 depicts the Input/Output (I/O) representation of the anesthesia problem. The components of an adequate anesthesia are labeled *unmeasurable* because they must be assessed by correlating them to available physiological measurements.

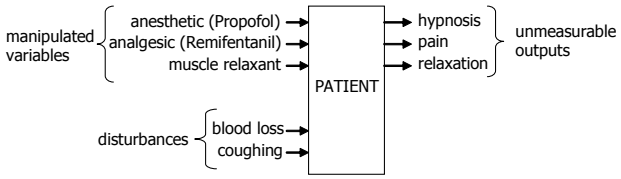

Figure-1. Input/Output representation of the anesthesia problem.

Muscle relaxation is induced to facilitate the access to internal organs and to depress movement responses to surgical stimulations. The degree of relaxation can be estimated by measuring the force of thumb adduction induced by stimulation of the ulnar nerve or by Single Twitch Force Depression (STFD) (Viby-Mogensen *et al.*, 2000).

Analgesia is pain relief and at present there are no specific measures to quantify it intra-operatively. A reason for this may be that it is even debatable to speak about pain perception when the subject is unconscious (Prys-Roberts, 1987). Another source of complexity results from the fact that clinical signs such as tearing, pupil reactivity, eye movement and grimacing (Cullen *et al.*, 1972) are partially suppressed by muscle relaxants, vasodilators and vasopressors.

Hypnosis is a general term indicating unconsciousness and absence of post-operative recall of events occurred during surgery (Goldmann, 1988). Some authors believe there is a sharp distinction between conscious and unconscious states (Prys-Roberts, 1987). In this respect, it would be improper to speak about depth of anesthesia. However, the patterns of the electroencephalogram (EEG) show gradual modifications as the drug concentrations increase in the body. Nowadays the EEG is considered as the major source of information to assess the level of hypnosis.

Better accepted measurements exist for the vital functions. Heart Rate (HR) and Mean Arterial Pressure (MAP) are considered the principal indicators for hemodynamic stability, while O_2 tissue saturation or end-tidal CO_2 concentrations provide useful feedback to anesthesiologists about the adequacy of the artificial ventilation.

To achieve adequate anesthesia, anesthesiologists regularly adjust the settings of several drug infusion devices as well as the parameters of the breathing system to modify the manipulated variables listed in Figure-1. This is done based on some patient specific target values and the monitor readings. Thus, anesthesiologists adopt the role of a feedback controller and it is natural to ask whether automatic controllers are capable of taking over and/or improving parts of such a complex decision process.

Several authors have recognized the advantages associated with the use of automatic controllers in anesthesia (Schwilden and Stoeckel, 1995; Chilcoat, 1980; O'Hara *et al.*, 1992; Derighetti, 1999). First, if the routine tasks are taken over by automatic controllers, anesthesiologists are able to concentrate on critical issues which may threaten the patient's safety.

Second, by exploiting both accurate infusion devices and newly developed monitoring techniques, automatic controllers would be able to provide drug administration profiles that, among other advantages, would avoid overdosing. Moreover, they may take advantage of the drug synergies, for which now a proper modeling framework was developed (Minto *et al.*, 2000). The ultimate advantage would be a reduction in costs due to the reduced drug consumption and the shorter time

spent by the patient in the Post Anesthesia Care Unit (PACU).

Further, if tuned properly, automatic controllers should be able to compensate for the inter-patient variability and to tailor the drug administration profile to the particular stimulation intensity of each surgical procedure (Linkens and Hacisalihzade, 1990). Ultimately, automatic controllers can be used for research as a 'reference' anesthesiologist in clinical studies.

In this contribution, real data measured from the patients are pre-processed in order to obtain a useful database for identification or control tasks. Because the real signals are recorded at variable sample-time intervals and to avoid numerical errors and erroneous results, it is therefore necessary to correct the following technical problems: Time intervals with lack of information and variable sampling time. In this manner, this paper provides an overview upon the problems posed by the variable sampling times of the data recorded in the hospital. The methods for a fixed resampling procedure are analyzed with respect to effort-result trade-off. The result is a useful database with variables to be used for identification and control purposes.

MATERIALS AND METHODS

The original database of the signals employed in this study was recorded when an anesthetic (Propofol) and an analgesic (Remifentanil) were administrated by the nurse during clinical trials on 25 patients in Intensive Care Unit (ICU). All patients were undergone to cardiac surgery before to go to ICU.

Due to that the original database is composed of around 100 signals, this should be reduced to take only a small group of signals which can be used for identification purposes, model validation, control development, etc. The proposed database must contain the following signals:

- Propofol infusion rate (mg/s) - henceforth called Propofol
- Remifentanil infusion rate (µg/s) - henceforth called Remifentanil
- Propofol plasma concentration (µg/ml) - henceforth called C_{pProp}
- Remifentanil plasma concentration (ng/ml) - henceforth called C_{pRem}
- Propofol effect site concentration (µg/ml) - henceforth called C_{eProp}
- Remifentanil effect site concentration (ng/ml) - henceforth called C_{eRem}
- Bispectral index - henceforth called BIS
- Electromyography (dB) - henceforth called EMG
- Signal Quality Index (%) - henceforth called SQI

The following Figures show a small section of the selected signals for patient-16.

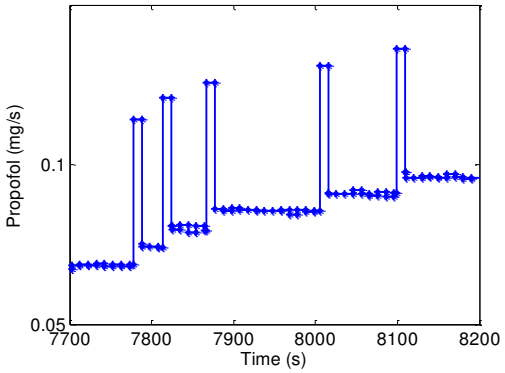

Figure-2. Original propofol during ICU trial.

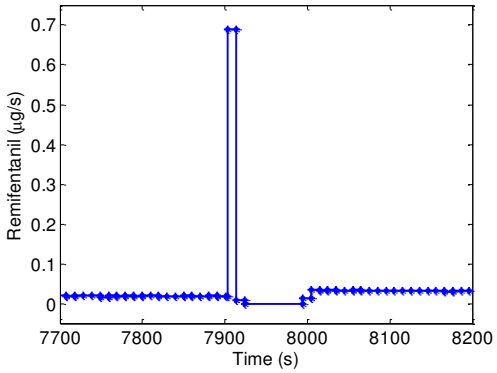

Figure-3. Original remifentanil during ICU trial.

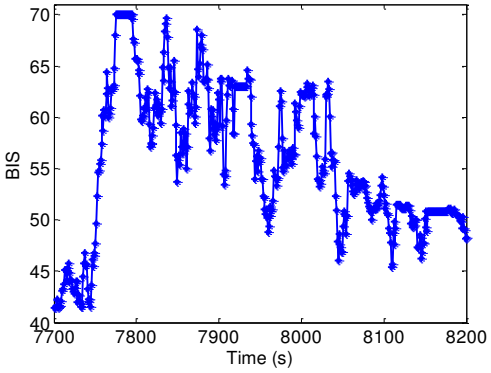

Figure-4. Original BIS during ICU trial.

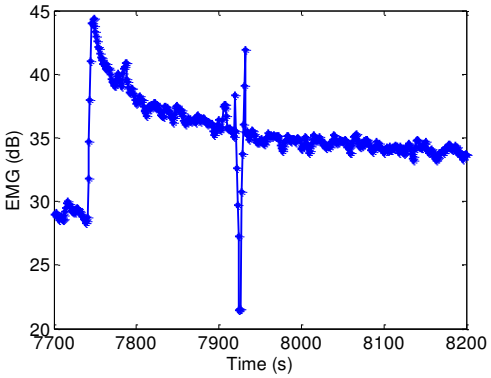

Figure-5. Original EMG during ICU trial.

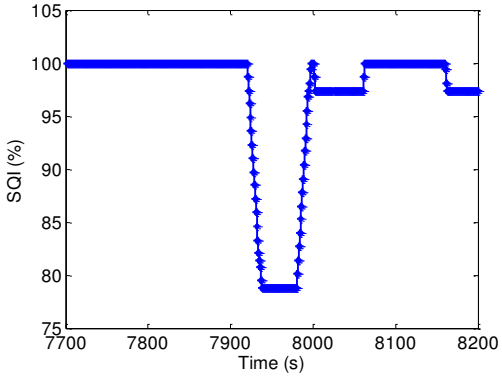

Figure-6. Original SQI during ICU trial.

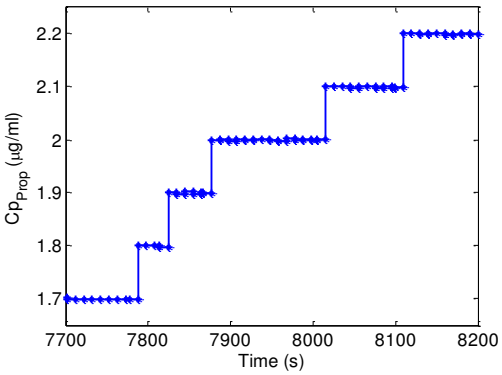

Figure-7. Original C_{pProp} during ICU trial.

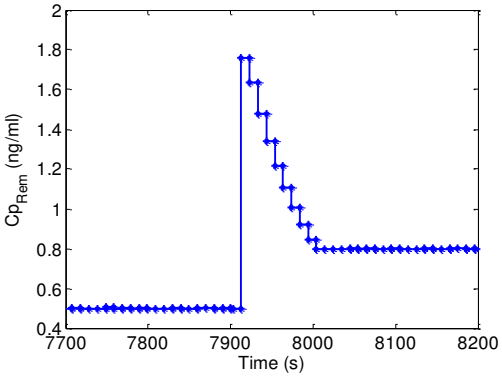

Figure-8. Original C_{pRem} during ICU trial.

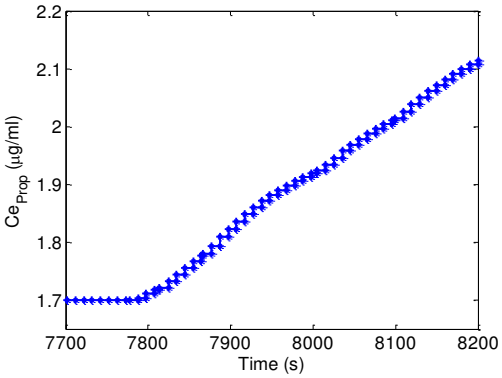

Figure-9. Original C_{eProp}during ICU trial.

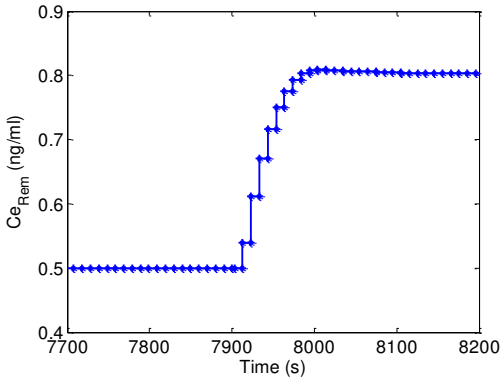

Figure-10. Original C_{eRem}during ICU trial

Taking a close look at the recorded data in the hospital, it can be observed that the time instant at which the data were saved into the database is not following a fixed interval. For instance, sometimes the data are available every second or every half of a second; sometimes almost every 10 seconds, and in some moments there are not recorded data for several hundreds of seconds. The reason for long periods of missing data is that the software that works in the hospital records a new value of time and a new value for the signals only when the value in the signal amplitude changes.

This protocol is justified by the fact that due to high number of data to be saved, the memory requirements are also high; therefore in this way the used memory amount can be reduced. In this manner, the principal feature of the data is that they are recorded at variable sample-time intervals. This is a major drawback when the signals are directly used in identification or control tasks, because the numerical errors are significant and lead to erroneous results.

RESULTS AND DISCUSSIONS

Briefly, the problem can be stated as following. In order to obtain a useful database for identification or control tasks, real data measured from the patients are necessary. However, the real signals are recorded at variable sample-time intervals and to avoid numerical errors and erroneous results it is therefore necessary to correct the following technical problems:

- Time intervals with lack of information; i.e. data is not saved if the value does not change; or the signal might be not available (strong artefact corruption).
- Variable sampling time.

For identification or control tasks, it is necessary that the data are available at the same fixed rate.In this case, a sampling time of 10 seconds is chosen.

Apart from Propofol and Remifentanil, all other signals are rather easy to resample correctly. That is, the signals are already recorded at time intervals close to 10 seconds and the relation between two consecutive values is a linear approximation. In this case, the following resampling procedure is proposed:

- Round the elements of the time vector.
- If the difference in time between two consecutive values is bigger than 1 second, the Zero Order Holder (ZOH) principle is applied and the signal is resampled every second.
- Create a new time vector in which the values are recorded every 10 seconds.

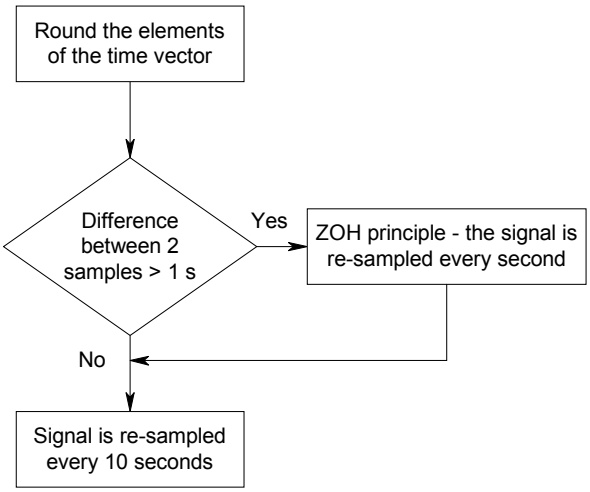

Figure-11. Resampling procedure used for C_{pProp}, C_{pRem}, C_{eProp}, C_{eRem}, BIS, EMG and SQI signals.

The following figures show a small section of theoriginal and resampled signals for patient-16.

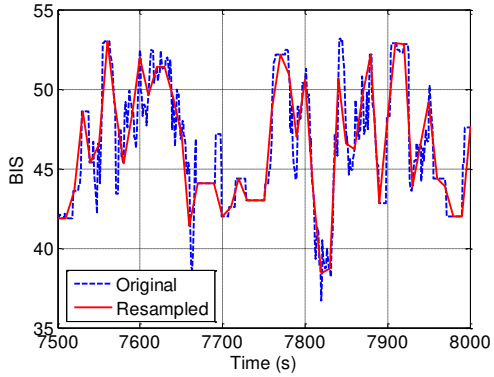

Figure-12. Detailed original and resampled BIS.

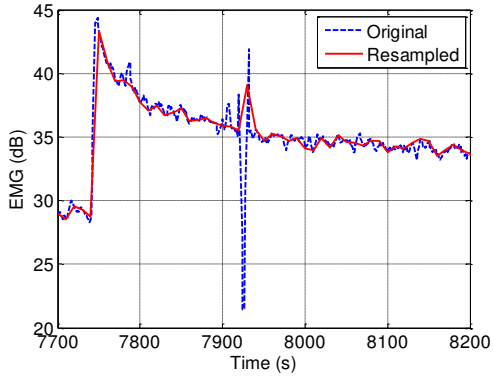

Figure-13. Detailed original and resampled EMG.

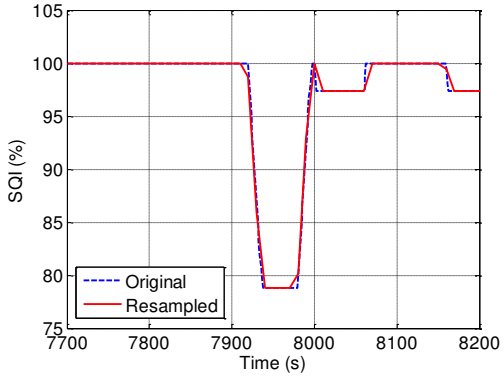

Figure-14. Detailed original and resampled SQI.

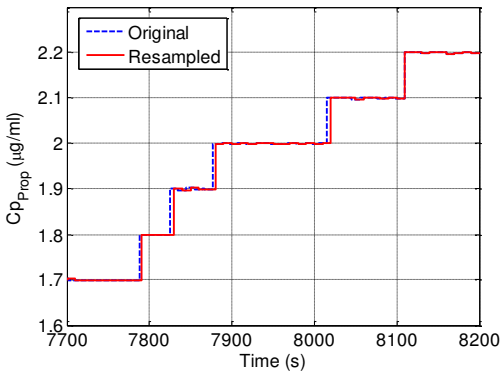

Figure-15. Detailed original and resampled C_{pProp}.

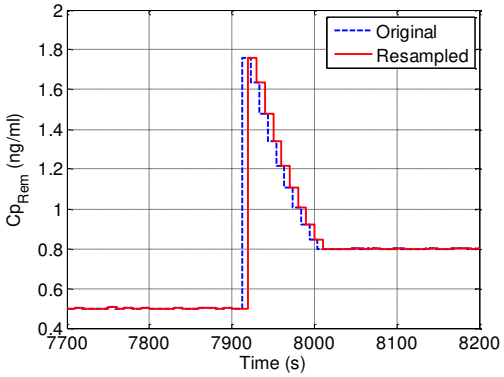

Figure-16. Detailed original and resampled C_{pRem}.

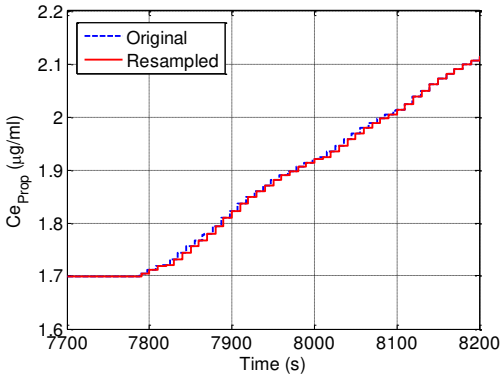

Figure-17. Detailed original and resampled C_{eProp}.

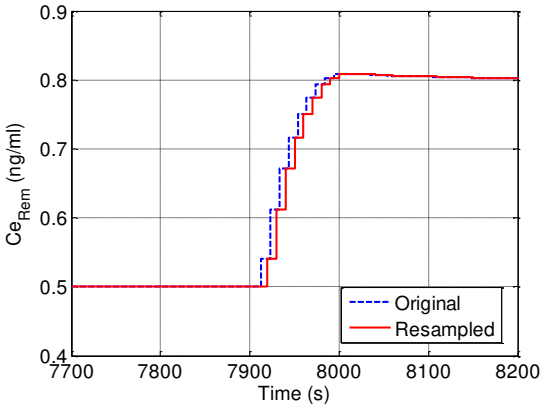

Figure-18. Detailed original and resampled C_{eRem}.

Resampling the Propofol and Remifentanil signals is a very difficult task. This is because the data are not saved every 10 seconds and additionally, there is a lot of missing data, which is necessary to be completed. Another problem appears when the data are saved in the new matrix at a sampling time of 10 seconds. There aremany data recorded at sample times less than 10 seconds in the original signal, sometimes as fast as every 1 second. As a result, when the new data are saved every 10 seconds, significant inter-sampled variations might be missed (i.e. variations within the 10 seconds interval).

For example, suppose that there is Y (mg/s) of Propofol from time 10 s to 12 s, and Z (mg/s) of Propofol from time 12 s to 15 s. Further on, there is again the value Y (mg/s) of Propofol from time 15s to 20s. When the procedure for resampling is applied the Propofol value at time 10 s is Y, and at 20 s is also Y. In this manner, the variation in the value from time 12 s to 15 s (Z) is missed. If these resampled signals are used blindly, it would affect significantly the values for identification and control tasks, and it would bring to erroneous conclusions.

If $Y < Z$, then the simulated output will be smaller than the real one. The error between the real value and the value obtained from the simulator is less than 10%, which from a control engineering standpoint is acceptable. But, if $Y > Z$, it will have an opposite influence on the output than previously. In this case, the error is still less than 10% but the problem is that the values of the simulated output are above the limitations imposed in the system (i.e. simulated C_{pProp} is bigger than 4.5 µg/ml, while real C_{pProp} is limited at 4.5 µg/ml due to patient safety).

Due to the fact that the original time vector of the Propofol and Remifentanil signals contains decimal values, then these signals were shifted in time to the left and to the right (depending on the data) with the purpose of reducing the standard deviation between the original time vector and the time vector of the shifted signals. Once the shifted time vector is obtained, the procedure remains the same as in the previous algorithm:

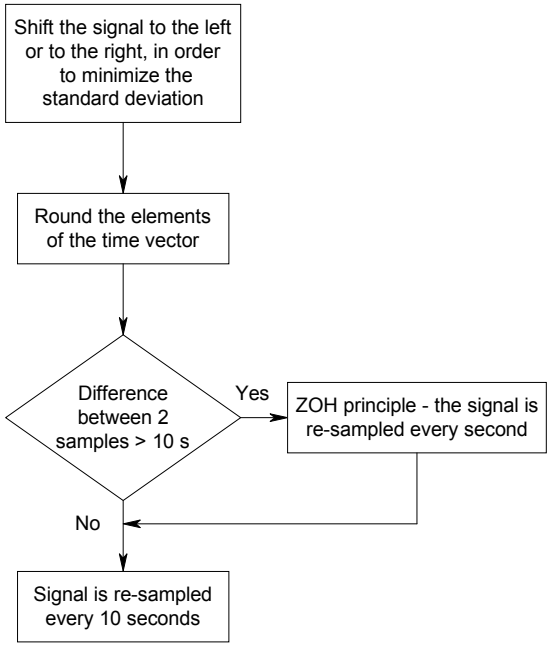

Figure-19. Resampling procedure used for Propofol and Remifentanil signals.

For patient-16, Figure-20 shows that the minimum standard deviation between the original Propofol signal and the shifted Propofol signal occurs when the Propofol signal is shifted in time 0.4 s to the right. Similarly, Figure-21 shows that the minimum standard deviation between the original Remifentanil signal and the shifted Remifentanil signal occurs when the Remifentanil signal is shifted in time 0.3 s to the right.

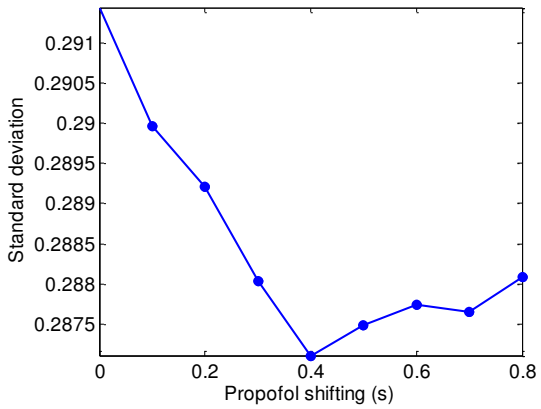

Figure-20. Standard deviation when Propofol is shifted in time.

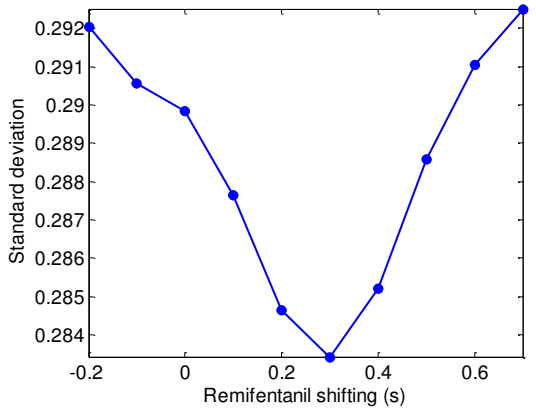

Figure-21. Standard deviation when Remifentanil is shifted in time.

No automatic procedure can be developed in this case, due to the strong variability in sampling of the original recorded data, however the following figures show that the result of the resampling algorithm is adequate.

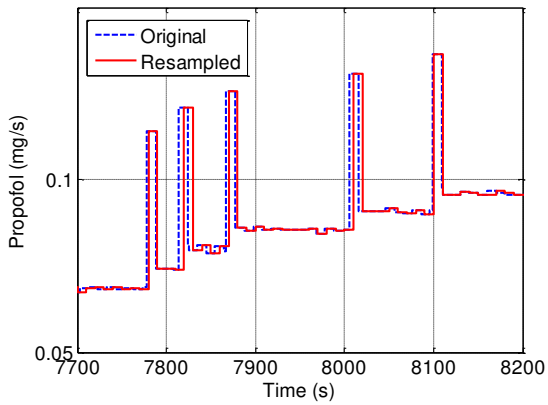

Figure-22. Detailed original and resampled Propofol for Patient-16.

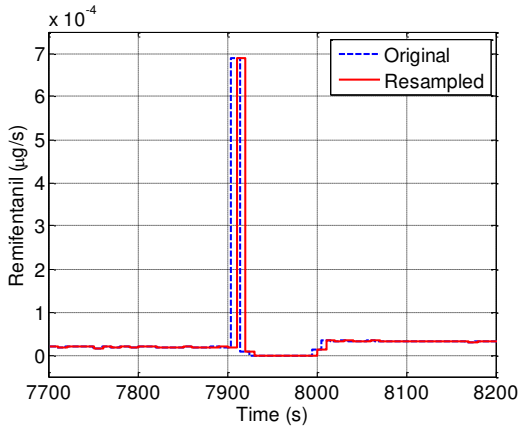

Figure-23. Detailed original and resampled Remifentanil for Patient-16.

In order to validate the performance of this resampling algorithm, the real and resampled Propofol signals are introduced in a simulator which uses a three-compartmental Schnider model of the patient (Schnider *et al.*, 1998) to obtain the Propofol plasma concentration (C_{pProp}) produced by each one of them and thus the quality of the resampled signals for Propofol can be evaluated.

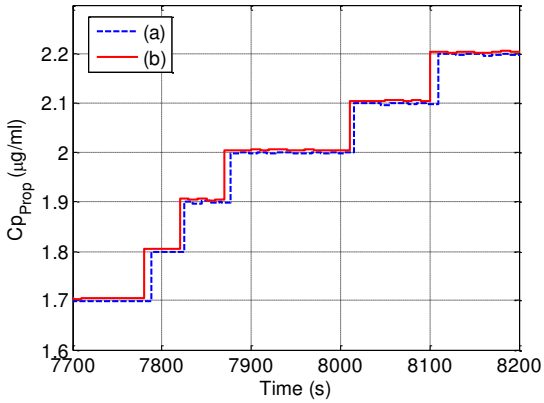

Figure-24. Detailed C_{pProp} obtained from the simulator using (a) original and (b) resampled Propofol (Patient-16).

In the figure above, it can be observed that the level of C_{pProp} obtained from the simulator using the resampled Propofol signal is very close to the level of C_{pProp}obtained when the original Propofol signal is used. In this manner, this paper provides an overview upon the problems posed by the variable sampling times of the data recorded in the hospital. The methods for a fixed resampling procedure allow obtaining appropriate signals employing few computational resources. The result is a useful database with variables to be used for identification and control purposes.

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