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Nonuniform sampling of urodynamic signals: a comparison of different methods

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Abstract Several different techniques for urodynamic signal compression have been proposed in the last few years. Using these techniques it is possible to reduce the requirements for digital storage or transmission. There are a number of applications where it is essential to use such techniques in diagnostic and ambulatory urodynamics. The purpose of this study is to compare different techniques of urodynamic data compression. the so-called FAN, voltage triggered, two point projection and second difference methods. The comparison between the methods is based on 65 pressure, 46 uroflow and 18 surface electromyogram signals. The reduction ratio achieved for different allowable errors between the original and compressed signals is calculated and compared for the different techniques. Results show that it is possible to store urodynamic signals accurately at a low sampling rate, where FAN and voltage triggered methods seem to be superior to the rest.

Key words Adaptive sampling · Computer · Storage · Urodynamic signals

Modern digital technology makes discrete time processing advantageous over analog processing. To achieve this, analog signals should be converted into discrete signals using analog/digital conversion systems that sample and quantize the signal at discrete time intervals. Usually the sampling is performed uniformly. The sampling rate must be high enough to adequately represent rapid changes in the signal. For urodynamic signals the sampling rate should be 10 samples per second or more for pressure and flow signals [7] and 1000 samples per second for surface electromyogram (EMG) signals [3]. Sampled signals are stored in computer memory for later processing or observation. The storage of all measured signals during a complete urodynamic procedure requires large amounts of storage space. More than 7 Mbyte of computer memory would be filled in an hour with one pressure, one flow and one EMG channel recording.

In order to increase the storage capacity of the signals databases and improve ambulatory systems, and to enable rapid and economical transmission of urodynamic signals over public telephone lines to a remote urodynamic center, there is a need for urodynamic signal compression. The problem is to store the signal using minimum storage size or transmit it economically, retaining the ability to reconstruct the signal within a given error. Data compression techniques have been utilized in different biomedical applications. It was shown that the choice of a data reduction technique is definitely a function of the input data. There are many applications for electrocardiac signal compression [2, 4, 5]. Urodynamic signals are different in that they are nonperiodic and their changes are unpredictable. These signals, as well as many other signals of biological origin, consist of intermittent rapid changes and relatively quiet intervals. The best way of sampling such signals would be to adjust the sampling rate to the changes in the signal being sampled. The signal would then be sampled at a high rate during periods of rapid change and at a low rate during the quiet periods. Such nonuniform sampling is also called adaptive sampling. Adaptive sampling can also produce higher-quality measurement than uniform sampling [1, 2] as it could work as a filter.

In this study four different methods of adaptive sampling are applied to urodynamic signals and compared. The methods were chosen on the basis of previous work done by the authors.

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Materials and methods

Detrusor pressure, flow rate and EMG signals were acquired and stored in a computer memory at a sampling rate of 10, 10 and 1000

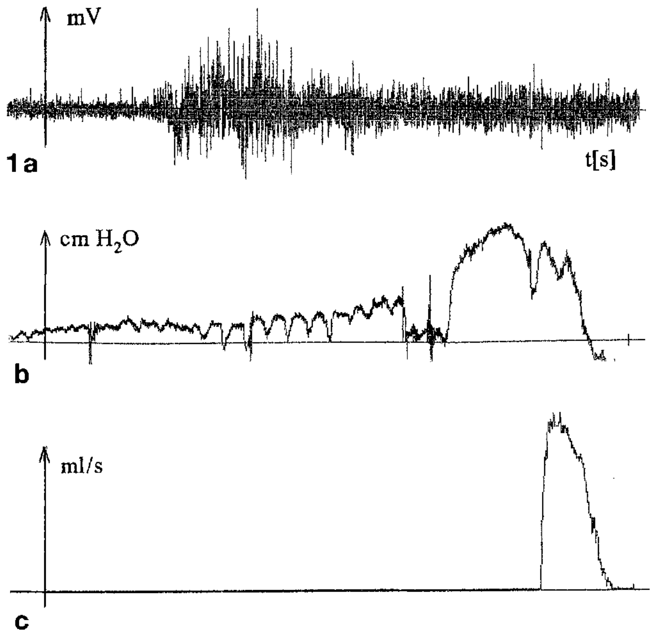

Fig. 1 An example of a surface electromyogram (Emg) (**a**), detrusor pressure (**b**) and uroflow signal (**c**)

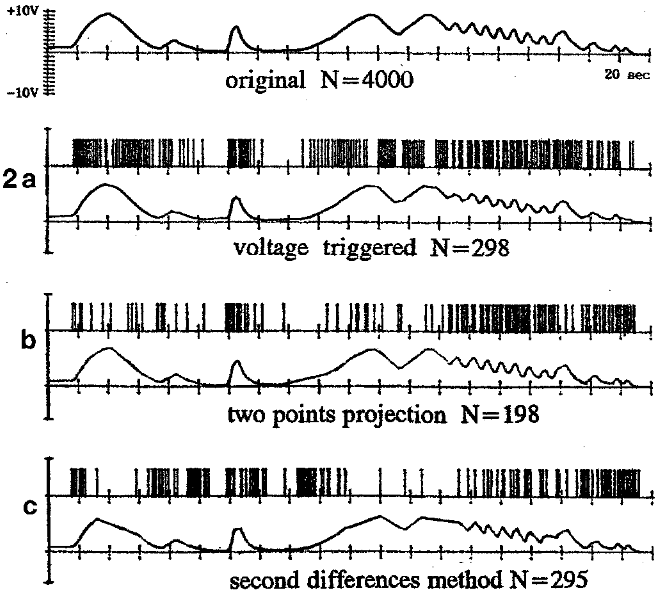

Fig. 2 a–c An illustration of voltage triggered (**a**), two point projection (**b**) and second difference (**c**) methods. The *bars* represent the permanent samples taken for each method. The *curves* under the bars represent the signals reconstructed after applying a certain data compression technique. *N*, number of permanent samples

samples per second respectively. The signals were acquired during routine cystometry procedures using fluid-filled transurethral catheters, standing voiding in a DISA flow meter and disposable surface electrodes on the perianal skin. An example of each signal is shown in Fig. 1. There were 65 pressure, 46 uroflow and 18 EMG signal recordings included in the study, comprising approximately 10 h (379407 samples) of pressure data, 6.5 h (233537 samples) of uroflow data and 6 min (359492 samples) of EMG data. Four different methods of data compression were used: voltage triggered, two point projection, FAN [6] and second difference.

Voltage triggered method

The voltage triggered method examines the absolute difference between two samples. If the sample $x(t_i)$ was stored at time t_i then the next sample $x(t_i+\tau)$ would be stored at the time $t_i+\tau$, when the absolute value of the difference between the two samples exceeds a given threshold P_0:

$$|x(t_i+\tau)-x(t_i)|>P_0$$

An illustration is given in Fig. 2.

Two point projection method

The two point projection method examines the slope of the signal. The first samples are used to calculate the slope of the signal. If the following samples fall within a given error P_1 of that slope, then they are ignored. The first sample that falls outside the error range is stored and used to calculate a new slope. The derivative of the signal at time t_i is denoted by $x(t_i)$. If a sample was stored at t_i the next sample will be stored at time $t_i+\tau$ when:

$$|x(t_i+\tau)-x(t_i)|>P_1$$

where the slope is estimated by:

$$\dot{x}(nT_s)=\frac{x(nT_s)-x[(n-1)T_s]}{T_s}$$

T_s is the sampling interval of the uniformly sampled signal $\{x(nT_s)\}$, $n=0,1\ldots$ An illustration is given in Fig. 2.

FAN method

The algorithm for the FAN method was published by Gardenhire [4]. The actual implementation of the original technique involves a process that calculates two slopes for each new sample. These slopes originating at the first sample form a "fan" of radial lines around subsequent samples. The slope of the first two lines passes through a point at a specified tolerance above and below the second sample. If the third sample falls between the two lines of the fan, a line can be drawn from sample 1 to sample 3 and any point on this line will be within the specified tolerance. New slopes are established from the first sample to points that are the selected tolerance above and below the third sample.

Second difference method

The second difference method examines the slope of the signal just before the current sample and just after it. Hence, the local change of the slope is calculated. The sample x_i is stored if:

$$|\dot{x}(t_i^+)-\dot{x}(t_i^-)|>P_2$$

where $\dot{x}(t_i^+)$ is the derivative of the signal just after the current sample and $\dot{x}(t_i^-)$ is the derivative of the signal just before it. The slope of the signal is calculated in the same way as in the two point projection method. An example is shown in Fig. 2.

The FAN algorithm was written in FORTRAN language while the other three were written in Hewlett Packard Basic language. Each algorithm was used a number of times with a different maximum allowable error between the original and the compressed measurement. The pressure and flow signals were digitized using a 12-bit bipolar A/D converter at a full range of 200 cmH_2O for detrusor pressure and 50 ml/s for flow. EMG signals were digitized using a 16-bit bipolar A/D converter with 20 Vpp. The smallest detectable change in the digitized signals (1 integer unit) is therefore approximately 0.1 cmH_2O for pressure signals, 0.025 ml/s for flow signals and 0.3 mV for EMG signals. The compressed signals were stored in a computer memory. From each compressed signal a reconstruction

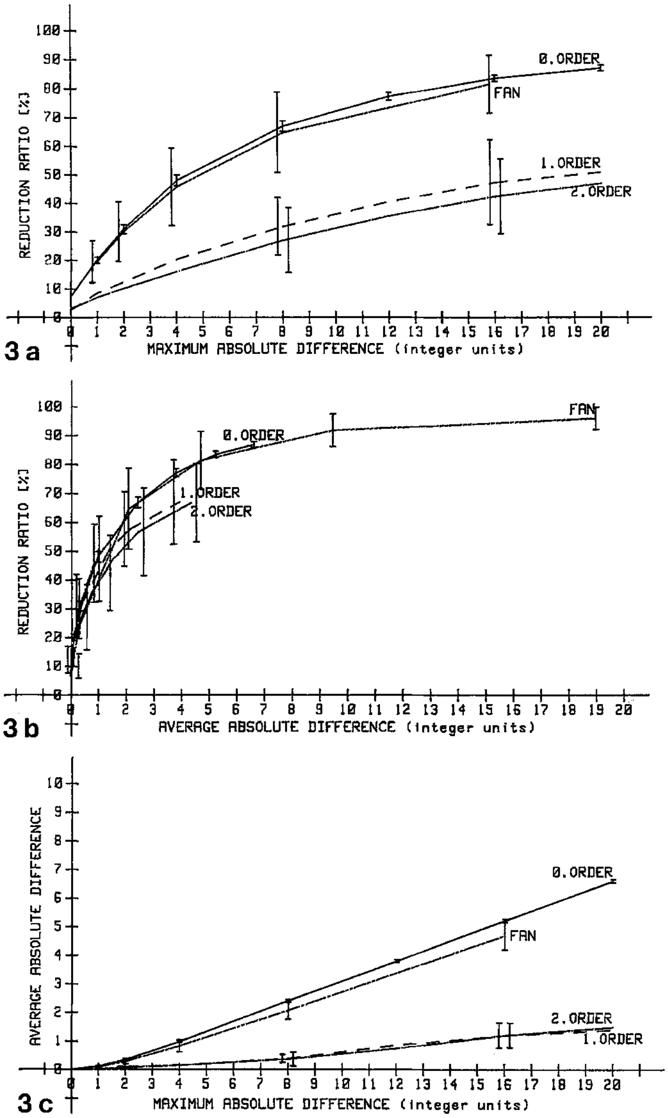

Fig. 3a–c Average of results from 65 pressure signals. **a** Percentage reduction ratio as a function of maximum absolute difference between reconstructed and original pressure signals. **b** Percentage reduction ratio as a function of average absolute difference between reconstructed and original pressure signals. **c** Average absolute error as a function of the maximum absolute difference between reconstructed and original pressure signals. *Error bars* are ± 1 SD

was made by linear interpolation between the samples. The average difference between reconstructed and original measurement, reduction ratio (i.e. the number of samples in the compressed signal divided by the number of samples in the original signal) and maximum error were calculated and stored for further statistical analysis. Statistical analysis was performed using the SPSS package for FAN method results and user-developed software for the voltage triggered, two point projection and second difference methods.

Results

The data compression algorithms were applied to "raw" pressure, flow and EMG signals. No preprocessing or smoothing was done. The relation between the average absolute difference and the percentage reduction ratio is given in Figs. 3b, 4b and 5b for pressure, flow and EMG signals respectively. Figures 3a, 4a and 5a show the relation between the maximum absolute difference and the percentage reduction ratio. Maximum absolute difference as a function of average absolute difference is plotted in Figs. 3c, 4c and 5c.

The results of the analysis based on 65 pressure signals show that it is possible to achieve a small reduction (a few percent) without causing any error (Fig. 3a, b) after the reconstruction. In that case only those consecutive samples that are of exactly the same value or have exactly the same slope as the previous and the following one are considered redundant. Therefore after linear interpolation on the reduced set of data no difference occurs between the original and reconstructed data. As the maximum absolute difference varies from 0 to 20 integer units (approx. 2 cm H_2O), the reduction ratio expressed as a percentage varies from approximately 3% to 85% (Fig. 3a). At a maximum absolute difference of 4 integer units (approx. 0.4 cm H_2O) the reduction ratio varies from approximately 10% (second difference method) to 45% (voltage triggered method). At approximately the same reduction ratio interval (approx. 8–90%) the average absolute difference varies from 0 to 6 integer units (0.6 cm H_2O) as can be seen in Fig. 3b.

Comparing the methods it is seen that the voltage triggered and FAN methods are superior to the other two, in this view. Figure 3c shows that there is an almost linear relationship between the maximum and the average absolute difference. At the same maximum absolute difference the average absolute difference is higher for the voltage triggered and FAN method than for the other two methods. This indicates that a difference exists in the relation between average and maximum error (Fig. 3c).

For the flow rate signals the results were different. Without causing any error a reduction of more than 50% was achieved using the voltage triggered, two point projection and second difference methods (Fig. 4a, b). This is due to the fact that flow rate signals consist of a long period of a constant (zero) flow rate with small disturbances. When consecutive samples have the same value, only the first and the last sample with the same value can be stored, without causing any error after the reconstruction. As the maximum absolute difference varies from 0 to 20 integer units (0 to 0.5 ml/s), flow signals are compressed from approximately 50% to 98% (Fig. 4a). Within the same interval the average absolute difference varies from 0 to 4 integer units (0 to 0.1 ml/s). There are no major differences between the methods although the FAN and voltage triggered methods seem to perform slightly better than the other two methods on these flow rate signals. The relation between the average and maximum absolute difference is not linear in general.

For EMG signals, the differences between the applied methods are more pronounced. Comparing the percentage reduction ratio for different methods as a function of the maximal and the average absolute error the FAN

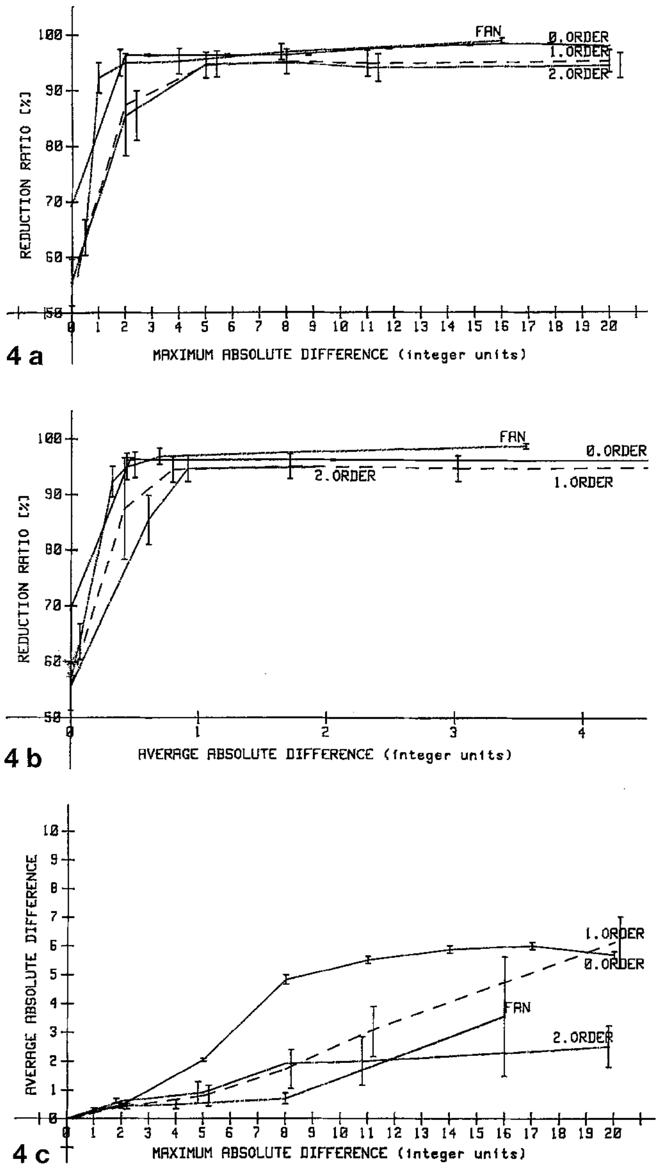

Fig. 4a–c Average of results from 46 flow signals. **a** Percentage reduction ratio as a function of maximum absolute difference between reconstructed and original flow signals. **b** Percentage reduction ratio as a function of average absolute difference between reconstructed and original flow signals. **c** Average absolute error as a function of the maximum absolute difference between reconstructed and original flow rate signals. *Error bars* are ± 1 SD

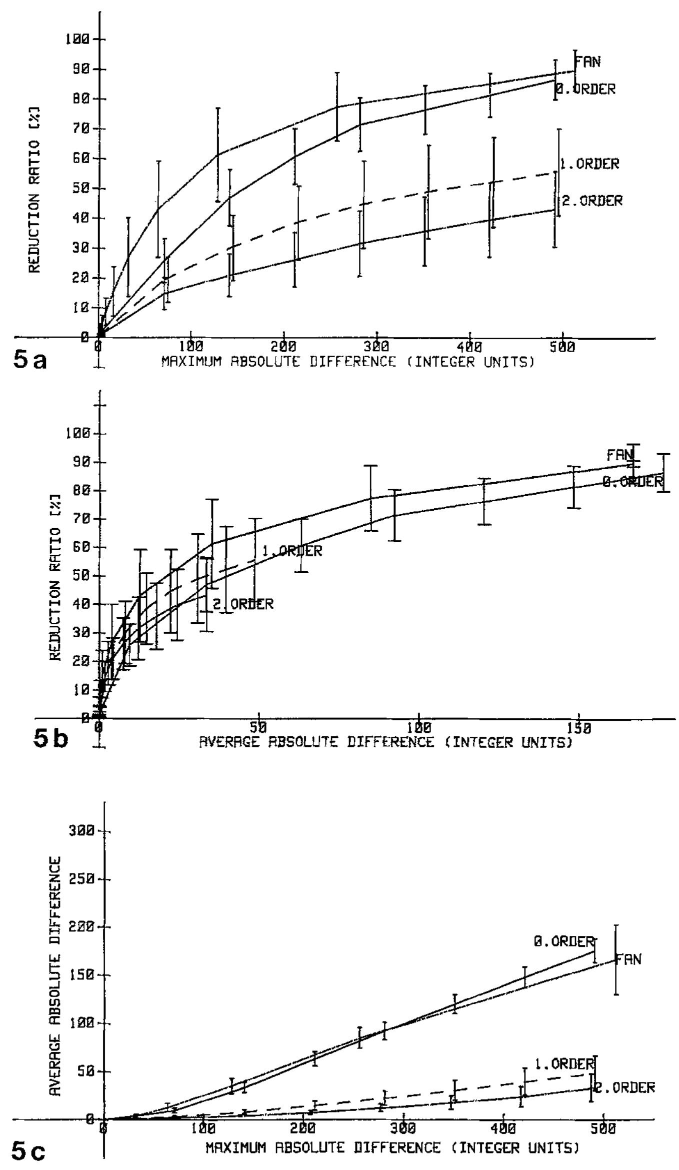

Fig. 5a–c Average of results from 18 EMG signals **a** Percentage reduction ratio as a function of maximum absolute difference between reconstructed and original EMG signals. **b** Percentage reduction ratio as a function of average absolute difference between reconstructed and original EMG signals. **c** Average absolute error as a function of maximum absolute difference between reconstructed and original EMG signals. *Error bars* are ± 1 SD

method seems to be superior to the others (Fig. 5a, b). The relation between the maximum and average absolute error is almost linear (Fig. 5c). As in the pressure signals, there is a large difference in this relation for the FAN and voltage triggered methods on the one hand, and the two point projection and second difference methods on the other.

Discussion

The behavior of the four techniques is different for different signals. It can be seen from Fig. 1a that the EMG signal is a rapidly changing signal with a high-frequency character, while the flow rate signal (Fig. 1c) often consists of a long period without any flow rate before micturition, during the filling phase of the cystometry procedure. During voiding the signal is normally smooth, without rapid changes. The pressure signal (Fig. 1b) has both characters. It is smooth sometimes with sudden variations, or may be unstable all the time, but the frequency content is much lower than that of the EMG. The results show similar behavior for EMG and pressure signals. For all signals tested the FAN and voltage triggered methods seem to be superior. For pressure signals the behavior of the FAN and voltage triggered method is almost identical but for EMG signals the FAN method performs slightly better. From Figs. 3c and 5c it is seen that there is almost a linear relationship between the maximum and average absolute error (for pressure and EMG signals). There is a large difference in this relation between the voltage triggered and FAN methods on the one hand and the two point projection and second difference methods on the other.

It is obvious that a different error distribution exists for maximum and average error. This is probably due to the fact the four methods act upon the signal in a different manner. The two point projection and second difference methods calculate and compare the slope of the signal and cause a higher maximum difference at the same average absolute difference compared with the voltage triggered and FAN methods. Using the four methods on pressure signals shows that at an error level of 16 integer units or 1.6 cmH_2O, which is suitable for urodynamics [6], a more than 80% reduction is achieved using the voltage triggered and FAN methods. The average absolute error at this error level is approximately 5 integer units or 0.5 cmH_2O (Fig. 3a–c). With this error level the signal can be reconstructed in great detail. With a greater maximum allowable error level the reduction rate could be further improved, but the average and maximum errors increase much faster than the percentage reduction. For EMG signals the results are similar to those for pressure signals but the FAN method seems to be superior to the voltage triggered method. At 80% reduction the maximum absolute error is approximately 300 integer units (90 mV) for the FAN method and approximately 400 integer units (120 mV) for the voltage triggered method. At these maximum errors the average absolute errors are approximately 100 integer units (30 mV) for the FAN method and 140 integer units (42 mV) for the voltage triggered method (Fig. 5a–c).

For uroflow signals a more than 90% reduction could be achieved using the FAN and voltage triggered methods, causing a maximum absolute difference of 2 integer units or 0.05 ml/s and an average absolute error of less than 1 integer unit or 0.025 ml/s (Fig. 4a–c). The signals reconstructed on the basis of the reduced data set stored in computer memory can be used for detailed analysis as they reconstruct the signal in great detail. It can be concluded that the data reduction methods described here are extremely suitable for uroflow data.

The results of the study are not in agreement with some other studies [2, 3]. It was shown on synthetic ECG signals that the two point projection method has advantages over the voltage triggered and second difference methods. It would be interesting to repeat the procedures by smoothing the data, because the signals we have used in the study contained additive noise. A drawback of all the methods is that the compressed data are no longer uniformly sampled. Therefore, information must be added to indicate the time of the sample.

For urodynamic signals, adaptive sampling can greatly reduce the storage requirements or the transmission rate over public telephone lines to a remote urodynamic center. In practice the algorithm should be integrated with the data acquisition procedure, so that compressed signals are stored directly.

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