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Challenges of ECG monitoring and ECG interpretation in dialysis units

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Abstract Patients on hemodialysis (HD) suffer from high cardiovascular morbidity and mortality due to high rates of coronary artery disease and arrhythmias. Electrocardiography (ECG) is often performed in the dialysis units as part of routine clinical assessment. However, fluid and electrolyte changes have been shown to affect all ECG morphologies and intervals. ECG interpretation thus depends on the time of the recording in relation to the HD session. In addition, arrhythmias during HD are common, and dialysis-related ECG artifacts mimicking arrhythmias have been reported. Studies using advanced ECG analyses have examined the impact of the HD procedure on selected repolarization descriptors and heart rate variability indices. Despite the challenges related to the impact of the fluctuant fluid and electrolyte status on conventional and advanced ECG parameters, further research in ECG monitoring during dialysis has the potential to provide clinically meaningful and practically useful information for diagnostic and risk stratification purposes.

Keywords: Dialysis; Electrocardiogram; QRS-T angle; Arrhythmias; Heart rate variability

Introduction

Decline in kidney function is associated with increased incidence and severity of coronary artery disease as well as ventricular and atrial arrhythmias [1]. Cardiovascular disease is highly prevalent in patients with end-stage renal disease treated with hemodialysis (HD) [2] contributing to very high mortality rates in these patients. Individuals receiving HD spend significant time of their life in hospital facilities attending HD treatment three times weekly. Standard electrocardiography (ECG) is often performed in the dialysis units as a part of initial clinical assessment due to a spectrum of symptoms related to the dialysis procedure; patients may present with fluid overload mimicking congestive heart failure or acute coronary syndrome, develop arrhythmias, or suffer from hypotension while at the dialysis units. In addition, standard ECG may be performed in the dialysis units for symptoms unrelated to the dialysis treatment simply because the unit is the first medical facility at which these patients seek medical attention because of the frequency of HD treatment. Furthermore, the potential use of the dialysis period for advanced ECG analyses for cardiac risk stratification purposes has also recently attracted interest. It is envisaged that this might minimize additional hospital visits and associated costs.

Dialysis-related fluid and electrolyte shifts

During HD treatment, blood flowing at a rate between 200 ml/min and 600 ml/min is exposed, through a semipermeable membrane, to a dialysate flowing to the opposite direction at a rate between 500 ml/min and 800 ml/min. The treatment is needed three times weekly with a usual duration that varies between different countries, ranging between 3.5 h per session in US and 4 h in Europe [3]. Water molecules and low molecular solutes including electrolytes that accumulated since the previous dialysis session are cleared by the process of diffusion, ultrafiltration, and convection. The HD process relies on the concentration gradient of low molecular weight solutes between the dialysate and the blood, the hydrostatic pressure gradient between the blood and the dialysate compartments as generated by a pump, the flows of the blood and the dialysate, the duration of the treatment, and the type of the membrane used. The attending nephrologist organizes the dialysis prescription based on regular monthly blood tests, body weights, and clinical examination for the assessment of the fluid status [3]. A usual dialysis solution contains potassium at 2.0 meq/L, sodium between 135 mEq/L and 140 mEq/L, calcium between 1.25 mmol/L and 1.5 mmol/L,

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magnesium between 0.25 meq/L and 1 meq/L, and bicarbonate as a buffer. Typically, potassium is removed from the blood to the dialysate by HD while the other electrolyte shifts may be bidirectional depending on the gradients between the blood and the dialysate. The required fluid removal is calculated based on the difference of the body weight at the beginning of the treatment to the so-called "target" weight at which the patient is euvolemic. This is clinically defined and set by the nephrologist. On average, dialysis patients gain about 10 kg of fluid weight per week, and the median fluid removal rate during dialysis is 10 ml/kg/h in US [3]. Fluid gains vary among different patients depending on compliance with fluid restriction and on residual urine output which, for the vast majority of patients, is less than 250 ml per day at the first year of HD [4].

Because of this intermittent alternate day treatment, dialysis patients exhibit tidal changes in their fluid and electrolyte status. Fluid and potassium mainly accumulate gradually from the end of the dialysis session to the beginning of the next session, followed by a rapid reduction during the four-hour treatment. These fluid and electrolyte changes have shown to affect the ECG wave amplitudes and ECG intervals. Consequently, ECG interpretation depends on the time of the recording acquisition in relation to the dialysis session.

Effects of fluid removal on the ECG waveforms

Augmentation at the end of dialysis of the P waves by a mean of 32% [5] to 40% [6] and of the QRS complexes by a mean of 22% [7] to 28% [6], calculated as the sum of P waves and QRS complexes from all 12 ECG leads has been reported. In addition, an increase in P wave duration in lead II by 2.6 ms and in the mean QRS duration from all ECG leads by 2.6 ms has been observed [6]. The underlying mechanism and its relation to fluid removal are a matter of debate. A relationship between blood volume reduction and augmentation of the QRS amplitude of the 12-lead ECG at the end of dialysis has been demonstrated [8], suggesting that water removal during HD may increase ECG voltage by changes in the conductivity of the transfer medium. This suggests predominantly impedance changes rather than factual electrophysiological alterations. It has also been suggested that the same effects on ECG amplitude due to water shifts may affect the QT patterns [9], resulting in the decrease in the measured QRS and QT duration before the dialysis due to a failure of an automatic ECG measurement algorithm. It has been speculated that this failure to properly detect Q onset and T offset is caused by their amplitude lowering due to fluid accumulation. On the contrary, fluid removal might contribute to QTc increase at the end of dialysis. Similar trends of QTc changes and fluid status characterized by QTc decrease with fluid retention and QTc increase after fluid removal were shown in non-dialysis patients with edema anasarca before and after diuretic treatment [9].

However, in HD patients, where electrolyte shifts affecting the QT occur simultaneously with fluid removal, the effect of the HD treatment on QTc may be variable [10,11]. Augmentation of the recorded voltages at the end of HD using vectorcardiography has also been reported by Vitolo et al. [12] who showed that vectorcardiographic parameters (R wave amplitude in X, Y and Z, Q wave amplitude in Z, maximal vector on frontal, sagittal and horizontal plane, and maximal spatial vector) increased at the end of the dialysis in 18 HD patients. They also reported that the changes in recorded voltages correlated with blood volume reduction during dialysis and that the vectorcardiographic loops appeared magnified but without distortion of the principal vectors at the end of HD. In contrast with the reported increase in P wave and QRS complex amplitudes, a decrease of the T wave amplitude has been reported after dialysis [11] likely because the intradialytic potassium T wave changes overwhelm the effects of fluid changes (Fig. 1).

Effect of electrolyte shifts on the ECG waveform

Electrolyte shifts during dialysis also affect ECG waveforms. Tezcan et al. [13] reported an intradialytic increase in P wave duration by 28% which was inversely associated with potassium and magnesium levels at the end of HD [13]. Szabo et al. [14] showed a 68% increase in P maximum at the end of dialysis which correlated inversely with potassium and positively with calcium. Berta et al. [15] reported increase in QRS duration at the end of HD associated with low potassium levels.

QTc duration at the end of dialysis has been shown to be affected by the concentration of potassium and calcium in the dialysate. Genovesi et al. [16] performed 24 Holter recordings in 16 HD patients using six randomized combinations of electrolytes concentrations of the dialysis bath. They reported that lower potassium and calcium dialysate concentrations were associated with QTc prolongation during the fourth hour of dialysis. Severi et al. [17] studied the QTc effects of different Ca and K dialysate concentrations both in 35 HD patients and by a computer model of human ventricular cardiomyocyte, showing an association between low calcium and potassium in the dialysate and prolonged QTc.

Arrhythmias during dialysis

Dialysis treatment also predisposes to arrhythmias. Studies with continuous Holter monitoring reported increased frequency of premature supraventricular and ventricular beats during HD [16,18,19]. Perhaps more importantly, recent evidence suggests that dialysis triggers the development of paroxysmal atrial fibrillation. Buiten et al. [20] analyzed the results of implantable cardioverter defibrillators (ICD) interrogations over 28 ± 16 months in 40 dialysis patients of the ICD 2 trial, a randomized controlled trial of prophylactic ICD for prevention of sudden cardiac death in dialysis patients. In this study, 14 out of the 40 patients were found to have at least one episode of AF. The AF onset was typically on the dialysis days, and the risk