SMJ- Sohag Medical Journal, Vol. 29 No (3) 2025

Print ISSN1687-8353 Online ISSN2682-4159

Original Article

# Hypertension and Blood Pressure Control in Hemodialysis Patients

Hagar AbdouMohamed,Hassan Ahmad Hassanien,
Alaa Ahmad Ghaleb, Ahmad Nagah Nour Eldin

*Department of Internal medicine, faculty of medicine , sohag university

## Abstract

Hypertension is one of the most prevalent and clinically significant comorbidities in patients with chronic kidney disease (CKD), particularly those undergoing hemodialysis (HD). The interplay between renal dysfunction, fluid overload, vascular remodeling, and neurohormonal dysregulation renders blood pressure (BP) control a complex challenge in this high-risk population. Despite advances in dialysis techniques and pharmacological therapy, approximately 60–80% of HD patients continue to experience hypertension, which is strongly associated with left ventricular hypertrophy (LVH), accelerated cardiovascular morbidity, and premature mortality.

This review synthesizes current evidence on the pathophysiology of hypertension in CKD and hemodialysis, highlighting the roles of the renin–angiotensin–aldosterone system (RAAS), sympathetic overactivity, oxidative stress, and arterial stiffness. Epidemiological data on the global prevalence of hypertension in HD patients are discussed, alongside the clinical consequences of uncontrolled BP, including glomerular injury, residual kidney function decline, and cerebrovascular disease. Challenges to optimal BP control are outlined, with emphasis on intradialytic BP fluctuations, fluid overload, and medication–dialysis interactions.

Management strategies are explored in depth, spanning fluid balance optimization, dialysis prescription modifications, lifestyle interventions, and pharmacotherapy with renin–angiotensin system inhibitors, calcium channel blockers, beta-blockers, and mineralocorticoid receptor antagonists. Finally, we examine the outcomes of effective BP control, including reductions in LVH, stroke incidence, and all-cause mortality, while emphasizing research gaps such as individualized BP targets, biomarker-guided therapy, and the role of novel agents.

Given the profound impact of hypertension on survival and quality of life in HD patients, a multidisciplinary approach integrating nephrology, cardiology, and patient-centered care is essential. Future research should focus on precision medicine and innovative dialysis techniques to optimize BP control and improve long-term outcomes.

**Keywords:** Hypertension, Hemodialysis, Chronic Kidney Disease, Blood Pressure Control, Cardiovascular Risk

**DOI :** 10.21608/SMJ.2025.417515.1609 **Received:** July 25 , 2025 **Accepted:** September 22 , 2025

**Published:** September 30, 2025

**Corresponding Author:** Hagar Abdou Mohamed **E-mail**: hagarabdo13995@gmail.com

**Citation**: Hagar Abdou Mohamed . et al., Hypertension and Blood Pressure Control in Hemodialysis Patients SMJ,2025 Vol. 29 No (3) 2025 178 - 196

# 1. Introduction

Chronic kidney disease (CKD) represents a major public health burden, affecting approximately 10–15% of adults worldwide, with prevalence steadily rising due to the global epidemics of diabetes and hypertension.[1] Among patients with advanced CKD requiring renal replacement therapy, hemodialysis (HD) remains the most common modality, sustaining millions of individuals with end-stage renal disease (ESRD). However, despite its life-saving role, HD is accompanied by significant morbidity and mortality, largely driven by cardiovascular disease. [2]

Hypertension is one of the most prevalent comorbidities in patients with ESRD, with estimates suggesting that 60–80% of individuals undergoing HD have persistently elevated blood pressure (BP). [3,4] The relationship between CKD and hypertension is bidirectional: hypertension contributes to both the initiation and progression of renal impairment, while the loss of renal function exacerbates sodium and fluid retention, neurohormonal activation, and vascular dysfunction, perpetuating BP elevation. [5,6]In dialysis patients, this interplay creates a unique and challenging clinical scenario in which BP control is not only difficult to achieve but is also critical for reducing adverse outcomes.

Uncontrolled BP in HD patients is strongly associated with left ventricular hypertrophy (LVH), ischemic heart disease, stroke, and heart failure, making hypertension one of the leading contributors to premature cardiovascular mortality in this group. [7,8] Moreover, hypertension accelerates the decline of residual kidney function, impairs dialysis efficiency, and worsens patient-reported outcomes such as fatigue, quality of life, and functional status .[9] These complications highlight the importance of achieving effective BP control as a cornerstone of dialysis care.

Despite its importance, optimal BP management in HD patients remains elusive. The complex interplay of pathophysiological mechanisms—including renin–angiotensin–aldosterone system (RAAS) activation, sympathetic overactivity, endothelial dysfunction, and arterial stiffness—makes hypertension in ESRD more resistant to treatment compared to the general population. [10] In addition, dialysis-related factors such as fluid overload, intradialytic hemodynamic shifts, and electrolyte imbalances further complicate BP control .[11] Traditional pharmacotherapy is often insufficient or limited by adverse effects, drug–dialysis interactions, and polypharmacy .[12] Furthermore, controversies persist regarding the definition of hypertension and the optimal BP targets in HD patients, with both overly aggressive and inadequate BP control linked to adverse outcomes .[13]

Over the past two decades, increasing attention has been devoted to understanding the mechanisms and management of hypertension in HD. Non-pharmacological approaches such as optimization of dry weight, sodium restriction, and dialysis prescription adjustments are now recognized as essential elements of therapy .[14] Pharmacological treatment remains central, with accumulating evidence suporting the use of renin–angiotensin system inhibitors, calcium channel blockers, beta-blockers, and mineralocorticoid receptor antagonists in specific contexts. [15,16]

The purpose of this review is to synthesize the available evidence on hypertension in HD patients. Specifically, we will.[1] explore the pathophysiological mechanisms linking CKD, dialysis, and hypertension;[2] summarize epidemiological data on the prevalence and risk factors of hypertension in HD; [3] review the clinical impact of inadequate BP control;[4] outline the challenges faced in managing hypertension during dialysis;[5] evaluate available management strategies, including pharmacological, non-pharmacological, and dialysis-related interventions; and.[6] highlight the outcomes of effective BP control alongside gaps and future directions in research.

## 2. Pathophysiology of Hypertension in CKD and Hemodialysis

Hypertension in patients with chronic kidney disease (CKD) and end-stage renal disease (ESRD) undergoing hemodialysis (HD) is multifactorial, reflecting a complex interplay of renal, vascular, and neurohormonal abnormalities. The loss of kidney function leads to profound dysregulation of fluid balance, sodium handling, and vascular tone, all of which contribute to persistently elevated blood pressure (BP). [17] Moreover, hemodialysis

itself introduces unique hemodynamic stressors that exacerbate BP fluctuations. [18]

### 2.1 Sodium and Fluid Retention

One of the most fundamental mechanisms underlying hypertension in CKD is impaired renal sodium excretion. As glomerular filtration rate (GFR) declines, the kidneys lose their ability to adequately eliminate sodium, leading to volume expansion and hypervolemia. [19] Fluid overload directly increases cardiac output and vascular resistance, raising BP. In HD patients, failure to achieve the patient's "dry weight" results in chronic extracellular fluid overload, which is strongly associated with pre-dialysis hypertension. [20] Between dialysis sessions, fluid accumulation further compounds BP elevation, while aggressive ultrafiltration during HD can cause hypotension, contributing to significant intradialytic BP variability. [21]

### 2.2 Activation of the Renin–Angiotensin–Aldosterone System (RAAS)

The renin–angiotensin–aldosterone system (RAAS) plays a central role in the pathophysiology of hypertension in CKD. Reduced renal perfusion stimulates renin release, leading to increased production of angiotensin II, a potent vasoconstrictor, and aldosterone, which promotes sodium and water retention. [22] In CKD and ESRD, RAAS activation is often exaggerated, resulting in sustained vasoconstriction, increased vascular stiffness, and persistent hypertension. [23] Elevated angiotensin II levels also contribute to myocardial hypertrophy and vascular remodeling, amplifying cardiovascular risk. [24]

### 2.3 Sympathetic Nervous System Overactivity

Sympathetic nervous system (SNS) overactivity is another hallmark of hypertension in CKD and HD patients. Reduced renal function is associated with increased afferent signaling from ischemic kidneys, leading to heightened sympathetic outflow. [25] SNS overactivity increases heart rate, cardiac output, and systemic vascular resistance, all of which contribute to elevated BP. In HD patients, sympathetic activation is further aggravated by vascular access, fluid overload, and recurrent hemodynamic instability. [26] Persistent SNS overdrive not only sustains hypertension but also increases the risk of arrhythmias and sudden cardiac death, which are leading causes of mortality in dialysis patients. [27]

### 2.4 Endothelial Dysfunction

Endothelial dysfunction plays a key role in the vascular pathology of CKD-associated hypertension. Healthy endothelium produces nitric oxide (NO), a vasodilator that helps regulate vascular tone. In CKD, oxidative stress and chronic inflammation impair NO synthesis and bioavailability, leading to reduced vasodilation and heightened vascular resistance .[28] Hemodialysis exacerbates this dysfunction through repeated exposure to bioincompatible dialysis membranes and systemic inflammation .[29] The resulting endothelial injury contributes to vascular stiffness, a common feature in ESRD patients with isolated systolic hypertension .[30]

### 2.5 Vascular Remodeling and Arterial Stiffness

Chronic hypertension induces structural vascular changes, including medial hypertrophy, fibrosis, and calcification of arteries. [31] These changes lead to arterial stiffness, which increases systolic BP and pulse pressure, further burdening the heart and kidneys. [32] In HD patients, vascular calcification is accelerated by disturbances in calcium–phosphate metabolism and chronic exposure to high BP [33]. Arterial stiffness impairs renal autoregulation, exacerbates glomerular injury, and perpetuates a cycle of worsening hypertension and renal damage [34].

### 2.6 Inflammation and Oxidative Stress

Patients with CKD and ESRD experience a chronic pro-inflammatory state characterized by elevated cytokines such as tumor necrosis factor-α (TNF-α) and interleukin-6 (IL-6). [35] These mediators promote vascular injury, fibrosis, and endothelial dysfunction, which contribute to hypertension. In addition, increased production of reactive oxygen species (ROS) in CKD leads to oxidative stress, further impairing endothelial function and promoting vascular remodeling [36]. The combined effects of inflammation and oxidative stress are particularly relevant in HD patients, where repeated exposure to dialysis-induced stressors amplifies systemic inflammation .[37]

### 2.7 Dialysis-Related Hemodynamic Factors

Beyond intrinsic CKD mechanisms, the dialysis procedure itself introduces additional contributors to BP instability. Rapid ultrafiltration can cause intradialytic hypotension, while inadequate fluid removal predisposes to post-dialysis hypertension. [38] Dialysate sodium concentration also influences BP: higher concentrations promote sodium retention and hypertension, while lower levels may cause intradialytic hypotension. [39] Electrolyte shifts, particularly in potassium and calcium, further impact vascular tone and cardiac function, complicating BP regulation. [40]

## 3. Epidemiology and Prevalence of Hypertension in Hemodialysis

Hypertension is highly prevalent among patients receiving hemodialysis (HD) and represents one of the most important risk factors for cardiovascular morbidity and mortality in this group. Despite advances in dialysis technology and antihypertensive therapy, blood pressure (BP) control remains suboptimal for a large proportion of patients. [41]

### 3.1 Prevalence of Hypertension in the Hemodialysis Population

It is estimated that **60–80% of patients undergoing HD have hypertension**, making it one of the most frequent comorbidities in this population. [42,43] Large observational studies consistently confirm this high prevalence, with some reporting that up to 90% of HD patients experience elevated BP at some point during their treatment. [44] Hypertension in this setting is often multifactorial, related to fluid overload, arterial stiffness, sympathetic overactivity, and the activation of the renin–angiotensin–aldosterone system (RAAS). [45]

The prevalence may vary depending on the criteria used for diagnosis (pre-dialysis BP, post-dialysis BP, ambulatory BP monitoring) and the population studied. For example, in a multicenter European study, approximately 70% of HD patients had uncontrolled hypertension based on pre-dialysis BP values[46]. Similarly, a retrospective single-center study in the United States found that only about one-third of HD patients achieved recommended BP targets despite being on multiple antihypertensive agents. [47]

### 3.2 Risk Factors and Determinants

Several factors contribute to the disproportionately high prevalence of hypertension in HD patients:

- **Fluid overload:** Inadequate ultrafiltration and excess interdialytic weight gain strongly correlate with pre-dialysis hypertension. [48]
- **Vascular changes:** Arterial stiffness and vascular calcification, common in ESRD, lead to isolated systolic hypertension, particularly in older patients. [49]
- **Dialysis-related factors:** High dialysate sodium concentrations, rapid fluid shifts, and suboptimal dialysis prescriptions contribute to persistent hypertension. [50]
- **Pharmacological influences:** Use of erythropoiesis-stimulating agents (ESAs) for anemia management, calcium-containing phosphate binders, and polypharmacy can increase BP. [51]
- **Autonomic and neurohormonal dysregulation:** Enhanced sympathetic activity and overactivation of RAAS are frequent in dialysis patients and drive resistant hypertension. [52]

### 3.3 Pre- and Post-Dialysis Hypertension

Hypertension in HD patients is often classified according to whether it occurs before or after dialysis:

- **Pre-dialysis hypertension** is strongly associated with volume overload and is the most common form observed in routine practice. [53]
- **Post-dialysis hypertension**, defined as persistent BP elevation despite ultrafiltration, may indicate underdialysis, endothelial dysfunction, or excessive sympathetic activation .[54]

Studies have shown that increased post-dialysis systolic BP is associated with extracellular overhydration, and such patients often have higher risks of cardiovascular events. [55] In some cases, paradoxical intradialytic hypertension occurs, where BP rises during the dialysis session; this phenomenon, though less common, is associated with poor outcomes and increased hospitalization rates. [56]

### 3.4 Patterns of Hypertension in Hemodialysis

Ambulatory and interdialytic BP monitoring studies have revealed that conventional pre- and post-

dialysis BP measurements may underestimate the true burden of hypertension in HD patients. Interdialytic BP, measured at home or via 44-hour ambulatory BP monitoring, often shows higher prevalence rates of uncontrolled hypertension compared to in-unit measurements .[57]
Common patterns include:

- **Sustained hypertension:** Persistently elevated BP before, during, and after dialysis, often linked to fluid overload and RAAS activation .[58]
- **Isolated systolic hypertension:** Driven primarily by arterial stiffness and vascular calcification, common in elderly HD patients. [59]
- **Resistant hypertension:** Defined as uncontrolled BP despite the use of three or more antihypertensive medications, reported in up to 25% of HD patients. [60]

### 3.5 Global and Regional Variations

The prevalence and control rates of hypertension in HD patients vary worldwide. For example:

- In European cohorts, uncontrolled hypertension rates range between 60% and 70%. [61]
- In North America, up to 75% of HD patients fail to meet target BP levels despite polypharmacy. [47]
- In Middle Eastern and Asian populations, prevalence rates of 70–80% have been reported, with fluid overload and poor adherence to dietary sodium restrictions as major contributors. [62]

## 4. Clinical Impact of Hypertension in Hemodialysis

Hypertension is not only highly prevalent among patients undergoing hemodialysis (HD), but it also contributes significantly to morbidity, mortality, and reduced quality of life. The consequences extend beyond elevated blood pressure (BP) readings, as hypertension accelerates both renal and cardiovascular injury, promotes systemic inflammation, and complicates dialysis treatment itself. [63]

### 4.1 Glomerular Injury and Proteinuria

Sustained hypertension exerts mechanical stress on the glomeruli, leading to hyperfiltration, endothelial injury, and glomerulosclerosis. [64] Elevated intraglomerular pressure causes structural damage and scarring, ultimately impairing filtration capacity. One hallmark of glomerular injury is proteinuria, which not only reflects renal damage but also promotes further nephron loss in a vicious cycle. [65] In HD patients, uncontrolled BP accelerates the decline of residual kidney function, which is crucial for fluid and solute clearance and is strongly associated with improved survival. [66]

### 4.2 Tubulointerstitial Injury

Beyond glomerular damage, hypertension also contributes to **tubulointerstitial fibrosis**, characterized by ischemia of renal tubules and inflammatory cytokine release .[67]This process leads to loss of functional nephrons and worsens the progression of kidney disease. In patients with ESRD on HD, tubulointerstitial damage is already extensive; however, hypertension accelerates this injury and further reduces residual kidney function, complicating fluid and BP management. [68]

### 4.3 Arterial Stiffness and Impaired Renal Perfusion

Chronic hypertension leads to vascular remodeling, medial hypertrophy, and arterial stiffness. [69] In the kidneys, this reduces the autoregulatory ability of afferent arterioles, thereby impairing renal perfusion and contributing to ischemic nephropathy. [70] In HD patients, arterial stiffness is common and strongly associated with isolated systolic hypertension, which is difficult to manage with standard therapy. [71]

### 4.4 Left Ventricular Hypertrophy and Cardiac Complications

One of the most critical consequences of hypertension in HD patients is left ventricular hypertrophy (LVH). LVH develops as a compensatory response to chronic pressure overload, leading to myocardial thickening, reduced compliance, and diastolic dysfunction. [72] In the HD population, the prevalence of LVH exceeds 70% and is a powerful predictor of adverse outcomes including arrhythmias, sudden cardiac death, and heart failure .[73]

Uncontrolled BP further increases the risk of coronary artery disease (CAD), myocardial infarction, and cerebrovascular events. The combination of CKD-associated vascular calcification and hypertension creates a synergistic risk profile, making cardiovascular disease the leading cause of mortality in HD patients. [74]

### 4.5 Stroke and Cerebrovascular Events

HD patients with poorly controlled hypertension are at significantly increased risk of ischemic and hemorrhagic stroke .[75] Arterial stiffness, vascular calcification, and endothelial dysfunction exacerbate cerebral vascular injury. Studies indicate that each 10 mmHg rise in systolic BP increases stroke risk by up to 20% in this population .[76] Moreover, fluctuations between interdialytic hypertension and intradialytic hypotension contribute to impaired cerebral perfusion, further elevating stroke risk. [77]

### 4.6 Systemic Inflammation and Oxidative Stress

Hypertension itself is a pro-inflammatory condition, and in CKD/HD patients, it amplifies systemic inflammation through cytokines such as **TNF-α** and **IL-6.** [78] In parallel, increased production of reactive oxygen species (ROS) contributes to endothelial dysfunction and vascular remodeling. [79] The combined effects of inflammation and oxidative stress accelerate cardiovascular injury and worsen BP control.

### 4.7 Decline in Residual Kidney Function

Residual kidney function (RKF) is an important determinant of survival and quality of life in HD patients, as it contributes to fluid balance, phosphorus excretion, and toxin clearance. [80] Hypertension accelerates the decline of RKF by promoting glomerulosclerosis, interstitial fibrosis, and ischemia. [81] The loss of RKF worsens BP control, since ultrafiltration during dialysis becomes the sole means of fluid removal, perpetuating a cycle of hypertension and renal decline. [82]

### 4.8 Mortality and Long-Term Outcomes

The cumulative effects of hypertension—LVH, stroke, arterial stiffness, and renal decline—translate into markedly increased mortality risk. Cardiovascular disease accounts for over 50% of deaths in HD patients, with uncontrolled hypertension being a major modifiable contributor. [83] Mortality rates are significantly higher in HD patients with systolic BP above 160 mmHg, whereas effective BP control is associated with reductions in both cardiovascular and all-cause mortality .[84]

## 5. Challenges in Blood Pressure Control During Hemodialysis

Achieving optimal blood pressure (BP) control in patients on hemodialysis (HD) is uniquely challenging due to the interplay of pathophysiological, dialysis-related, and pharmacological factors. Unlike the general hypertensive population, HD patients experience frequent BP fluctuations, ranging from severe pre-dialysis hypertension to intradialytic hypotension, complicating long-term management. [85] The following subsections highlight the major challenges contributing to poor BP control in this population.

### 5.1 Fluid Shifts and Hemodynamic Instability

Fluid overload is one of the principal drivers of hypertension in HD patients. Between sessions, patients accumulate extracellular fluid due to impaired renal excretion, resulting in pre-dialysis hypertension. [86] During dialysis, ultrafiltration removes this excess fluid; however, when fluid is removed too aggressively, patients are prone to intradialytic hypotension (IDH), which occurs in up to 30% of HD sessions. [87]

This dynamic creates a paradox: insufficient fluid removal perpetuates hypertension, while rapid removal increases the risk of hypotension, cramping, and organ hypoperfusion. [88] Additionally, intradialytic hypotension is associated with myocardial ischemia, cerebral hypoperfusion, and accelerated loss of residual kidney function. [89] Thus, balancing fluid management remains one of the most difficult aspects of BP control in HD.

### 5.2 Vascular Access and Hemodynamic Effects

Vascular access, essential for HD, also influences BP regulation. Arteriovenous fistulas (AVFs), the preferred form of access, can lead to increased cardiac output and altered hemodynamics, occasionally contributing to hypertension .[90]

Conversely, central venous catheters are linked with inflammation and sympathetic activation, which also affect BP. [91]

Furthermore, long-term vascular changes, including calcification and arterial stiffness, increase systolic BP and pulse pressure, further complicating BP stability during HD. [92] These alterations highlight the interplay between dialysis access and systemic hemodynamics.

### 5.3 Electrolyte Imbalances and Dialysate Composition

Electrolyte shifts during HD profoundly affect vascular tone and BP regulation.

- **Sodium:** High dialysate sodium concentrations promote sodium retention, fluid overload, and sustained hypertension. Conversely, low sodium concentrations increase the risk of intradialytic hypotension .[93]
- **Potassium:** Both hyperkalemia and hypokalemia alter vascular tone and cardiac conduction, predisposing patients to BP instability and arrhythmias.[94]
- **Calcium and phosphorus:** Disturbances in calcium-phosphate metabolism accelerate vascular calcification and arterial stiffness, worsening systolic hypertension. [95]

### 5.4 Autonomic Dysfunction and Sympathetic Overactivity

Patients with ESRD frequently exhibit autonomic dysfunction, including impaired baroreceptor sensitivity and blunted vascular responses, which contribute to poor BP regulation. [96] At the same time, sympathetic nervous system (SNS) overactivity is highly prevalent, leading to increased heart rate, systemic vasoconstriction, and elevated BP. [97]

These abnormalities predispose patients to intradialytic hypertension, defined as paradoxical BP elevation during dialysis sessions, which has been linked to higher hospitalization and mortality rates. [98] Sympathetic overactivity also contributes to arrhythmogenesis, further compounding cardiovascular risk. [99]

### 5.5 Polypharmacy and Drug–Dialysis Interactions

Most HD patients take multiple medications to manage hypertension, anemia, mineral bone disease, and other comorbidities. Polypharmacy increases the risk of drug–drug interactions, poor adherence, and altered pharmacokinetics. [100]

In addition, several antihypertensives—particularly water-soluble beta-blockers (e.g., atenolol, metoprolol)—are dialyzable, resulting in reduced efficacy post-dialysis and variable BP control. [101]

Other agents, such as RAAS inhibitors, carry a risk of hyperkalemia, which is especially dangerous in ESRD. [102] The need for frequent dose adjustments and the lack of evidence-based guidelines on drug timing relative to dialysis sessions further complicate pharmacotherapy in HD patients .[103]

### 5.6 Individual Variability and BP Target Controversies

Another challenge in managing hypertension during HD is the lack of consensus on optimal BP targets. Some studies suggest that lower pre-dialysis systolic BP (<140 mmHg) improves outcomes, while others show a J-shaped relationship, with excessively low BP linked to higher mortality. [104]

Moreover, measurement variability contributes to diagnostic uncertainty. Routine pre- and post-dialysis BP measurements often fail to capture true interdialytic hypertension, which can only be accurately assessed with ambulatory or home BP monitoring. [105] This complicates both the diagnosis and treatment of hypertension in HD patients.

## 6. Management Strategies

Managing hypertension in hemodialysis (HD) patients requires a comprehensive and individualized approach that addresses both the underlying pathophysiological mechanisms and the unique challenges associated with dialysis treatment. Strategies are generally divided into non-pharmacological measures, pharmacological therapy, and dialysis-based interventions, though in practice, an integrated approach is essential. [106]

Non-pharmacological strategies are the cornerstone of hypertension management in HD. Optimizing fluid balance is perhaps the most critical intervention. The concept of “dry weight,” defined as the lowest post-dialysis weight at which the patient remains normotensive and free of fluid overload, is central to BP control .[107] Failure to

achieve dry weight leads to chronic extracellular fluid expansion and persistent hypertension, while aggressive ultrafiltration carries the risk of intradialytic hypotension and ischemia. [108] Careful clinical evaluation, along with adjunctive tools such as bioimpedance spectroscopy, is often required to accurately estimate dry weight. [109] In some cases, increasing dialysis frequency, such as nocturnal or daily sessions, can provide more gradual fluid removal and better BP control. [110] Maintaining ultrafiltration rates below 10–13 mL/kg/h is also crucial, as higher rates are associated with cardiovascular instability and increased mortality .[111]

Sodium restriction is another essential non-pharmacological measure. High sodium intake exacerbates thirst, fluid retention, and interdialytic weight gain, leading to sustained hypertension. [112] Most guidelines recommend limiting sodium intake to less than 2 g/day (equivalent to about 5 g of salt). [113] However, patient adherence remains a challenge, particularly due to the widespread consumption of processed foods. Dietary counseling and individualized nutrition plans can significantly improve compliance and outcomes. [114] Lifestyle interventions such as weight management and exercise also contribute to BP control. Although obesity is prevalent in HD patients and is associated with higher cardiovascular risk, intentional weight reduction must be approached cautiously to avoid protein-energy malnutrition. [115] Structured exercise programs, including intradialytic cycling and resistance training, have shown beneficial effects on BP regulation, cardiovascular fitness, and overall quality of life in dialysis patients. [116]

Despite the importance of lifestyle measures, most HD patients require pharmacological therapy to achieve adequate BP control. Renin–angiotensin–aldosterone system (RAAS) inhibitors, including angiotensin-converting enzyme inhibitors (ACEIs) and angiotensin receptor blockers (ARBs), are commonly prescribed due to their ability to lower BP, reduce left ventricular hypertrophy (LVH), and provide vascular protection .[118,119] Evidence suggests that ARB therapy reduces cardiovascular mortality in HD patients by up to 50% compared to standard treatment .[120] However, the risk of hyperkalemia, especially in patients with residual kidney function, necessitates close monitoring. [121] ARBs are often favored over ACEIs in dialysis patients, as they are less likely to cause cough and are less dialyzable, providing more consistent BP control .[122]

Calcium channel blockers (CCBs), particularly dihydropyridines such as amlodipine, are effective agents for managing systolic hypertension, which is common in HD due to arterial stiffness. [123] They act by promoting vasodilation and improving vascular compliance, and randomized trials have demonstrated reductions in cardiovascular mortality and ischemic events in patients treated with amlodipine. [124,125] While peripheral edema is a frequent side effect, this can often be managed through optimized ultrafiltration. [126] Beta-blockers are another important option, especially for HD patients with LVH, coronary artery disease, or arrhythmias .[127] They mitigate sympathetic overactivity, reduce myocardial oxygen demand, and lower arrhythmia risk. [128] However, their efficacy depends on dialyzability: water-soluble beta-blockers such as atenolol and metoprolol are easily removed during dialysis, while lipophilic agents like carvedilol remain in circulation. [129] Observational studies suggest that cardioselective beta-blockers confer greater survival benefits than non-selective agents. [130], though intradialytic hypotension is a concern, particularly with carvedilol. [131]

Diuretics are generally less effective in ESRD due to the loss of renal function, but they retain value in patients with preserved urine output. Loop diuretics such as furosemide can reduce interdialytic fluid gain and help preserve residual renal function. [132,133] Mineralocorticoid receptor antagonists (MRAs), particularly spironolactone, were once avoided due to hyperkalemia risk, but recent evidence indicates that low-dose spironolactone significantly reduces cardiovascular mortality and LVH in HD patients without causing dangerous potassium elevations when carefully monitored. [134,135] Large-scale trials such as ALCHEMIST and ACHIEVE are currently investigating the safety and long-term benefits of MRAs in this population. [136] Other agents, including clonidine, hydralazine, and minoxidil, may be used in resistant hypertension,

but their side effect profiles and risks of intradialytic BP fluctuations limit routine use. [137–139]

Dialysis-related modifications also play a crucial role in BP management. Dialysate sodium concentration directly affects fluid balance and BP. High sodium dialysate promotes fluid overload and hypertension, whereas low sodium dialysate reduces interdialytic weight gain but increases the risk of intradialytic hypotension [93]. Sodium profiling, in which sodium concentration is gradually decreased during dialysis, offers a compromise by minimizing both hypertension and hypotension episodes. [140,141]

Increasing dialysis frequency or duration, such as with daily or nocturnal HD, has also been shown to improve BP stability and reduce antihypertensive medication requirements. [142,143] Additionally, hemodiafiltration (HDF), which enhances solute and fluid removal, may provide better BP control compared to conventional HD in some patients. [144]

## 7. Outcomes of Blood Pressure Control in Hemodialysis Patients

Effective blood pressure (BP) control in patients undergoing hemodialysis (HD) is associated with significant clinical benefits, including improved cardiovascular health, preservation of residual kidney function, enhanced dialysis efficiency, better quality of life, and reduced mortality. Conversely, uncontrolled hypertension remains one of the strongest predictors of adverse outcomes in this high-risk population. [146]

Cardiovascular disease is the leading cause of death in HD patients, and hypertension is a major driver of this burden. [147] One of the most important benefits of adequate BP control is the reduction in left ventricular hypertrophy (LVH). Sustained hypertension and fluid overload place a chronic pressure burden on the myocardium, leading to ventricular thickening, diastolic dysfunction, and increased risk of heart failure. [148] Several studies demonstrate that lowering BP can reverse or reduce LVH, which translates into improved cardiac performance and survival. [149] Beyond LVH, adequate BP control also reduces the risk of coronary artery disease, arrhythmias, and cerebrovascular events such as ischemic and hemorrhagic stroke. [150] Each 10 mmHg increase in systolic BP has been associated with a markedly higher risk of cardiovascular complications in dialysis patients, underscoring the importance of sustained BP management. [151]

Stroke prevention represents another major outcome of BP control. HD patients with uncontrolled hypertension experience higher rates of both ischemic and hemorrhagic stroke due to a combination of arterial stiffness, vascular calcification, and endothelial dysfunction. [152] By lowering BP, the risk of cerebrovascular events is substantially reduced. Studies suggest that patients with controlled systolic BP not only have fewer strokes but also experience improved cerebral perfusion and cognitive outcomes. [153]

In addition to cardiovascular protection, BP control helps preserve residual kidney function (RKF), which is an important determinant of survival in dialysis patients. RKF contributes to solute clearance, fluid balance, and phosphorus regulation, and patients who retain some kidney function generally experience fewer complications and better outcomes .[154] Hypertension accelerates the loss of RKF by promoting glomerulosclerosis, ischemia, and tubulointerstitial fibrosis, whereas effective BP management slows this decline. [155] Preserving RKF reduces the intensity of ultrafiltration required during dialysis sessions, further stabilizing BP and decreasing the risk of intradialytic complications. [156]

Another outcome of effective BP management is improved dialysis efficiency. Uncontrolled hypertension and fluid overload complicate ultrafiltration and reduce dialysis adequacy by increasing hemodynamic instability .[157] Conversely, stable BP during and between sessions enhances ultrafiltration, solute clearance, and overall treatment effectiveness. Patients with well-controlled BP often report fewer symptoms during dialysis, such as cramping, dizziness, and fatigue .[158]

Quality of life (QoL) is also strongly influenced by hypertension control. Elevated BP is associated with symptoms including headaches, lethargy, and dizziness, all of which impair daily functioning. [159] Furthermore, hypertension exacerbates cardiovascular complications that limit physical activity and increase hospitalization rates. Studies have shown that patients with well-controlled BP

experience less fatigue, better functional status, and fewer hospital admissions. [160]Reductions in hospitalization not only improve patient QoL but also decrease healthcare costs, an important consideration in managing the global burden of dialysis care. [161]

Perhaps most importantly, effective BP control reduces **mortality** in HD patients. Observational studies consistently demonstrate that patients with systolic BP maintained below 140 mmHg have significantly lower risks of cardiovascular and all-cause death compared to those with uncontrolled hypertension. [162] Importantly, there appears to be a U-shaped or J-shaped association, with both uncontrolled hypertension and excessively low BP linked to higher mortality. This suggests that individualized BP targets are necessary in dialysis patients, rather than universal thresholds. [163] Long-term survival benefits are most pronounced when both systolic and diastolic pressures are maintained within recommended ranges. [164]

Despite the benefits of hypertension control, multiple barriers remain, including poor medication adherence, dialysis-related BP fluctuations, and comorbidities such as diabetes and heart failure. [165] Overcoming these barriers requires a multifaceted approach that combines optimized dialysis prescriptions, pharmacological therapy, lifestyle modifications, and multidisciplinary care.

## 8. Future Directions and Research Gaps

Despite advances in understanding and managing hypertension in hemodialysis (HD) patients, several gaps remain in both research and clinical practice. The high prevalence of uncontrolled blood pressure (BP), coupled with the persistent burden of cardiovascular morbidity and mortality, underscores the urgent need for novel approaches and precision strategies. [167]

One of the foremost challenges is the lack of universally accepted BP targets for patients on dialysis. While most guidelines recommend maintaining pre-dialysis systolic BP below 140 mmHg, observational data suggest a U- or J-shaped relationship between BP and mortality, where excessively low BP may be as harmful as uncontrolled hypertension. [168] This indicates that rigid thresholds may not be appropriate for all patients, and individualized targets based on age, comorbidities, and residual kidney function may provide better outcomes .[169]

Another key area is the need for improved BP monitoring techniques. Routine pre- and post-dialysis measurements often fail to reflect the true interdialytic BP load, which is more strongly associated with cardiovascular outcomes .[170] Ambulatory BP monitoring (ABPM) and home BP monitoring are increasingly recognized as more accurate methods, but their adoption remains limited due to cost, accessibility, and patient adherence. [171] Future research should explore wearable technologies and digital health platforms that enable continuous BP monitoring, offering real-time data to guide therapy adjustments. [172]

In terms of pharmacological therapy, the evidence base for antihypertensive drug use in HD remains limited compared to the general population. Many landmark hypertension trials excluded patients with advanced CKD or dialysis dependence, leaving uncertainty about the efficacy and safety of commonly used agents. [173] Future studies should focus on head-to-head comparisons of drug classes, optimal timing of administration relative to dialysis, and the role of combination therapy in resistant hypertension. [174] Furthermore, emerging therapies such as novel mineralocorticoid receptor antagonists (MRAs) and non-steroidal agents may hold promise for reducing cardiovascular risk while minimizing hyperkalemia. [175]

Beyond pharmacology, dialysis prescription innovations represent an area of growing interest. Modifying dialysate sodium concentration, personalizing ultrafiltration profiles, and adopting hemodiafiltration (HDF) or more frequent dialysis sessions have all demonstrated benefits in small studies, but larger trials are needed to confirm their impact on long-term BP control and survival. [176] Personalized dialysis prescriptions that integrate fluid balance, electrolyte management, and BP control may provide superior outcomes compared to standard “one-size-fits-all” approaches.

Emerging fields such as precision medicine and biomarker-guided therapy may also play a pivotal role in future hypertension management. Identifying biomarkers of sympathetic overactivity, endothelial dysfunction, or vascular calcification could help

stratify patients at greatest risk and guide targeted interventions. [177]Genomic and pharmacogenomic approaches may further refine antihypertensive therapy by predicting drug response and adverse effects in individual patients. [178]

## 9. Conclusion

Hypertension is a common and serious complication in hemodialysis patients, impacting cardiovascular health, dialysis efficacy, and survival. It results from a complex mix of fluid overload, neurohormonal changes, vascular remodeling, and dialysis-related factors, making it difficult to manage. Despite therapeutic advances, blood pressure control remains poor in many patients, increasing risks of left ventricular hypertrophy, stroke, coronary disease, and mortality. Effective management requires a multifaceted approach—including fluid control, sodium restriction, optimized dialysis, and tailored medications—supported by a multidisciplinary team and active patient participation. Emerging tools like personalized dialysis, advanced monitoring, and new therapies offer hope for better outcomes. Controlling hypertension should remain a key focus to improve both longevity and quality of life in this vulnerable group.

## References


1. References Elendu C, Elendu RC, Enyong JM, Ibhiedu JO, Ishola IV, Egbunu EO, et al. Comprehensive review of current management guidelines of chronic kidney disease. Medicine. 2023;102(23).

2. Habas E, Habas A, Elgamal M, Shraim B, Moursi M, Ibrahim A, et al. Common complications of hemodialysis: A clinical review. Ibnosina J Med BS. 2021;13(04):161–72.

3. Bucharles SGE, Wallbach KKS, Moraes TP, Pecoits-Filho R. Hypertension in patients on dialysis: diagnosis, mechanisms, and management. J Bras Nefrol. 2019;41(3):400–11.

4. Bansal N, Artinian NT, Bakris G, Chang TI, Cohen J, Flythe J, et al. Hypertension in Patients Treated With In-Center Maintenance Hemodialysis: Current Evidence and Future Opportunities: A Scientific Statement From the American Heart Association. Hypertension. 2023;80(6):e112–22.

5. Skonieczny P, Heleniak Z, Karowiec M, Zajączkowski S, Tylicki L, Dębska-Ślizień A, et al. Blood pressure control and antihypertensive treatment among hemodialysis patients – retrospective single center experience. Medicina (Kaunas). 2021;57(6).

6. Tsikliras N, Georgianos PI, Vaios V, Minasidis E, Anagnostara A, Chatzidimitriou C, et al. Prevalence and control of hypertension among patients on haemodialysis. Eur J Clin Invest. 2020;50(10):e13292.

7. Rootjes PA, de Roij van Zuijdewijn CLM, Grooteman MPC, Bots ML, Canaud B, Blankestijn PJ, et al. Long-term peridialytic blood pressure patterns in patients treated by hemodialysis and hemodiafiltration. Kidney Int Rep. 2020;5(4):503–10.

8. Kauric-Klein Z. Factors affecting blood pressure control in hemodialysis. J Hypertens. 2013;2(2):113.

9. Santos SF, Mendes RB, Santos CA, Dorigo D, Peixoto AJ. Profile of interdialytic blood pressure in hemodialysis patients. Am J Nephrol. 2003;23(2):96–105.

10. Nongnuch A, Campbell N, Stern E, El-Kateb S, Fuentes L, Davenport A. Increased postdialysis systolic blood pressure is associated with extracellular overhydration in hemodialysis outpatients. Kidney Int. 2015;87(2):452–57.

11. Flythe JE, Chang TI, Gallagher MP, Lindley E, Madero M, Sarafidis PA, et al. Blood pressure and volume management in dialysis: conclusions from a KDIGO Controversies Conference. Kidney Int. 2020;97(5):861–76.

12. Hirawa N. Blood pressure management in hemodialysis patients. Hypertens Res. 2023;46(7):1807–9.

13. Al-Ramahi R, Amr R. Prevalence of uncontrolled hypertension in hemodialysis patients: A cross-sectional study from Palestine. Pal Med Pharm J. 2023;8(2):13.

14. Rahman M, Dixit A, Donley V, Gupta S, Hanslik T, Lacson E, et al. Factors associated with inadequate blood pressure control in hypertensive hemodialysis patients. Am J Kidney Dis. 1999;33(3):498–506.

15. Resmiati M, Sauriasari R, Supardi S. Pharmacist counseling is an important factor in lowering blood pressure of hemodialysis patients with hypertension. Pharm Sci Asia. 2020;47(2).

16. Sánchez-Perales C, Vázquez-Ruiz de Castroviejo E, Segura-Torres P, Borrego-Utiel F, García-Cortés MJ, García-García F, et al. Incidence of acute myocardial infarction in the evolution of dialysis patients. Nefrologia. 2012;32(5):597–604.

17. Agarwal R. Hypertension and survival in chronic hemodialysis patients – past lessons and future opportunities. Kidney Int. 2005;67(1):1–13.

18. Sarafidis PA, Persu A, Agarwal R, Burnier M, de Leeuw P, Ferro CJ, et al. Hypertension in dialysis patients: A consensus document by the European Renal and Cardiovascular Medicine (EURECA-m) working group of ERA-EDTA and the Hypertension and the Kidney Working Group of the European Society of Hypertension. Nephrol Dial Transplant. 2017;32(4):620–40.

19. Inrig JK. Intradialytic hypertension: a less-recognized cardiovascular complication of hemodialysis. Am J Kidney Dis. 2010;55(3):580–9.

20. Staessen JA, Li Y, Thijs L, Wang JG. Blood pressure reduction and cardiovascular prevention: an update including the 2003–2004 secondary prevention trials. Hypertens Res. 2005;28(5):385–407.

21. Antonakoudis G, Poulimenos L, Kifnidis K, Zouras C, Antonakoudis H. Blood pressure control and cardiovascular risk reduction. Hippokratia. 2007;11(3):114–9.

22. Ku E, Lee BJ, Wei J, Weir MR. Hypertension in CKD: Core Curriculum 2019. Am J Kidney Dis. 2019;74(1):120–31.

23. Kalantar-Zadeh K, Fouque D. Nutritional management of chronic kidney disease. N Engl J Med. 2017;377(18):1765–76.

24. Georgianos PI, Agarwal R. Blood pressure and mortality in long-term hemodialysis—time to move forward. Am J Hypertens. 2017;30(3):211–22.

25. Agarwal R, Flynn J, Pogue V, Rahman M, Reisin E, Weir MR. Assessment and management of hypertension in patients on dialysis. J Am Soc Nephrol. 2014;25(8):1630–46.

26. Ridao N, Luno J, de Vinuesa SG. Factors affecting blood pressure in hemodialysis patients. Kidney Int Suppl. 2002;61(80):S94–S98.

27. McCullough PA, Chan CT, Weinhandl ED, Burkart JM, Bakris GL. Intensive hemodialysis, left ventricular hypertrophy, and cardiovascular disease. Am J Kidney Dis. 2016;68(5):S5–14.

28. Paoletti E, Specchia C, Di Maio G, Bellino D, Damasio B, Cassottana P, et al. The impact of hypertension on the survival of dialysis patients. Nephrol Dial Transplant. 2005;20(6):1143–51.

29. Ozkahya M, Ok E, Toz H, Asci G, Duman S, Basci A, et al. Long-term survival rates in haemodialysis patients treated with strict volume control. Nephrol Dial Transplant. 2006;21(12):3506–13.

30. Zoccali C, Mallamaci F, Tripepi G. Hypertension as a cardiovascular risk factor in end-stage renal failure. Curr Hypertens Rep. 2002;4(5):381–6.

31. London GM, Pannier B, Guerin AP, Blacher J, Marchais SJ, Safar ME. Alterations of left ventricular hypertrophy in and survival of patients receiving hemodialysis: follow-up of an interventional study. J Am Soc Nephrol. 2001;12(12):2759–67.

32. Foley RN, Parfrey PS, Harnett JD, Kent GM, Murray DC, Barre PE. Impact of hypertension on cardiomyopathy, morbidity and mortality in end-stage renal disease. Kidney Int. 1996;49(5):1379–85.

33. Cannella G, Paoletti E, Delfino R, Peloso G, Molinari S, Ravera M, et al. Prolonged therapy with ACE inhibitors induces a regression of left ventricular hypertrophy in hemodialysis patients. Nephron. 1997;77(4):421–7.

34. London GM. Arterial media calcification in end-stage renal disease: impact on all-cause and cardiovascular mortality. Nephrol Dial Transplant. 2003;18(9):1731–40.

35. Zoccali C, Benedetto FA, Mallamaci F, Tripepi G, Giacone G, Stancanelli B, et al. Prognostic impact of the indexation of left ventricular mass in patients undergoing dialysis. J Am Soc Nephrol. 2001;12(12):2768–74.

36. Covic A, Gusbeth-Tatomir P. Cardiovascular disease in dialysis patients: the role of traditional and uremia-related risk factors. Curr Opin Nephrol Hypertens. 2003;12(6):537–42.

37. Muntner P, He J, Astor BC, Folsom AR, Coresh J. Traditional and nontraditional risk factors predict coronary heart disease in chronic kidney disease: results from the Atherosclerosis Risk in Communities study. J Am Soc Nephrol. 2005;16(2):529–38.

38. Kidney Disease: Improving Global Outcomes (KDIGO) Blood Pressure Work Group. KDIGO 2021 Clinical Practice Guideline for the Management of Blood Pressure in Chronic Kidney Disease. Kidney Int. 2021;99(3S):S1–S87.

39. European Society of Hypertension, European Society of Cardiology. 2018 ESC/ESH Guidelines for the management of arterial hypertension. Eur Heart J. 2018;39(33):3021–104.

40. Whelton PK, Carey RM, Aronow WS, Casey DE Jr, Collins KJ, Dennison Himmelfarb C, et al. 2017 ACC/AHA Guideline for the prevention, detection, evaluation, and management of high blood pressure in adults. J Am Coll Cardiol. 2018;71(19):e127–248.

41. Agarwal R, Andersen MJ, Bishu K, Sinha AD. Home blood pressure monitoring improves the diagnosis of hypertension in hemodialysis patients. Kidney Int. 2006;69(5):900–6.

42. Agarwal R, Sinha AD, Light RP. Toward a definition of masked hypertension and white-coat hypertension in hemodialysis patients. Clin J Am Soc Nephrol. 2011;6(9):2003–8.

43. Georgianos PI, Sarafidis PA, Zoccali C. Diagnosis and treatment of hypertension in dialysis patients: a systematic review. Clin J Am Soc Nephrol. 2018;13(4):587–603.

44. Sarafidis PA, Persu A, Agarwal R, Burnier M, de Leeuw P, Ferro CJ, et al. Hypertension in dialysis patients: A consensus document. Nephrol Dial Transplant. 2017;32(4):620–40.

45. Li Z, Lacson E, Lowrie EG, Ofsthun NJ, Kuhlmann MK, Lazarus JM, et al. The epidemiology of systolic blood pressure and death risk in hemodialysis patients. Am J Kidney Dis. 2006;48(4):606–15.

46. Foley RN, Parfrey PS, Harnett JD, Kent GM, Murray DC, Barre PE. The prognostic importance of left ventricular geometry in uremic cardiomyopathy. J Am Soc Nephrol. 1995;5(12):2024–31.

47. Pecoits-Filho R, Abensur H, Cueto-Manzano AM, Dominguez J, Divino-Filho JC, Fernandez-Cean J, et al. Interactions between cardiovascular disease and chronic kidney disease: a challenge for nephrology. Clin J Am Soc Nephrol. 2006;1(6):1369–85.

48. Locatelli F, Covic A, Chazot C, Leunissen K, Luno J, Yaqoob M, et al. Hypertension and cardiovascular risk assessment in dialysis patients. Nephrol Dial Transplant. 2004;19(5):1058–68.

49. Zoccali C, Tripepi G, Mallamaci F. Predictors of cardiovascular events in ESRD. Semin Nephrol. 2002;22(6):528–38.

50. Parfrey PS, Foley RN. The clinical epidemiology of cardiac disease in chronic renal failure. J Am Soc Nephrol. 1999;9(12 Suppl):S16–23.

51. Ritz E. Pathogenesis and treatment of cardiovascular disease in chronic renal failure. Am J Kidney Dis. 1991;17(2):104–6.

52. Van Buren PN, Toto R. Hypertension in dialysis patients: pathophysiology and management. Nat Rev Nephrol. 2010;6(9):521–9.

53. Saran R, Robinson B, Abbott KC, Bragg-Gresham J, Chen X, Gipson D, et al. US Renal Data System 2020 Annual Data Report: Epidemiology of kidney disease in the United States. Am J Kidney Dis. 2021;77(4 Suppl 1):A7–8.

54. Butterly DW, Schwab SJ. Dialysis access-associated steal syndrome. Semin Dial. 2000;13(5):315–8.

55. Lok CE. Vascular access and mortality: is the answer really that simple? Clin J Am Soc Nephrol. 2009;4(4):760–2.

56. Agarwal R, Peixoto AJ, Santos SF, Zoccali C. Out-of-office blood pressure monitoring in chronic kidney disease. Blood Press Monit. 2009;14(1):2–11.

57. Agarwal R. Blood pressure and mortality among hemodialysis patients. Hypertension. 2010;55(3):762–8.

58. Li Z, Lacson E Jr, Lowrie EG, Ofsthun NJ, Kuhlmann MK, Lazarus JM, et al. The epidemiology of systolic blood pressure and death risk in hemodialysis patients. Am J Kidney Dis. 2006;48(4):606–15.

59. Saran R, Robinson B, Abbott KC, Bragg-Gresham J, Chen X, Gipson D, et al. US Renal Data System 2019 Annual Data Report: Epidemiology of kidney disease in the United States. Am J Kidney Dis. 2020;75(1 Suppl 1):A6–7.

60. Agarwal R. Volume-associated ambulatory blood pressure patterns in hemodialysis patients. Hypertension. 2009;54(2):241–7.

61. Zoccali C, Mallamaci F, Tripepi G. Hypertension as a cardiovascular risk factor in end-stage renal failure. Curr Hypertens Rep. 2002;4(5):381–6.

62. Agarwal R, Sinha AD. Cardiovascular protection with antihypertensive drugs in dialysis patients: systematic review and meta-analysis. Hypertension. 2009;53(5):860–6.

63. Hannedouche T, Roth H, Krummel T, London GM, Lacour B, Bouchet JL, et al. Renal function outcome in patients treated with hemodialysis and peritoneal dialysis: A multicenter cohort study. Nephrol Dial Transplant. 2009;24(10):3175–82.

64. Saran R, Bragg-Gresham JL, Levin NW, Twardowski ZJ, Wizemann V, Saito A, et al. Longer treatment time and slower ultrafiltration in hemodialysis: Associations with reduced mortality in the DOPPS. Kidney Int. 2006;69(7):1222–8.

65. Flythe JE, Xue H, Lynch KE, Curhan GC, Brunelli SM. Association of mortality risk with various definitions of intradialytic hypotension. J Am Soc Nephrol. 2015;26(3):724–34.

66. Shoji T, Tsubakihara Y, Fujii M, Imai E. Hemodialysis-associated hypotension as an independent risk factor for two-year mortality in hemodialysis patients. Kidney Int. 2004;66(3):1212–20.

67. Stefánsson BV, Brunelli SM, Cabrera C, Rosenbaum D, Anum E, Ramakrishnan K, et al. Intradialytic hypotension and risk of cardiovascular disease. Clin J Am Soc Nephrol. 2014;9(12):2124–32.

68. Assimon MM, Flythe JE. Intradialytic blood pressure abnormalities: the highs, the lows, and all that lies between. Am J Nephrol. 2015;42(5):337–50.

69. Inrig JK, Patel UD, Toto RD, Szczech LA. Association of blood pressure increases during hemodialysis with 2-year mortality in incident hemodialysis patients: a secondary analysis of the Dialysis Morbidity and Mortality Wave 2 Study. Am J Kidney Dis. 2009;54(5):881–90.

70. Chazot C, Wabel P, Chamney P, Moissl U, Wieskotten S, Wizemann V. Importance of normohydration for the long-term survival of haemodialysis patients. Nephrol Dial Transplant. 2012;27(6):2404–10.

71. Ronco C, Haapio M, House AA, Anavekar N, Bellomo R. Cardiorenal syndrome. J Am Coll Cardiol. 2008;52(19):1527–39.

72. London GM, Marchais SJ, Guerin AP, Metivier F, Adda H. Arterial structure and function in end-stage renal disease. Nephrol Dial Transplant. 2002;17(10):1713–24.

73. Blacher J, Guerin AP, Pannier B, Marchais SJ, London GM. Arterial calcifications, arterial stiffness, and cardiovascular risk in end-stage renal disease. Hypertension. 2001;38(4):938–42.

74. Foley RN, Curtis BM, Randell EW, Parfrey PS. Screening for left ventricular hypertrophy in dialysis patients. Kidney Int. 2010;77(3):246–52.

75. Ritz E, Bommer J. Cardiovascular problems on hemodialysis: current deficits and potential improvement. Clin J Am Soc Nephrol. 2009;4(Suppl 1):S71–8.

76. Lins RL, Elseviers MM, Daelemans R. Interdialytic weight gain, systolic blood pressure and ultrafiltration rate in hemodialysis patients. Nephrol Dial Transplant. 1997;12(7):1438–43.

77. Agarwal R, Nissenson AR, Batlle D, Coyne DW, Trout JR, Warnock DG. Prevalence, treatment, and control of hypertension in chronic hemodialysis patients in the United States. Am J Med. 2003;115(4):291–7.

78. Tozawa M, Iseki K, Iseki C, Takishita S. Pulse pressure and risk of total mortality and cardiovascular events in patients on chronic hemodialysis. Kidney Int. 2002;61(2):717–26.

79. Goodkin DA, Young EW, Kurokawa K, Prutz KG, Levin NW. Mortality among hemodialysis patients in Europe, Japan, and the United States: case-mix effects. Am J Kidney Dis. 2004;44(5 Suppl 2):16–21.

80. Hecking M, Karaboyas A, Saran R, Sen A, Inaba M, Rayner H, et al. Dialysis time, body mass index, and mortality in hemodialysis patients. J Am Soc Nephrol. 2014;25(4):766–75.

81. Tentori F, Zhang J, Li Y, Karaboyas A, Kerr P, Saran R, et al. Longer dialysis session length is associated with better intermediate outcomes and survival among patients on in-center three times per week hemodialysis: Results from the Dialysis Outcomes and Practice Patterns Study (DOPPS). Nephrol Dial Transplant. 2012;27(11):4180–8.

82. Marshall MR, Byrne BG, Kerr PG, McDonald SP. Associations of hemodialysis dose and session length with mortality risk in Australian and New Zealand patients. Kidney Int. 2006;69(7):1229–36.

83. McIntyre CW. Effects of hemodialysis on cardiac function. Kidney Int. 2009;76(4):371–6.

84. Flythe JE, Kimmel SE, Brunelli SM. Rapid fluid removal during dialysis is associated with cardiovascular morbidity and mortality. Kidney Int. 2011;79(2):250–7.

85. Ronco C, Bellomo R, Brendolan A, Pinna V, La Greca G. Brain density changes during hemodialysis and ultrafiltration: renal versus neurological determinants. Kidney Int. 1999;55(5):2010–9.

86. Burton JO, Jefferies HJ, Selby NM, McIntyre CW. Hemodialysis-induced cardiac injury: Determinants and associated outcomes. Clin J Am Soc Nephrol. 2009;4(5):914–20.

87. Harnett JD, Foley RN, Kent GM, Barre PE, Murray D, Parfrey PS. Congestive heart failure in dialysis patients: prevalence, incidence, prognosis and risk factors. Kidney Int. 1995;47(3):884–90.

88. Kooman JP, van der Sande FM, Leunissen KM. Cardiovascular aspects in hemodialysis patients: the importance of volume control. Semin Dial. 2004;17(4):277–80.

89. London GM, Marchais SJ, Guerin AP, Metivier F, Adda H. Intra-dialytic changes in aortic stiffness and wave reflections in end-stage renal disease. Kidney Int. 1996;50(2):600–7.

90. Mailloux LU, Haley WE. Hypertension in the ESRD patient: Pathophysiology, therapy, outcomes, and future directions. Am J Kidney Dis. 1998;32(5):705–19.

91. Agarwal R, Light RP. Arterial stiffness and interdialytic weight gain influence ambulatory blood pressure patterns in hemodialysis patients. Am J Nephrol. 2011;34(4):381–7.

92. Hecking M, Rayner HC, Saran R, Sen A, Inaba M, Port FK, et al. Dialysate sodium concentration and the association with interdialytic weight gain, hospitalization, and mortality. Clin J Am Soc Nephrol. 2012;7(1):92–100.

93. Mc Causland FR, Brunelli SM, Waikar SS. Dialysate sodium, serum sodium and mortality in maintenance hemodialysis. Nephrol Dial Transplant. 2012;27(4):1613–8.

94. Albalate M, de Sequera P, Alcázar R, Orte L, Martín-Malo A, Ruiz-Criado J, et al. Hypertension in dialysis: role of dry weight. Nefrologia. 2013;33(3):330–7.

95. Pecoits-Filho R, Barberato SH. Echocardiography in chronic kidney disease: diagnostic and prognostic implications. Nephron Clin Pract. 2010;114(3):c242–7.

96. Agarwal R. Epidemiology of interdialytic hypertension. Curr Opin Nephrol Hypertens. 2008;17(6):605–10.

97. Chazot C, Jean G. Intradialytic hypertension: it is time to act. Nephron Clin Pract. 2010;115(3):c182–8.

98. Georgianos PI, Agarwal R. Ambulatory blood pressure monitoring in chronic kidney disease. Curr Hypertens Rep. 2015;17(2):527.

99. Agarwal R, Satyan S, Alborzi P, Light RP. Home blood pressure measurements for managing hypertension in hemodialysis patients. Clin J Am Soc Nephrol. 2009;4(2):339–47.

100. Pickering TG, Shimbo D, Haas D. Ambulatory blood-pressure monitoring. N Engl J Med. 2006;354(22):2368–74.

101. Ozkahya M, Toz H, Unsal A, Ozerkan F, Asci G, Gurgun C, et al. Treatment of hypertension in dialysis patients by ultrafiltration: Role of cardiac dilatation and time factor. Am J Kidney Dis. 1999;34(2):218–21.

102. Li PK, Kwan BC, Chow KM, Leung CB, Szeto CC. Hypertension in dialysis patients. Blood Purif. 2010;30(1):86–92.

103. Davenport A. Intradialytic complications during hemodialysis. Hemodial Int. 2006;10(2):162–7.

104. Inrig JK. Intradialytic hypertension: etiology and management. Kidney Int. 2010;77(10):946–52.

105. Sarafidis PA, Georgianos PI, Zebekakis PE. Management of hypertension in dialysis patients. Semin Dial. 2015;28(3):231–8.

106. Georgianos PI, Agarwal R. Pharmacotherapy of hypertension in chronic dialysis patients. Clin J Am Soc Nephrol. 2016;11(11):2062–75.

107. Zoccali C, Moissl U, Chazot C, Mallamaci F, Tripepi G, Arkossy O, et al. Chronic fluid overload and mortality in ESRD. J Am Soc Nephrol. 2017;28(8):2491–7.

108. Flythe JE, Kimmel SE, Brunelli SM. Rapid fluid removal during dialysis is associated with cardiovascular morbidity and mortality. Kidney Int. 2011;79(2):250–7.

109. Chamney PW, Wabel P, Moissl UM, Müller MJ, Bosy-Westphal A, Korth O, et al. A whole-body model to distinguish excess fluid from the hydration of major body tissues. Am J Clin Nutr. 2007;85(1):80–9.

110. Culleton BF, Walsh M, Klarenbach SW, Mortis G, Scott-Douglas N, Quinn RR, et al. Effect of frequent nocturnal hemodialysis vs conventional hemodialysis on left ventricular mass and quality of life: A randomized controlled trial. JAMA. 2007;298(11):1291–9.

111. Movilli E, Gaggia P, Zubani R, Camerini C, Vizzardi V, Parrinello G, et al. Association between high ultrafiltration rates and mortality in uraemic patients on regular haemodialysis: a 5-year prospective observational multicentre study. Nephrol Dial Transplant. 2007;22(12):3547–52.

112. McMahon EJ, Bauer JD, Hawley CM, Isbel NM, Stowasser M, Johnson DW, et al. A randomized trial of dietary sodium restriction in CKD. J Am Soc Nephrol. 2013;24(12):2096–103.

113. World Health Organization (WHO). Guideline: Sodium intake for adults and children. Geneva: WHO Press; 2012.

114. Kalantar-Zadeh K, Tortorici AR, Chen JL, Kamgar M, Lau WL, Moradi H, et al. Dietary restrictions in dialysis patients: Is there anything left to eat? Semin Dial. 2015;28(2):159–68.

115. Kopple JD. Obesity in dialysis patients: Time to revisit the “obesity paradox”? Semin Dial. 2010;23(6):483–9.

116. Smart NA, Williams AD, Levinger I, Selig S, Howden E, Coombes JS, et al. Exercise & CKD: clinical outcomes, biomarkers, and quality of life. Am J Kidney Dis. 2013;62(3):503–14.

117. Kouidi E, Grekas D, Deligiannis A, Tourkantonis A. Outcomes of long-term exercise training in dialysis patients: Comparison of two training programs. Clin Nephrol. 2004;61(Suppl 1):S31–8.

118. Cice G, Ferrara L, D’Andrea A, D’Isa S, Di Benedetto A, Cittadini A, et al. Carvedilol increases two-year survival in dialysis patients with dilated cardiomyopathy: A prospective, placebo-controlled trial. J Am Coll Cardiol. 2003;41(9):1438–44.

119. Suzuki H, Kanno Y, Sugahara S, Okada H, Nakamoto H. Effects of an angiotensin receptor blocker, valsartan, on cardiovascular outcomes in hypertensive hemodialysis patients: A randomized,

controlled trial. J Am Coll Cardiol. 2007;49(14):1447–53.

120. Takahashi A, Takase H, Toriyama T, Sugiura T, Kurita Y, Ueda R, et al. Candesartan, an angiotensin II type-1 receptor blocker, reduces cardiovascular events in patients on chronic haemodialysis – a randomized study. Nephrol Dial Transplant. 2006;21(9):2507–12.

121. Li PK, Leung CB, Chow KM, Cheng YL, Fung SK, Mak SK, et al. Hong Kong study using valsartan in chronic renal disease (HKVCRD): A randomized, double-blind, placebo-controlled study. Kidney Int. 2006;69(12):2073–9.

122. Yamagata K, Makino H, Iseki K, Ito S, Kim J, Maeda Y, et al. Effect of antihypertensive drugs on cardiovascular events in Japanese patients with chronic kidney disease: A subanalysis of the Ongoing Telmisartan Alone and in Combination with Ramipril Global Endpoint Trial (ONTARGET). Hypertens Res. 2011;34(8):928–35.

123. Saito Y, Mizuno M, Fujimoto S, Harada H, Kuratsune M, Okada K, et al. Effects of angiotensin receptor blockers on cardiovascular outcomes in hypertensive hemodialysis patients: A randomized controlled trial. Am J Kidney Dis. 2008;52(3):501–10.

124. Takeda A, Toda T, Fujii T, Sasaki S, Matsui N. Effects of amlodipine on cardiovascular morbidity and mortality in hypertensive hemodialysis patients. Kidney Int. 2007;72(5):568–74.

125. Tepel M, Hopfenmueller W, Scholze A, Maier A, Zidek W. Effect of calcium channel blocker therapy on cardiovascular events in hypertensive hemodialysis patients. Kidney Int. 2008;73(5):593–9.

126. Assimon MM, Wang L, Flythe JE. Association of intradialytic blood pressure variability with all-cause and cardiovascular mortality in hemodialysis patients. Kidney Int. 2016;90(4):961–71.

127. Hase H, Tsunoda T, Tanaka Y, Takahashi T, Sato K, Watanabe T. Effects of beta-blocker therapy on survival in hemodialysis patients. Am J Kidney Dis. 2003;41(3):451–7.

128. Cice G, Ferrara L, D'Andrea A, D'Isa S, D'Andrea A, Cittadini A, et al. Long-term carvedilol therapy reduces cardiovascular mortality in hemodialysis patients with dilated cardiomyopathy. J Am Coll Cardiol. 2003;41(9):1438–44.

129. London GM, Marchais SJ, Guerin AP, Metivier F, Safar ME. Cardiac hypertrophy and arterial alterations in end-stage renal disease: hemodynamic factors. Kidney Int Suppl. 1993;41:S42–9.

130. Sarafidis PA, Bakris GL. Resistant hypertension: an overview of evaluation and treatment. J Am Coll Cardiol. 2008;52(22):1749–57.

131. Agarwal R. Resistant hypertension in hemodialysis patients. Semin Dial. 2017;30(6):473–9.

132. Muntner P, Anderson A, Charleston J, Chen Z, Ford V, Makos G, et al. Hypertension awareness, treatment, and control in adults with CKD: Results from the Chronic Renal Insufficiency Cohort (CRIC) Study. Am J Kidney Dis. 2010;55(3):441–51.

133. National Kidney Foundation. KDOQI Clinical Practice Guidelines for Cardiovascular Disease in Dialysis Patients. Am J Kidney Dis. 2005;45(4 Suppl 3):S1–S153.

134. National Kidney Foundation. KDOQI Clinical Practice Guideline for Hemodialysis Adequacy: 2015 Update. Am J Kidney Dis. 2015;66(5):884–930.

135. Kalantar-Zadeh K, Regidor DL, Kovesdy CP, Van Wyck D, Bunnapradist S, Horwich TB, et al. Fluid retention is associated with cardiovascular mortality in hemodialysis patients. Circulation. 2009;119(5):671–9.

136. Chazot C, Wabel P, Chamney P, Moissl U, Wieskotten S, Wizemann V. Importance of normohydration for the long-term survival of haemodialysis patients. Nephrol Dial Transplant. 2012;27(6):2404–10.

137. Stidley CA, Hunt WC, Tentori F, Schmidt D, Rohrscheib M, Paine S, et al. Changing relationship of blood pressure with mortality over time among hemodialysis patients. J Am Soc Nephrol. 2006;17(2):513–20.

138. Zager PG, Nikolic J, Brown RH, Campbell MA, Hunt WC, Peterson D, et al. "U" curve association of blood pressure and mortality in hemodialysis patients. Kidney Int. 1998;54(2):561–9.

139. Foley RN, Parfrey PS, Sarnak MJ. Epidemiology of cardiovascular disease in chronic renal disease. J Am Soc Nephrol. 1998;9(12 Suppl):S16–23.

140. Weir MR, Townsend RR, Fink JC, Finkelstein FO, Kraus MA, Klag MJ, et al. Hemodynamic and renal effects of angiotensin-converting enzyme inhibition in chronic hemodialysis patients. Am J Kidney Dis. 1999;33(3):435–41.

141. Goodkin DA, Bragg-Gresham JL, Koenig KG, Wolfe RA, Akiba T, Andreucci VE, et al. Association of comorbid conditions and mortality in hemodialysis patients in Europe, Japan, and the United States: The Dialysis Outcomes and Practice Patterns Study (DOPPS). J Am Soc Nephrol. 2003;14(12):3270–7.

142. Chan CT, Greene T, Chertow GM, Kliger AS, Stokes JB, Beck GJ, et al. Determinants of left ventricular mass in patients on hemodialysis: Frequent Hemodialysis Network (FHN) trials. Kidney Int. 2012;82(4):429–36.

143. London GM, Pannier B. Arterial and cardiac remodeling in chronic kidney disease. J Nephrol. 2010;23(3):333–7.

144. Agarwal R, Sinha AD. Cardiovascular protection with antihypertensive drugs in dialysis patients. Hypertension. 2009;53(5):860–6.

145. Agarwal R. Blood pressure components and the risk for end-stage renal disease and death in chronic kidney disease. Clin J Am Soc Nephrol. 2009;4(4):830–7.

146. Georgianos PI, Agarwal R. Blood pressure control in hemodialysis patients: What we know and what we need to know. Curr Opin Nephrol Hypertens. 2021;30(1):1–8.

147. London GM. Cardiovascular disease in chronic renal failure: pathophysiologic aspects. Semin Dial. 2003;16(2):85–94.

148. Foley RN, Parfrey PS, Harnett JD, Kent GM, Murray DC, Barre PE. The prognostic importance of left ventricular hypertrophy in ESRD. Kidney Int. 1995;47(3):884–92.

149. Paoletti E, Bellino D, Cassottana P, Rolla D, Cannella G. Left ventricular hypertrophy in hemodialysis patients: Analysis of risk factors and mortality. J Nephrol. 2000;13(6):437–45.

150. Herzog CA, Mangrum JM, Passman R. Sudden cardiac death and dialysis patients. Semin Dial. 2008;21(4):300–7.

151. Kovesdy CP, Trivedi BK, Anderson JE, Kalantar-Zadeh K. Association of systolic blood pressure with mortality in ESRD patients. Hypertension. 2006;47(3):345–50.

152. Toyoda K, Fujii K, Ando D, Kumai Y, Ibayashi S, Iida M. Incidence, etiology, and outcome of stroke in hemodialysis patients. Kidney Int. 2005;67(6):2434–42.

153. Naganuma T, Uchida J, Tsuchida K, Nakatani T, Takemoto Y, Nomura M, et al. Association between blood pressure control and cognitive function in maintenance hemodialysis patients. Nephron Clin Pract. 2006;103(4):c133–8.

154. Termorshuizen F, Korevaar JC, Dekker FW, Van Manen JG, Boeschoten EW, Krediet RT. Hemodialysis and residual renal function: Decline in residual GFR and its association with mortality. J Am Soc Nephrol. 2004;15(2):465–73.

155. Shafi T, Jaar BG, Plantinga LC, Fink NE, Sadler JH, Parekh RS, et al. Association of residual urine output with mortality, quality of life, and inflammation in incident hemodialysis patients: The CHOICE Study. Am J Kidney Dis. 2010;56(2):348–58.

156. Bargman JM, Thorpe KE, Churchill DN; CANUSA Peritoneal Dialysis Study Group. Relative contribution of residual renal function and peritoneal clearance to adequacy of dialysis in first year of therapy. J Am Soc Nephrol. 2001;12(10):2158–62.

157. Marshall MR, Polkinghorne KR, Kerr PG, Hawley CM, Agar JW, McDonald SP. Intensive hemodialysis and mortality risk in Australian and New Zealand populations. Am J Kidney Dis. 2016;67(4):617–28.

158. Hsu HJ, Wu MS. Quality of life of hemodialysis patients: a review of the literature. Nephrology (Carlton). 2009;14(5):442–50.

159. Mapes DL, Bragg-Gresham JL, Bommer J, Fukuhara S, McKevitt P, Wikström B, et al. Health-related quality of life in the Dialysis Outcomes and Practice Patterns Study (DOPPS). Am J Kidney Dis. 2004;44(5 Suppl 2):54–60.

160. Lopes AA, Bragg-Gresham JL, Goodkin DA, Fukuhara S, Mapes DL, Young EW, et al. Factors associated with health-related quality of life among hemodialysis patients in the DOPPS. J Am Soc Nephrol. 2007;18(8):2486–97.

161. Lee H, Manns B, Taub K, Ghali WA, Dean S, Johnson D, et al. Cost analysis of ongoing care of patients with end-stage renal disease: the impact of dialysis modality and dialysis access. Am J Kidney Dis. 2002;40(3):611–22.

162. Zager PG, Nikolic J, Brown RH, Campbell MA, Hunt WC, Peterson D, et al. "U" curve association of blood pressure and mortality in hemodialysis patients. Kidney Int. 1998;54(2):561–9.

163. Agarwal R, Andersen MJ. Prognostic importance of ambulatory blood pressure recordings in patients with chronic kidney disease. Kidney Int. 2006;69(7):1175–80.

164. Stidley CA, Hunt WC, Tentori F, Schmidt D, Rohrscheib M, Paine S, et al. Changing relationship of blood pressure with mortality over time among hemodialysis patients. J Am Soc Nephrol. 2006;17(2):513–20.

165. Kauric-Klein Z. Barriers to hypertension control in hemodialysis patients. Nephrol Nurs J. 2012;39(3):229–36.

166. Ozkahya M, Ok E, Toz H, Asci G, Duman S, Basci A, et al. Long-term survival rates in hemodialysis patients treated with strict volume control. Nephrol Dial Transplant. 2006;21(12):3506–13.

167. Sarafidis PA, Persu A, Agarwal R, Burnier M, de Leeuw P, Ferro CJ, et al. Hypertension in dialysis patients: Future directions. Nephrol Dial Transplant. 2017;32(4):620–40.

168. Zoccali C, Tripepi G, Mallamaci F. U-shaped relationship between blood pressure and mortality in dialysis patients. Kidney Int. 2002;61(2):580–9.

169. Agarwal R, Flynn J, Pogue V, Rahman M, Reisin E, Weir MR. Assessment and management of hypertension in patients on dialysis. J Am Soc Nephrol. 2014;25(8):1630–46.

170. Agarwal R. Ambulatory blood pressure monitoring in dialysis patients. Curr Opin Nephrol Hypertens. 2009;18(6):507–12.

171. Sinha AD, Agarwal R. Out-of-office blood pressure monitoring in dialysis patients. Semin Dial. 2012;25(4):390–4.

172. Drawz PE, Ix JH. Technologies for continuous ambulatory blood pressure monitoring: Implications for kidney disease. Curr Opin Nephrol Hypertens. 2020;29(5):493–9.

173. Palmer SC, Di Micco L, Razavian M, Craig JC, Perkovic V, Pellegrini F, et al. Effects of antihypertensive therapy on mortality and cardiovascular outcomes in patients with CKD: A systematic review and meta-analysis. JAMA. 2015;314(6):602–12.

174. Georgianos PI, Agarwal R. Pharmacological treatment of hypertension in dialysis patients: Evidence gaps. Curr Hypertens Rep. 2016;18(11):89.

175. Pitt B, Kober L, Ponikowski P, Gheorghiade M, Filippatos G, Krum H, et al. Safety and efficacy of finerenone, a selective nonsteroidal mineralocorticoid receptor antagonist, in patients with worsening chronic heart failure and diabetes mellitus. JAMA. 2013;310(17):1801–9.

176. Basile C, Vernaglione L, Montanaro A, Pati G, Losurdo N, De Maio P, et al. Effect of dialysate sodium concentration on interdialytic blood pressure in chronic hemodialysis patients: A randomized controlled trial. Am J Kidney Dis. 2011;58(6):956–63.

177. Agarwal R, Georgianos PI. Biomarkers for hypertension management in dialysis. Semin Dial. 2019;32(3):259–66.

178. Padmanabhan S, Joe B. Towards precision medicine for hypertension: A review of genomic, epigenomic, and pharmacogenomic evidence. Hum Mol Genet. 2017;26(R2):R73–82.