BMC Nephrology

RESEARCH

Open Access

Indications and complications associated with centrifuge-based therapeutic plasma exchange - a retrospective review

David Warner[1], Heather Duncan[2], Prakash Gudsoorkar[2] and Manish Anand[2*]

Abstract

Background Therapeutic Plasma Exchange (TPE) is an extracorporeal treatment modality used to manage certain conditions caused by plasma deficiencies, autoantibodies, alloantibodies, toxins, and immune complexes. We describe our experience of using TPE for various disease indications and associated complications.

Methods This is a retrospective, single-center review of centrifuge-based TPE performed by the division of nephrology at a tertiary care academic center between July 2018 to June 2022. 1219 TPE treatments in 145 patients were included.

Results The most common indications for TPE were Antibody-Mediated Rejection (AMR) of a kidney transplant (20%), autoimmune encephalitis (16%), and neuromyelitis optica (11%). Rare indications for TPE included Chronic Relapsing Inflammatory Optic Neuropathy (CRION), AMR of a pancreas transplant, osmotic demyelination, and belatacept removal in the setting of COVID-19. The most common complications were depletion coagulopathy (47.6%), hypocalcemia (44.1%), and hypokalemia (36.6%). Rare complications included stiff person crisis and pseudohypertriglyceridemia. 31.7% of patients received TPE for conditions managed by nephrologists.

Conclusion TPE is an extracorporeal treatment modality for managing various renal and non-renal diseases. The study demonstrated that 18.7% of the patients at our center received TPE for conditions in which its role is not yet established, suggesting the need for further research on the use of TPE. In addition, this study supports the necessity of nephrology training program to include education on TPE as almost one-third of the indications for TPE in our center were for conditions managed by nephrologists.

Keywords Therapeutic plasma exchange, Apheresis, Extracorporeal

*Correspondence:
Manish Anand
anandmh@ucmail.uc.edu
[1]University of Cincinnati College of Medicine, Cincinnati, OH, US
[2]Department of Medicine, Division of Nephrology, University of Cincinnati Medical Center, 231 Albert Sabin Way, Cincinnati, OH 45267, US

© The Author(s) 2025. **Open Access** This article is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License, which permits any non-commercial use, sharing, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if you modified the licensed material. You do not have permission under this licence to share adapted material derived from this article or parts of it. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit http://creativecommons.org/licenses/by-nc-nd/4.0/.

Background

Therapeutic Plasma Exchange (TPE) is an extracorporeal treatment modality that involves the removal of plasma and returning the cellular components of the blood while replacing the plasma with a replacement fluid, such as albumin and/or fresh frozen plasma (FFP). Two methods to separate the plasma component from whole blood include a centrifuge-based or semipermeable membrane-based separation method [1, 2]. Initially used to treat hyperviscosity syndrome in multiple myeloma [3], TPE has become a widely available treatment option for several other conditions linked to deficiencies in plasma components, as well as those involving the circulation of autoantibodies, alloantibodies, toxins, and immune complexes [4, 5]. The American Society for Apheresis (ASFA) continuously reviews, categorizes, and grades the indications for TPE [6]. TPE is mostly overseen by hematologists, or transfusion medicine specialists in the United States. However, in 2001, the Renal Physicians Association (RPA) released a position statement, asserting that nephrologists should have expertise in extracorporeal therapies, including TPE [7, 8]. Kaplan similarly argues that nephrologists should have expertise in TPE as they belong to the only field of medicine with fellowship training in extracorporeal blood purification treatment [9]. The renal indications of plasmapheresis are outlined in Table 1, which supports the importance of nephrologists having expertise in TPE [6, 10, 11].

There are a variety of complications of TPE, such as hypotension, citrate toxicity, acid-base disequilibrium, dyselectrolytemia, depletion coagulopathy, and infections. To provide a perspective from the field of nephrology and in response to a dearth of research on the prevalence of the complications of TPE, a multi-year retrospective review of TPE treatments managed by the nephrology department at a tertiary care academic center was conducted to identify the diagnoses designated as indications for TPE as per the American Society for Apheresis (ASFA) guidelines and the complications resulting from TPE.

Methods

This is a retrospective single center review of all TPE treatments managed by the nephrology department at a tertiary care academic center between June 2018 to June 2022 with no exclusion criteria. Patient demographics, clinical and laboratory data, TPE prescription and patient outcomes were characterized after manual review of the electronic medical record. Study data were collected and managed using REDCap electronic data capture tools hosted at the University of Cincinnati. Physician and nursing notes, as well as laboratory results were utilized to identify the complications associated with TPE and their management.

All TPE treatments included in the study utilized the centrifuge-based method of plasma separation from whole blood. The form of citrate used for anticoagulation at our center was Acid Citrate Dextrose Solution A (ACD-A), and patients received either calcium gluconate or calcium chloride to replete calcium. 98% of treatments were performed via a central line while 2% of treatments were performed via a peripheral line. 5% albumin was used as the replacement fluid in most cases, with three exceptions in which 100% FFP was used for catabolic antiphospholipid syndrome, TMA secondary to SLE, and diffuse alveolar hemorrhage secondary to ANCA vasculitis. The fluid balance was 100% in all cases. The volume of plasma exchange was 1.5 in 70% of cases and 1.0 in 30% of cases.

Laboratory values were obtained the morning after TPE in the inpatient setting or prior to the patient's next TPE session in the outpatient setting. For the purposes of the review, hypocalcemia was defined as a serum calcium value less than 8.0 mg/dL, hypokalemia was defined as a serum potassium value less than 3.5 mEq/L, and hypomagnesemia was defined as a serum magnesium less than 1.5 mg/dL. Metabolic alkalosis was defined as an arterial blood gas pH greater than 7.45 and/or a serum bicarbonate greater than 28 mEq/L. Depletion coagulopathy was defined in the patients who required fresh frozen plasma based on low fibrinogen levels (less than 150 mg/dL) with or without evidence of bleeding.

Results

Patient characteristics

Overall, 1219 TPE treatments were performed on 145 patients for a total of 23 indications, as outlined in Table 3. The median age of the patients in this study was 49 years (range 20–78 years), 42.7% were men, 56.6% women, and one non-binary patient. The majority were Caucasians 69%, 24.1% were Black, 1.4% were LHS+, 4.1% were Asian and 1.4% identified as "Other". 54% of patients received TPE in inpatient setting and the rest 46% were managed as outpatient treatments. Central line was the most common choice for vascular access in 98% of the patients.

The breakdown of TPE procedures performed by ASFA category is outlined in Table 2. Most patients received TPE for a Category I or II indication. However, 18.7% of patients received TPE for conditions in which the role of TPE is not yet established (ASFA Category III or ASFA Category Unknown).

Indication of TPE (Table 3)

The most common indications for TPE included antibody-mediated rejection (AMR) in kidney transplant patients (20%), autoimmune encephalitis (16%), and neuromyelitis optica (11%).

Table 1 Primary and secondary renal diseases managed with TPE

Indication	ASFA Category
Recurrent Focal segmental glomerulosclerosis (FSGS)	I
Anti-GBM, Goodpasture Syndrome with Dialysis Independence or Diffuse Alveolar Hemorrhage	
Kidney transplant	
● ABO compatible	
○ Antibody-mediated rejection (AMR)	
○ Desensitization, living donor	
● ABO incompatible	
○ Desensitization, living donor	
Thrombotic microangiopathy	
● TTP	
● Complement-mediated (Factor H autoantibody)	
● Secondary to Ticlopidine	
Catastrophic antiphospholipid syndrome (CAPS)	
Amyloidosis, systemic, dialysis-related	II
Myeloma cast nephropathy	
Systemic lupus erythematosus (severe)	
Kidney transplant	
● ABO incompatible (Antibody-mediated rejection)	
Graft-versus-host disease	
Cryoglobulinemia	
Anti- GBM, Goodpasture Syndrome (Dialysis-dependence, no diffuse alveolar hemorrhage)	III
Steroid-Resistant FSGS in Native Kidney	
Thrombotic Microangiopathy	
● Coagulation-mediated	
● Complement- mediated (gene mutation)	
● Secondary to Clopidogrel	
● Pregnancy-associated	
○ Severe or extremely preterm preeclampsia	
● Infection-associated	
○ STEC[a] or post-transplant HUS[b]	
● Transplantation-associated	
ANCA[c]-associated vasculitis	
MPA[d], GPA[e], or EGPA[f]	
IgA nephropathy (crescentic, chronic progressive)	
IgA vasculitis (Crescentic RPGN[g] or severe extrarenal manifestations)	
Nephrogenic systemic fibrosis	
Medication overdose	
Thrombotic Microangiopathy Secondary to Gemcitabine or Quinine	IV

[a]Shigatoxigenic *Escherichia coli*

[b]Hemolytic-uremic syndrome

[c]Antineutrophil cytoplasmic antibodies

[d]Microscopic polyangiitis

[e]Granulomatosis with polyangiitis

[f]Eosinophilic granulomatosis with polyangiitis

[g]Rapidly progressive glomerulonephritis

Table 2 TPE procedures performed per ASFA category

ASFA Category	Number (%)
I	87 (60)
II	31 (21.4)
III	23 (15.9)
Unknown	4 (2.8)

Complications of TPE

In total, 28 (19.3%) patients have died since the start date of the study. However, none of the patients died as a direct result of TPE. Complications of TPE are outlined in Fig. 1. The most common complications identified by our study were depletion coagulopathy followed by electrolytes imbalances, namely hypocalcemia, hypokalemia and hypomagnesemia.

Depletion coagulopathy occurs when using albumin as a replacement fluid, which was the most common replacement fluid used in our study. Our study showed that depletion coagulopathy was higher in patients who were prescribed anticoagulants (53%) prior to the administration of TPE compared to those who were not on any anticoagulation (47.0%).

Chest discomfort, dizziness and hypotension were the most common symptoms or signs in patients with

Table 3 Indications for TPE

Diagnosis	ASFA Category	Number of Patients (%)	Number of Treatments (%)
Renal Conditions			
AMR, kidney transplant	I	29 (20.0)	166 (13.6)
Recurrent FSGS, post-transplant	I	6 (4.2)	192 (15.8)
CAPS	I	1 (0.7)	5 (0.4)
TTP	I	1 (0.7)	14 (1.1)
TMA, secondary to SLE	II	1 (0.7)	14 (1.1)
Myeloma cast nephropathy	II	1 (0.7)	4 (0.3)
ANCA Vasculitis	III	4 (2.8)	13 (1.1)
Belatacept removal in the setting of COVID-19	Unknown	1 (0.7)	2 (0.2)
Neurological Conditions			
Autoimmune encephalitis	I	23 (15.9)	132 (10.8)
Myasthenia gravis, acute	I	14 (9.7)	111 (9.1)
AIDP	I	7 (4.8)	37 (3.0)
CIDP	I	2 (1.4)	208 (17.1)
Neuromyelitis optica, acute	II	16 (11.0)	94 (7.7)
Multiple Sclerosis	II	12 (8.3)	65 (5.3)
Steroid-responsive encephalopathy associated with autoimmune thyroiditis	II	1 (0.7)	7 (0.6)
Lambert-Eaton Syndrome	II	1 (0.7)	23 (1.9)
Paraneoplastic neurological syndromes	III	8 (5.5)	40 (3.3)
Stiff Person Syndrome	III	3 (2.1)	17 (1.4)
Central pontine myelinolysis	Unknown	1 (0.7)	5 (0.4)
CRION	Unknown	1 (0.7)	5 (0.4)
Other Conditions			
AMR, heart/liver transplant	III	9 (6.2)	51 (4.2)
Medication Overdose	III	2 (1.4)	3 (0.2)
AMR, pancreas transplant	Unknown	1 (0.7)	4 (0.3)

hypocalcemia. The average serum calcium for all 145 patients in the study was 9.0 mg/dL. Notably, one patient with history of seizures experienced an active seizure with normal serum calcium levels. Of the patients who experienced muscle spasms during the TPE procedure, two were being treated for autoimmune encephalitis and two for neuromyelitis optica.

Of the 8 patients who were documented to have metabolic alkalosis in our study, only 3 had concomitant hypokalemia.

Hypotension is usually caused by fluid shifts during the TPE procedure. Among the patients who experienced hypotension during the administration of TPE, two patients were administered IV fluids, TPE was halted in one patient who received only three treatments out of the five prescribed, and one treatment had their dose of losartan temporarily halted until the remaining treatments were performed.

In our study, six patients (4.1%) developed catheter related infections, most of whom received TPE for an extended duration of time. Blood cultures grew Staphylococcus epidermidis in two patients, Pseudomonas aeruginosa in one patient, and 3 patients were empirically treated for culture-negative infection. In addition to IV antibiotics, catheters were exchanged in two patients.

One patient who had restlessness was prescribed pramipexole to relieve symptoms. Finally, one patient with CIDP received iron infusions and another patient with FSGS received recombinant erythropoietin to treat the anemia.

Discussion

Expertise in extracorporeal blood purification is mandatory for nephrology trainees [9]. However, only 40% of nephrology fellowship programs offer trainees the opportunity to perform TPE [12]. A 2023 American Society of Nephrology survey of nephrology fellows showed that only 24% of graduating fellows listed managing apheresis as part of their responsibilities in their first position [13].

At our institution, 30% of patients received TPE for management of renal diseases, with AMR of kidney transplant as the most common indication. Electrolytes imbalances after depletion coagulopathy were the most common complication after TPE. Our study therefore highlights the utility of including TPE training during nephrology fellowship.

A few of the cases in which TPE was utilized to manage conditions for which the role of TPE is not yet established by the ASFA are outlined below.

The patient with osmotic pontine myelinolysis had a history of chronic alcoholism who presented to the emergency room with worsening gait ataxia, confusion, and seizures and was found to have a serum sodium of 109 mmol/L. Osmotic stress may cause the release of myelin toxins that contribute to the demyelination process, which can be eliminated through TPE [14]. Although the use of TPE in the management of osmotic pontine myelinolysis is not established in the 2023 ASFA guidelines, several case reports have demonstrated at least partial reversal of symptoms after treatment with TPE, supporting the use of this modality in the management of osmotic pontine myelinolysis [14–17].

One living kidney donor recipient on maintenance belatacept for immunosuppression was admitted to ICU with acute respiratory failure secondary to COVID-19 infection. Belatacept is a cytotoxic T-lymphocyte-associated protein 4 (CTLA-4) fusion protein used as an immunosuppression therapy in kidney transplant recipients. One case report postulated that belatacept interferes with the cytokine storm and led to a milder course of COVID-19 in a patient who had received a kidney transplant [18]. However, another case report demonstrated improvement in a patient with a severe COVID-19 infection after mycophenolate mofetil and belatacept

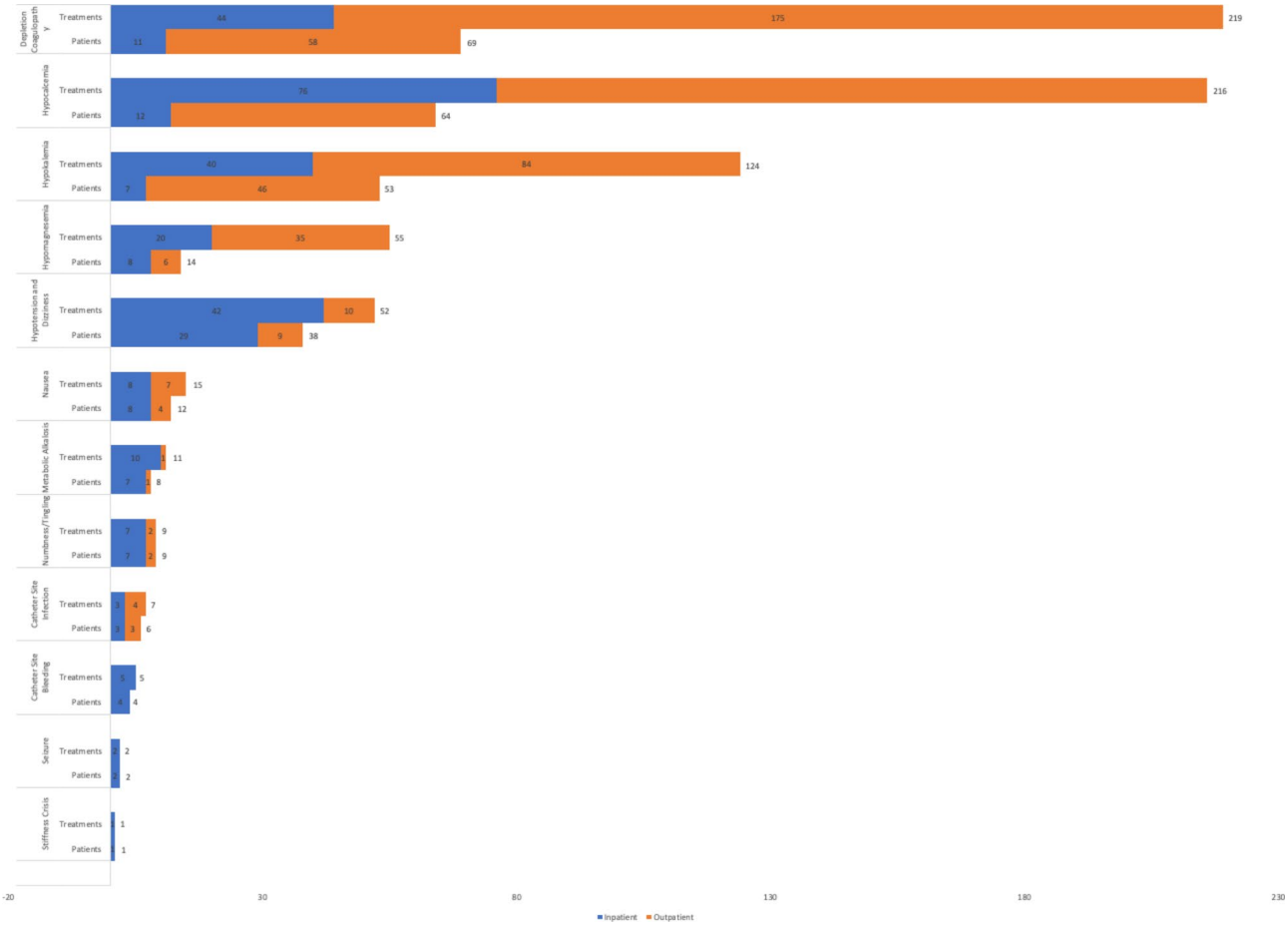

Fig. 1 Complications of TPE

were held. The authors hypothesized that belatacept may interfere with immune responses to viruses and recommended the avoidance of belatacept until viral clearance could be achieved [19].

Two patients in our study received TPE for the indication of intentional polysubstance overdose. TPE is most effective in removing drugs that are > 80% protein-bound in the plasma with a small volume of distribution. TPE is also more effective with decreased time between drug administration and TPE start-time and when used to remove drugs that have a longer half-life [20].

One patient was suspected to have overdosed on carvedilol. Carvedilol is 95–98% protein-bound but has a large volume of distribution, so while TPE is useful in the treatment of carvedilol, prompt treatment is required [21]. Another patient presented with hypotension and metabolic alkalosis after overdosing on quetiapine and an unknown amount of amlodipine. Quetiapine is 83% protein-bound and has a large volume of distribution [22]. Amlodipine is 98% protein-bound and also has a large volume of distribution [23].

CRION is a syndrome that is thought to be at least partially immune-mediated with features including recurrent painful vision loss that responds to early treatment with steroids. A 2019 case report by Yassa and Bakbak [24]. reported a patient who also had severe impairment in color vision. The management of CRION is IV methylprednisolone pulses, although plasmapheresis has been used in patients who do not respond to this treatment option [25].

For the most part, TPE is a relatively safe procedure with positive patient outcomes and few complications requiring treatment. However, there are a few complications of TPE to note including citrate toxicity. Citrate is an anticoagulant used to prevent clotting in the extracorporeal circuit. The most common complication of citrate toxicity is hypocalcemia and hypomagnesemia, as citrate binds to calcium and magnesium in the plasma [26]. Severe symptoms of hypocalcemia include seizures and prolonged QT interval and patients with underlying cardiac arrythmias, and neuromuscular disorders are particularly vulnerable to these side effects [26].

To prevent citrate-induced hypocalcemia, calcium gluconate, calcium chloride, or calcium carbonate are administered when performing TPE. Citrate toxicity also causes metabolic alkalosis, as its metabolism in the liver

via the tricarboxylic acid cycle produces bicarbonate, particularly in patients with respiratory failure, impaired citrate metabolism in hepatic insufficiency and compromised renal excretion of bicarbonate [26–28]. Metabolic alkalosis also can further precipitate hypokalemia [26]. Hypokalemia and metabolic alkalosis can also be caused by the increased activation of the renin-angiotensin-aldosterone system in the setting of hypovolemia.

Infections are also common and divided into three categories: post-TPE due to immunoglobulin depletion, vascular access-related, or viral transmission from FFP.

Other known complications of TPE include hyperglycemia related to dextrose contained in the citrate solution, transfusion-related acute lung injury (TRALI), transfusion-associated circulatory overload (TACO), urticaria, and aluminum toxicity due to the presence of aluminum in 5% albumin [29, 30].

Our study highlights some of the rarer complications of TPE that have not been noted in the published literature. Stiffness crisis presenting as severe muscle spasms and pain manifested during the TPE procedure in one patient undergoing TPE for Stiff Person Syndrome.

Pseudo-hypertriglyceridemia was noted in a patient who received 5 treatments of TPE for tumefactive multiple sclerosis. The triglyceride returned to baseline following completion of TPE.

Strengths and limitations

Overall, this is one of the most comprehensive retrospective reviews of all TPE procedures performed by a nephrology department. The study includes a variety of indications for TPE, including a few indications that have been rarely reported in the literature. Our study also includes a detailed account of the complications of TPE that have been observed, including stiffness crisis and pseudo hypertriglyceridemia, which have never been reported to our knowledge.

However, our study also has several limitations. 75% of TPE procedures at our institution are performed by the nephrology division while 25% of TPE procedures are performed in an outpatient blood center, which describes the sparsity of hematologic conditions in our study. Additionally, this was a retrospective study with limited numbers that utilized physician and nursing notes, as well as laboratory values to identify the complications of TPE. Studying larger populations or a multi-center design would offer more conclusive results on rare indications and complications noted in this cohort. With the simultaneous use of multiple strategies in the treatment of underlying disease indication, it is difficult to fully ascertain the impact of each individual treatment regimen. There was some variability in how different providers documented the TPE procedure and the associated complications. An example is the inability to obtain BNP and chest radiography to diagnose TACO. In addition, aluminum levels and blood gases were not routinely measured in our lab order sets therefore aluminum toxicity and metabolic alkalosis may be underreported as complications of TPE in this study. Cardiac monitoring was also not performed as a standard procedure in patients receiving TPE, limiting our ability to identify cardiac arrhythmias that may have developed as a complication of TPE. Hyperglycemia as a complication of TPE was difficult to define due to the high incidence of Type 2 Diabetes Mellitus among patients in this study and was therefore not reported. Finally, IgG levels were not routinely assessed, which limits our ability to decipher if infections were attributed to immunoglobulin deficiency secondary to TPE.

Conclusion

Therapeutic Plasma Exchange (TPE) is an extracorporeal treatment modality for managing various renal and non-renal diseases. Nephrologists and dialysis staff with extracorporeal therapy training are uniquely positioned and well-equipped to manage TPE. This study demonstrated that 18.7% of the patients at our center received TPE for conditions in which the role of TPE is not yet established. This supports the need for further research on the use of TPE. There were some indications of TPE that were not included in the 2023 ASFA guidelines, such as CRION, antibody-mediated rejection of a pancreas transplant, central pontine myelinolysis, and belatacept removal in the setting of COVID-19. There were also a few rare complications documented in this review, including stiff person crisis and pseudohypertriglyceridemia. This study exemplifies the utility of having a systematic audit to review the practice patterns and complications of TPE and supports the inclusion of education on TPE indications and complications in nephrology training programs.

Abbreviations

ACD-A	Acid Citrate Dextrose Solution A
AIDP	Acute inflammatory demyelinating polyneuropathy
AMR	Antibody-mediated rejection
ANCA	Antineutrophil cytoplasmic antibodies
Anti-GBM	Anti-glomerular basement membrane
ASFA	American Society for Apheresis
CAPS	Catastrophic antiphospholipid syndrome
CIDP	Chronic inflammatory demyelinating polyneuropathy
CRION	Chronic Relapsing Inflammatory Optic Neuropathy
CTLA-4	Cytotoxic T-lymphocyte-associated protein 4
EGPA	Eosinophilic granulomatosis with polyangiitis
FFP	Fresh frozen plasma
FSGS	Focal segmental glomerulosclerosis
GPA	Granulomatosis with polyangiitis
HUS	Hemolytic-uremic syndrome
LHS+	Latino, Hispanic, or of Spanish Origin+
MPA	Microscopic polyangiitis
MRI	Magnetic resonance imaging
NMDAR	N-methyl-D-aspartate receptor
NMOSD	Neuromyelitis optica spectrum disorders

RPA	Renal Physicians Association
RPGN	Rapidly progressive glomerulonephritis
SLE	Systemic Lupus Erythematosus
STEC	Shigatoxigenic Escherichia coli
TACO	Transfusion-associated circulatory overload
TMA	Thrombotic microangiopathy
TRALI	Transfusion-related acute lung injury
TPE	Therapeutic plasma exchange
TTP	Thrombotic thrombocytopenic purpura

Acknowledgements
We appreciate grant support (UL1TR001425) for the collection and management of study data via REDCap electronic data capture tools hosted at the University of Cincinnati.

Author contributions
MA conceived the idea for the project, provided the information on the patients included in the study, and provided extensive edits of the manuscript. DW analyzed and interpreted the patient data regarding indications and complications of TPE and wrote the initial draft for the manuscript. PG performed extensive edits of the manuscript. HD assisted with data collection and IRB approval. All authors read and approved the final manuscript.

Funding
Study data were collected and managed using REDCap electronic data capture tools hosted at the University of Cincinnati with grant support (UL1TR001425).

Data availability
The data that support the findings of this study are not openly available due to reasons of sensitivity and are available from the corresponding author upon reasonable request.

Declarations

Ethics approval
statement: Ethical approval to report this original article was obtained from the University of Cincinnati Institutional Review Board, IRB ID: 2024 – 0393.

Consent for publication
Per 45 CFR 46.116, the IRB has waived the requirement to obtain informed consent for all adult participants. Per 45 CFR 164.512 the IRB has granted a waiver from the requirement to obtain an authorization for the use and/or disclosure of protected health information (PHI).

Competing interests
PG serves on the editorial board for BMC Nephrology.

Clinical trial registration
N/A.

Received: 22 November 2024 / Accepted: 17 January 2025
Published online: 19 February 2025

References

1. Ahammed Nizar OT, Rai P, Rao SN, Shenoy MP, Plasmapheresis. A retrospective audit of procedures from a tertiary care center in Southern India. Indian J Crit Care Med. 2017;21(12):857–60.
2. Williams ME, Balogun RA. Principles of separation: indications and therapeutic targets for plasma exchange. Clin J Am Soc Nephrol. 2014;9(1):181–90.
3. Adams WS, Blahd WH, Bassett SH. A method of human plasmapheresis. Proc Soc Exp Biol Med. 1952;80(2):377–9.
4. McLeod BC. Therapeutic apheresis: history, clinical application, and lingering uncertainties. Transfusion. 2010;50(7):1413–26.
5. Clark WF, Huang SS. Introduction to therapeutic plasma exchange. Transfus Apher Sci. 2019;58(3):228–9.
6. Padmanabhan A, Connelly-Smith L, Aqui N, Balogun RA, Klingel R, Meyer E, et al. Guidelines on the use of therapeutic apheresis in clinical practice - evidence-based approach from the writing committee of the American Society for Apheresis: the eighth special issue. J Clin Apher. 2019;34(3):171–354.
7. Renal Physicians Association. RPA position on development of effective collaborative practice models for chronic renal care. Ren Physicians Association Clin Nephrol. 2001;56(3):255–6.
8. Balogun RA. Therapeutic apheresis for nephrologists: an introduction. Semin Dial. 2012;25(2):113.
9. Kaplan AA. Why nephrologists should perform therapeutic plasma exchange. Dialysis & Transplantation. 2009 [cited 2024 Mar 28];38(2):65–70. Available from: https://onlinelibrary.wiley.com/doi/https://doi.org/10.1002/dat.20293
10. Stevenson ME, Leung N, Winters JL. What are the newer applications for therapeutic apheresis in nephrology? Current indications for therapeutic plasma exchange in Nephrology. Semin Dial. 2016;29(5):350–3.
11. Gashti CN. Membrane-based therapeutic plasma exchange: a new frontier for nephrologists. Semin Dial. 2016;29(5):382–90.
12. Berns JS, O'Neill WC. Performance of procedures by nephrologists and nephrology fellows at U.S. nephrology training programs. Clin J Am Soc Nephrol. 2008;3(4):941–7.
13. Pivert KA, Burgner AM, Chowdhury R, Cobb J, Halbach S, Jain K et al. 2023 ASN Nephrology Fellow Survey. 2023 [cited 2024 Mar 28]. Available from: https://data.asn-online.org/posts/2023_fellow_survey
14. Bibl D, Lampl C, Gabriel C, Jüngling G, Brock H, Köstler G. Treatment of central pontine myelinolysis with therapeutic plasmapheresis. Lancet. 1999;353(9159):1155.
15. McNamara PH, Williams J, McCabe DJH, Walsh RA. Striking central pontine myelinolysis in a patient with alcohol dependence syndrome without hyponatremia. JAMA Neurol. 2016;73(2):234–5.
16. Atchaneeyasakul K, Tipirneni A, Gloria S, Berry AC, Shah K, Yavagal DR. Osmotic demyelination syndrome: plasmapheresis versus intravenous immunoglobulin? Intern Emerg Med. 2017;12(1):123–6.
17. Wijayabandara M, Appuhamy S, Weerathunga P, Chang T. Effective treatment of osmotic demyelination syndrome with plasmapheresis: a case report and review of the literature. J Med Case Rep. 2021;15(1):6.
18. Ahmad SH, Smith R, Camilleri B. Belatacept, kidney transplantation and COVID-19: successful management of the first reported case within the United Kingdom. Clin Transpl. 2020;34(9):e14026.
19. Marx D, Moulin B, Fafi-Kremer S, Benotmane I, Gautier G, Perrin P, et al. First case of COVID-19 in a kidney transplant recipient treated with belatacept. Am J Transpl. 2020;20(7):1944–6.
20. Cheng CW, Hendrickson JE, Tormey CA, Sidhu D. Therapeutic plasma exchange and its impact on drug levels. American Journal of Clinical Pathology. 2017 [cited 2024 Mar 28];148(3):190–8. Available from: http://academic.oup.com/ajcp/article/148/3/190/4057092/Therapeutic-Plasma-Exchange-and-Its-Impact-on-Drug
21. Morgan T. Clinical pharmacokinetics and pharmacodynamics of carvedilol. Clin Pharmacokinet. 1994;26(5):335–46.
22. Curry DE, Richards BL. A brief review of quetiapine. American Journal of Psychiatry Residents' Journal. 2022 [cited 2024 Mar 28];18(2):20–2. Available from: https://doi.org/10.1176/appi.ajp-rj.2022.180207
23. Meredith PA, Elliott HL. Clinical pharmacokinetics of amlodipine. Clin Pharmacokinet. 1992;22(1):22–31.
24. Yassa ET, Bakbak B. Chronic relapsing inflammatory optic neuropathy. Sisli Etfal Hastan Tip Bul. 2019;53(4):437–40.
25. Molina-Carrión LE, Lira-Tecpa J, Jiménez-Arellano MP, Cruz-Domínguez MP, Medina G. Disease course of chronic relapsing inflammatory optic neuropathy (CRION) in a single care center. Arq Neuropsiquiatr. 2022;80(5):510–5.
26. Lee G, Arepally GM. Anticoagulation techniques in apheresis: from heparin to citrate and beyond. J Clin Apher. 2012;27(3):117–25.
27. Pearl RG, Rosenthal MH. Metabolic alkalosis due to plasmapheresis. Am J Med. 1985;79(3):391–3.
28. Marques MB, Huang ST. Patients with thrombotic thrombocytopenic purpura commonly develop metabolic alkalosis during therapeutic plasma exchange. J Clin Apher. 2001;16(3):120–4.
29. Mokrzycki MH, Kaplan AA. Therapeutic plasma exchange: complications and management. Am J Kidney Dis. 1994;23(6):817–27.
30. Kaplan A. Complications of apheresis. Semin Dial. 2012;25(2):152–8.

Publisher's note

Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.