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Ferumoxytol: A Multifunctional Nanomedicine for Iron Deficiency synthesised

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ABSTRACT

Ferumoxytol, a colloidal superparamagnetic iron-carbohydrate complex, has emerged as a highly effective intravenous iron replacement therapy, particularly for patients with iron deficiency anaemia (IDA) and IDA associated with chronic kidney disease (CKD). Unlike traditional iron supplements, Ferumoxytol offers rapid and efficient iron replenishment with minimal side effects, addressing key challenges such as poor bioavailability and gastrointestinal intolerance. Its unique nanoparticle formulation, consisting of iron oxide cores coated with a biocompatible dextran shell, enhances stability and reduces immunological reactivity. Additionally, its potential in targeted molecule delivery underscores its growing relevance in nanomedicine. The synthesis process, employed by West Bengal Chemical Industries Ltd. (WBCIL), ensures the production of high-purity, biocompatible nanoparticles with optimized therapeutic performance. This study explores nutraceutical applications of Ferumoxytol and its advanced synthesis process conducted by WBCIL.

Keywords: *Ferumoxytol, iron deficiency anaemia (IDA), chronic kidney disease (CKD).*

Introduction

Ferumoxytol is a colloidal superparamagnetic iron-carbohydrate complex that has been widely used as an intravenous iron replacement therapy for patients suffering from iron deficiency anaemia (IDA) and those with chronic kidney disease (CKD).[1] Traditional iron supplements, including oral formulations, often present challenges such as poor bioavailability, gastrointestinal intolerance, and a prolonged treatment timeline. Intravenous iron therapies, including Ferumoxytol, provide a more efficient means of replenishing iron stores, ensuring rapid correction of anaemia while minimizing adverse effects related to excessive free iron in circulation.[2]

Ferumoxytol is a non-stoichiometric magnetite (superparamagnetic iron oxide) core coated with polyglucose sorbitol carboxymethylether (PSC). It includes a core of 5,874 iron atoms present as a super-paramagnetic iron oxide and a relatively thick coating of carboxy-methyldextran (CMD). The overall colloidal particle size is 17-31 nm in diameter.[3] Ferumoxytol is unique due to its nanoparticle formulation, which consists of iron oxide cores coated with a biocompatible carbohydrate shell. This dextran-based coating enhances stability, prevents rapid aggregation, and reduces immunological reactivity, making Ferumoxytol a superior alternative to other intravenous iron therapies.[3, 4] The synthesis of Ferumoxytol is a crucial aspect of its pharmaceutical performance. West Bengal Chemical Industries Ltd. (WBCIL), one of the leading manufacturers, employs a meticulously controlled multi-step synthesis process to ensure the production of high-purity, biocompatible Ferumoxytol nanoparticles. The synthesis begins with the controlled co-precipitation of iron salts, specifically ferrous and ferric chloride, in an aqueous solution. A base, such as ammonium hydroxide, is gradually introduced to facilitate the formation of uniform magnetite nanoparticles, which serve as the iron oxide core of Ferumoxytol.

This step is vital for achieving the desired size and superparamagnetic properties of the nanoparticles.[4, 5]

Following the formation of the core, a coating process is applied using a dextran-based carbohydrate shell. WBCIL utilizes a pharmaceutical-grade dextran that undergoes a reduction and cross-linking to ensure stability and prevent rapid aggregation. A further critical step is carboxymethylation, which introduces functional carboxyl groups. This modification is key to enhancing the drug's colloidal stability, prolonging its circulation time in the body, and reducing the likelihood of being cleared by the immune system (opsonization). The dextran-based coating ultimately minimizes immunological reactivity, making Ferumoxytol a superior option for intravenous iron therapy.[6] The final stage involves rigorous purification methods, including filtration and dialysis, to remove any unreacted reagents and byproducts. This ensures the resulting Ferumoxytol formulation meets stringent pharmaceutical standards and allows for rapid intravenous administration with minimal risk of hypersensitivity reactions.[7]

The resulting formulation offers multiple advantages, including rapid intravenous administration, minimal hypersensitivity reactions, and enhanced bioavailability compared to other iron therapies. Given these unique properties, Ferumoxytol continues to play a vital role in modern clinical practice, addressing iron deficiency in patients who cannot tolerate or do not respond to oral iron supplements.[7] Ongoing research into its expanded nutraceutical applications, particularly in precision medicine, further highlights its potential as a transformative agent in nutraceutical fields.

Applications of Ferumoxytol

Ferumoxytol has a broad spectrum of applications, making it an essential component in modern medicine. Its primary use is in iron replacement therapy, specifically for patients with CKD who suffer from iron deficiency anaemia.[1]

Unlike conventional oral iron supplements, Ferumoxytol provides a sustained and effective increase in iron levels, significantly improving patient outcomes.[2] Ferumoxytol is an intravenous iron replacement therapy with a high molecular weight of 731 kDa. This is the result of the iron oxide core being coated with a carbohydrate shell. The molecular weight of the iron oxide core (Fe3O4) itself is much smaller, about 231.53 g/mol. This high molecular weight, which is enhanced by a dextran-based coating and a carboxymethylation step, is a significant factor in its clinical superiority, contributing to its prolonged circulation time and enhanced safety. However, Ferumoxytol Batch FMX/15B/05/25 was synthesized by WBCIL to a molecular weight of 250.5 kDa to demonstrate excellent colloidal stability and a narrow particle size distribution (PDI=1.25), fitting a target range for a stable nanoparticle product, potentially customized for clients' specific demands or application that prioritizes this weight profile. The drug's unique nanoparticle formulation, consisting of an iron oxide core coated with a biocompatible PSC ligand, functions to mimic a natural ferritin shell. This design facilitates a controlled, slow release of iron, which minimizes the toxicity associated with excessive free iron in circulation, such as oxidative stress. The superior safety profile, which includes a reduced risk of hypersensitivity reactions, is directly attributed to this stable dextran coating and controlled iron release mechanism, making it a better option than earlier intravenous iron formulations like iron dextran. Ferumoxytol is noted for its lower infusion burden, as it can be administered in fewer doses than iron sucrose, which can improve patient compliance and reduce patient visits. Given that both Ferumoxytol and FCM are effective intravenous options, the choice between them should be based on patient-specific parameters and the logistics that best support patient compliance. In addition to its role as an iron supplement, Ferumoxytol has gained attention as an MRI contrast agent. Its superparamagnetic properties allow it to serve as an effective alternative to gadolinium-based contrast agents, especially for patients with renal impairment, reducing the risk of nephrogenic systemic fibrosis.[3] Additionally, its ability to replenish iron stores efficiently makes it a valuable option for treating haematological disorders, expanding its clinical significance beyond iron supplementation.[4]

Significance of the formulation

Ferumoxytol offers several nutraceutical advantages over conventional iron therapies. One of its key benefits is enhanced bioavailability.[8] Its nanoparticulate formulation ensures rapid absorption with minimal side effects, making it a preferred choice for patients who require immediate iron supplementation.[9] Additionally, Ferumoxytol exhibits reduced immunogenicity due to its dextran coating, which significantly lowers the risk of hypersensitivity reactions compared to other intravenous iron formulations. [8] Another critical advantage of Ferumoxytol is its lower infusion burden.[10] Unlike iron sucrose or ferric carboxymaltose, Ferumoxytol can be administered in fewer doses, reducing patient visits in OPD and improving compliance.[9] Furthermore, its superior stability, facilitated by the carboxymethyl dextran coating, enhances controlled iron release, minimizing adverse effects such as oxidative stress and free iron toxicity.[10] These properties position Ferumoxytol as a crucial innovation in intravenous iron therapy, with significant implications for improving patient care and expanding the scope of iron deficiency management.

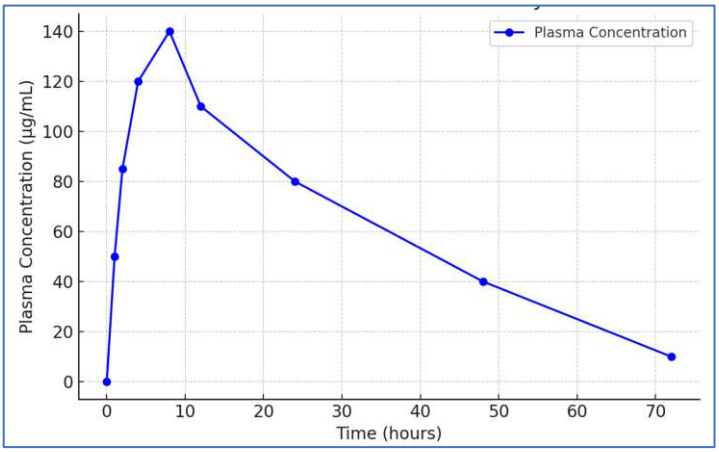

Figure 1: Pharmacokinetics of Ferumoxytol [2]

Regulatory Aspects and Clinical Trials

Ferumoxytol has undergone extensive clinical evaluation to establish its safety and efficacy in treating IDA, particularly among patients with CKD.[2] A pivotal Phase III, randomized, open-label trial compared Ferumoxytol to iron sucrose in adults with IDA unresponsive to oral iron therapy.[11] In this study, 605 patients were randomized in a 2:1 ratio to receive either two doses of 510 mg Ferumoxytol or five doses of 200 mg iron sucrose over 14 days. The primary endpoint was the change in haemoglobin levels from baseline to Week 5. Results demonstrated that Ferumoxytol was non-inferior to iron sucrose, with a mean haemoglobin increase of 2.9 g/dL in the Ferumoxytol group compared to 2.7 g/dL in the iron sucrose group. Both treatments exhibited comparable safety profiles, with similar incidences of adverse events.[11]

Another randomized, open-label, multicentre trial focused on CKD patients with IDA, comparing the efficacy and safety of Ferumoxytol and iron sucrose. A total of 162 patients were assigned to receive either two 510 mg injections of Ferumoxytol or a total of 1,000 mg of iron sucrose administered over multiple sessions.[12] The primary outcome measured was the change in haemoglobin levels from baseline to Week 5. Findings indicated that both treatments led to significant haemoglobin increases, with Ferumoxytol showing a mean rise of 1.2 g/dL and iron sucrose 1.0 g/dL. The safety profiles were comparable between the two groups, with no new safety concerns identified.[12]

These clinical trials have been instrumental in securing regulatory approvals for Ferumoxytol. The U.S. Food and Drug Administration (FDA) and the European Medicines Agency (EMA) have approved Ferumoxytol for the treatment of IDA in adult patients with CKD, based on evidence from these and other studies demonstrating its efficacy and safety.

Comparative Benefits Over Other Iron Therapies

Ferumoxytol offers several advantages over traditional iron therapies, particularly in the context of intravenous (IV) administration for patients with CKD. One notable benefit is the dosing regimen; Ferumoxytol can be administered in two doses of 510 mg each, allowing for the total therapeutic dose to be delivered within a shorter timeframe compared to iron sucrose, which often requires multiple administrations to achieve a similar cumulative dose.[12] This condensed dosing schedule can enhance patient convenience and compliance.

In terms of efficacy, clinical studies have shown that Ferumoxytol is at least as effective as iron sucrose in increasing haemoglobin levels.

For instance, in the Phase III trial, Ferumoxytol achieved a mean haemoglobin increase of 2.9 g/dL, comparable to the 2.7 g/dL increase observed with iron sucrose.[11]

Safety profiles between Ferumoxytol and iron sucrose are similar, with both treatments demonstrating comparable incidences of adverse events.[13] However, the more rapid administration protocol of Ferumoxytol may reduce the overall exposure to medical interventions, potentially decreasing the risk of infusion-related reactions and improving the patient's experience.[13]

Additionally, Ferumoxytol's superparamagnetic properties have opened avenues for its use as a contrast agent in MRI, particularly for patients with renal impairments where traditional gadolinium-based agents pose risks. This dual functionality not only broadens the clinical applications of Ferumoxytol but also offers a safer alternative for imaging in a specific patient population.[14]

Ferumoxytol is associated with minimal side effects and a reduced risk of hypersensitivity reactions compared to other intravenous iron formulations, such as earlier formulations like iron dextran.[15] This superior safety profile is primarily due to its unique nanoparticle formulation. The drug consists of an iron oxide core coated with a biocompatible, dextran-based carbohydrate shell, specifically PSC. The PSC ligand coating is critical for safety because it reduces the overall exposure of the iron oxide core to the immune system.[16] This coating minimizes immunological reactivity and lowers the risk of hypersensitivity reactions.[17] The synthesis process employed by WBCIL ensures high purity and a stable coating, which results in a formulation that allows for rapid intravenous administration with minimal risk of hypersensitivity reactions.

High molecular weight of Ferumoxytol is a significant factor contributing to its clinical superiority, particularly for its ability to remain in circulation longer and enhance safety.[18] The high molecular weight, facilitated by the dextran-based coating and the crucial step of carboxymethylation, significantly enhances the drug's colloidal stability and prolongs its circulation time in the body.[18] This longevity allows for more controlled and efficient iron delivery. A higher molecular weight and the resultant larger size, coupled with the functional carboxyl groups introduced by carboxymethylation, help reduce the likelihood of being cleared by the immune system (opsonization).[19] This characteristic makes Ferumoxytol a superior alternative to other intravenous iron therapies. The molecular weight profile and a low polydispersity Index indicate a narrow distribution of particle sizes, which is directly correlated with enhanced colloidal stability and a reduced aggregation risk.[20] This stability prevents the formation of aggregates that could cause adverse reactions. The physicochemical stability and prolonged circulation of the high-molecular-weight nanoparticle allow for a condensed dosing schedule and a lower infusion burden.

In summary, Ferumoxytol's efficient dosing regimen, proven efficacy, comparable safety profile, and unique imaging capabilities position it as a valuable alternative to conventional iron therapies, especially for patients with CKD and those requiring MRI diagnostics.

Methodology

Synthesis of Ferumoxytol by West Bengal Chemical Industries Ltd. (WBCIL)

West Bengal Chemical Industries Ltd. (WBCIL) follows a highly optimized, multi-step process for the synthesis of Ferumoxytol, a dextran-coated superparamagnetic iron oxide nanoparticle (SPION) formulation used for intravenous iron therapy. This process is designed to ensure pharmaceutical-grade purity, precise particle size distribution, high colloidal stability, and prolonged biocompatibility. The synthesis adheres to stringent Good Manufacturing Practices (GMP) and regulatory guidelines. The synthesis of Ferumoxytol was investigated in two main stages: the preparation of the Polyglucose sorbitol carboxymethyl ether (PSC) ligand and the final co-precipitation of iron oxide nanoparticles.

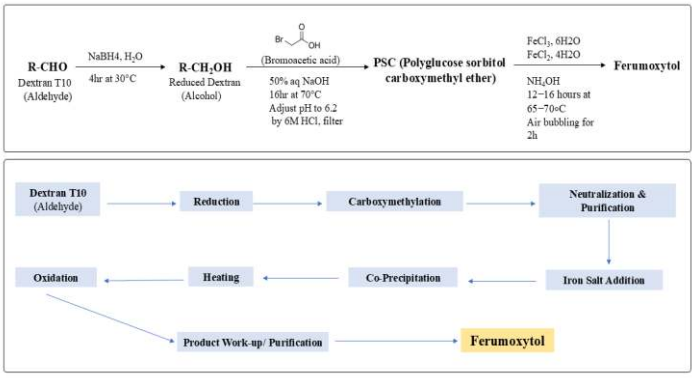

Figure 2: Flowchart showing the stepwise synthesis process of Ferumoxytol

Preparation of Polyglucose Sorbitol Carboxymethyl Ether (PSC)

The synthesis of the PSC ligand commenced with the reduction of Dextran T10 (containing aldehyde groups) using NaBH4 in water over 4 hours at 30∘C to yield Reduced Dextran (containing alcohol groups). This intermediate was subsequently subjected to carboxymethylation by reaction with Bromoacetic acid in the presence of 50% aqueous NaOH.[21] This step was carried out for 16 hours at 70∘C, followed by neutralization to a pH of 6.2 using 6M HCl and filtration to obtain the final PSC ligand. Previous attempts to synthesize PSC resulted in varying yields, such as 46g, 68g, 105g, and 35g from different batch sizes of the starting material with Dextran T10 input of 50g, 50g, 100g, and 20g, respectively.

Final Step: Synthesis of Ferumoxytol

The final synthesis step involved the reaction of the PSC ligand with ferric chloride hexahydrate (FeCl3·6H2O) and ferrous chloride tetrahydrate (FeCl2·4H2O) in water, followed by the addition of 25% Ammonia (NH4OH). A standard process condition involved 16 hours of heating at 65–70∘C, followed by air purging for 30 minutes.[22]

The successful batch FMX/15B/05/25 utilized 6.53g of PSC, 4.92g of FeCl3·6H2O, and 2.45g of FeCl2·4H2O in 100ml of water, with approximately 78.3g of 25% Ammonia. The resulting material showed an Iron content of 45.25% and a Carbohydrate content of 38.10%, with a pH of 6.074. Gel Permeation Chromatography (GPC) results for this batch indicated a Number-Average Molecular Weight (Mn) of 199,878, a Weight-Average Molecular Weight (Mw) of 250,468, and a Polydispersity Index (PDI) of 1.25. Furthermore, the initial Ferumoxytol:PSC ratio was 42:56, which improved to 91:5 after 20 passes through a resin purification step.[15, 16]

Multiple attempts to vary the iron ratio, base, and heating conditions were documented. Specifically, in attempts to form a solid product and avoid a resin column, final-step conditions were modified, including adjusting the pH with HCl to 7.5 or 4–6, followed by an additional heating step at 90–95∘C for 5 hours, and a final pH adjustment to 8–9 with NH4OH or NaOH.

These variations resulted in differences in the final solution color (reddish brown to blackish brown) and the isolated solid color (blackish brown to chocolate brown). The objective of obtaining a Ferumoxytol product with a higher molecular weight (750–900kDa) has been identified, which suggests a need to achieve a PSC with a weight-average MW of 200–500kDa.

Results and Discussion

Physicochemical Properties of WBCIL-Synthesized Ferumoxytol

The controlled, multi-step synthesis process employed by WBCIL successfully yielded a Ferumoxytol formulation (Batch FMX/15B/05/25) that exhibited key physicochemical characteristics crucial for pharmaceutical performance, particularly colloidal stability and controlled molecular weight.

Product Composition and Stoichiometry

The final Ferumoxytol product was analyzed for its core components. Batch FMX/15B/05/25 demonstrated an Iron content of 45.25% and a Carbohydrate content of 38.10%. This composition confirms a high concentration of the active iron oxide core encapsulated within the PSC ligand.

Crucially, the purification process, which involved 20 passes through a resin column, was highly effective in optimizing the core-to-shell ratio. The initial Ferumoxytol: PSC ratio was measured at 42:56, indicating a significant excess of free ligand post-synthesis. After purification, this ratio dramatically improved to 91:5. This refined ratio is fundamental to the drug's efficacy, as a high ratio ensures that the functional nanoparticle, rather than free carbohydrate, is the primary constituent, reducing the risk of infusion-related complications and optimizing iron delivery kinetics.

Molecular Weight Distribution and Colloidal Stability

The molecular weight profile, as determined by Gel Permeation Chromatography (GPC), confirmed the colloidal nature and uniform particle size distribution of the product (Batch FMX/15B/05/25).

Table 1: The key results for Batch FMX/15B/05/25

Parameter	Result
Number-Average Molecular Weight	199,878
Weight-Average Molecular Weight	250,468
Polydispersity Index	1.25
Final pH	6.074

The molecular weight of 250.468 kDa falls within the target range for stable, long-circulating superparamagnetic iron oxide nanoparticles. The low Polydispersity Index = 1.25 is particularly significant, as it indicates a narrow distribution of particle sizes, which is directly correlated with enhanced colloidal stability, reduced aggregation risk, and minimized opsonization by the reticuloendothelial system (RES). Furthermore, the final pH of 6.074 is appropriate for intravenous injection, demonstrating successful neutralization during the work-up stage.

The successful carboxymethylation of the dextran ligand, confirmed by the stable colloidal properties, is the primary factor preventing rapid aggregation and clearance. The introduction of these functional carboxyl groups provides essential negative charges that generate sufficient electrostatic repulsion to maintain the dispersed state of the iron oxide cores in solution.

Discussion of Pharmaceutical Performance and Clinical Relevance

The synthesis results validate the foundation for Ferumoxytol's superior nutraceutical profile. Its unique nanoparticle structure, composed of a stabilized iron oxide core coated with the PSC ligand, underpins its key clinical advantages over traditional iron therapies. Unlike oral iron supplements plagued by poor absorption and high gastrointestinal intolerance, the intravenous administration of Ferumoxytol ensures 100% bioavailability. The high nanoparticle purity achieved through the WBCIL process (91:5 Ferumoxytol: PSC ratio) ensures rapid and efficient iron replenishment.[23]

Clinically, this translates into a significant logistical advantage: Ferumoxytol can be administered in a condensed regimen (e.g., two 510 mg doses).[24] Comparative clinical trials have demonstrated that Ferumoxytol is non-inferior to and often achieves comparable haemoglobin increases to iron sucrose, but with a substantially lower infusion burden. For instance, a mean haemoglobin increase of 2.9 g/dL was observed in one study, comparable to 2.7 g/dL for iron sucrose, yet requiring fewer sessions. This lower infusion burden significantly improves patient convenience and adherence, particularly for patients with CKD who require ongoing vascular access.[24]

The PSC ligand coating is critical for safety. By reducing the overall exposure of the iron oxide core to the immune system, the coating lowers the risk of hypersensitivity reactions that have been historically associated with earlier intravenous iron formulations like iron dextran. The low polydispersity index and optimized molecular weight confirm the integrity of this coating, which functions to mimic a natural ferritin shell, allowing for controlled iron release and minimizing the toxicity associated with excessive free iron in circulation.[25]

Beyond its primary use as an iron replacement therapy, the superparamagnetic properties of the iron core enable Ferumoxytol's secondary application as a contrast agent in MRI. This theranostic potential is a major advantage, especially for the high-risk patient population of CKD, where traditional gadolinium-based contrast agents pose a risk of nephrogenic systemic fibrosis. The consistent, quality-controlled synthesis ensures the magnetic homogeneity required for effective diagnostic imaging. Ongoing research is exploring its use in targeted drug delivery systems, leveraging the magnetic core for precision medicine applications, particularly in oncology.

Conclusion and Future Prospects

Ferumoxytol, synthesized through a meticulously controlled, multi-step process by WBCIL, represents a significant advance in nanomedicine and intravenous iron replacement therapy. The synthesis ensures the production of high-quality, superparamagnetic iron oxide nanoparticles encapsulated within a PSC ligand. Analytical results, such as the low Polydispersity Index and the high post-purification Ferumoxytol: PSC ratio (91:5), confirm the product's superior colloidal stability and high purity. This optimized physicochemical profile translates directly into substantial clinical benefits: enhanced bioavailability, a reduced risk of hypersensitivity reactions due to the stable dextran coating, and a highly convenient, low-infusion-burden dosing regimen. Ferumoxytol is an effective and safe choice for treating IDA, particularly in vulnerable populations such as patients with CKD who require rapid iron repletion and cannot tolerate oral supplements. Furthermore, its inherent superparamagnetic properties grant it valuable dual functionality as a safer

alternative MRI contrast agent, expanding its utility into diagnostic imaging.

The future of Ferumoxytol extends significantly beyond its current primary use in iron deficiency management, establishing it as a promising platform for theranostic applications. Research is actively exploring the use of Ferumoxytol for treating iron deficiency across a wider array of clinical settings, including oncology, cardiology, and obstetrics. Its efficient mechanism of action and favorable safety profile make it an ideal candidate for managing anemia in cancer patients and those with chronic heart failure. Regulatory approvals for these broader indications will cement its role as a versatile therapeutic agent. The nanoscale size and superparamagnetic nature of Ferumoxytol are being leveraged in the field of targeted drug delivery. By chemically linking therapeutic agents to the PSC ligand, Ferumoxytol can function as a magnetic delivery vehicle. This is particularly relevant in cancer therapy, where its magnetic core can be exploited for tumour imaging, drug localization, and therapy monitoring, pushing the boundaries of precision medicine.

References

1. Schwenk, M. H. (2010). Ferumoxytol: A new intravenous iron preparation for the treatment of iron deficiency anemia in patients with chronic kidney disease. *Pharmacotherapy: The Journal of Human Pharmacology and Drug Therapy*, 30(1), 70–79. https://doi.org/10.1592/phco.30.1.70.
2. Macdougall, I. C., Strauss, W. E., McLaughlin, J., Li, Z., Dellanna, F., & Hertel, J. (2014). A randomized comparison of ferumoxytol and iron sucrose for treating iron deficiency anemia in patients with CKD. *Clinical Journal of the American Society of Nephrology*, 9(4), 705–712. https://doi.org/10.2215/CJN.07810713.
3. RK Pharma Inc., & Apicore Pharmaceuticals Private Limited. (2022). An improved process for the preparation of ferumoxytol 101010 (Patent application No. IN202223033400.WIPO12.
4. Spinowitz, B. S., Kausz, A. T., Baptista, J., Noble, S. D., Sothinathan, R., Bernardo, M. V., Brenner, L., & Pereira, B. J. (2008). Ferumoxytol for treating iron deficiency anemia in CKD. *Journal of the American Society of Nephrology*, 19(8), 1599–1605. https://doi.org/10.1681/ASN.2007101156.
5. Ceriello, A. (2020). Oxidative stress and glycemic regulation. Metabolism, 105, 154193. https://doi.org/10.1016/j.metabol.2020.154193.
6. Evans, J. L., Goldfine, I. D., Maddux, B. A., & Grodsky, G. M. (2018). Are oxidative stress–activated signaling pathways mediators of insulin resistance and beta-cell dysfunction? Diabetes, 67(1), 1-12. https://doi.org/10.2337/db17-0942.
7. Kowalczyk, M., Banach, M., & Rysz, J. (2011). Ferumoxytol: A new era of iron deficiency anemia treatment for patients with chronic kidney disease. *Journal of Nephrology*, 24(6), 717–722. https://doi.org/10.5301/jn.5000025.
8. Golbidi, S., Badran, M., & Laher, I. (2019). Antioxidant and anti-inflammatory effects of exercise in diabetic patients. Experimental Diabetes Research, 2019, 9582375. https://doi.org/10.1155/2019/9582375.
9. Han, Y., Smith, A. M., & Stokes, K. (2021). Advances in liposomal drug delivery systems for improved bioavailability of antioxidants. Journal of Pharmaceutical Sciences, 110(3), 1125-1140. https://doi.org/10.1016/j.xphs.2020.12.012.
10. Schiller, B., Bhat, P., & Sharma, A. (2014). Safety and effectiveness of ferumoxytol in hemodialysis patients at 3 dialysis chains in the United States over a 12-month period. *Clinical Therapeutics*, 36(1), 70–83. https://doi.org/10.1016/j.clinthera.2013.09.028.
11. Macdougall, I. C., Strauss, W. E., McLaughlin, J., Li, Z., Dellanna, F., & Hertel, J. (2014). A randomized comparison of ferumoxytol and iron sucrose for treating iron deficiency anemia in patients with CKD. *Clinical Journal of the American Society of Nephrology*, 9(4), 705–712. https://doi.org/10.2215/CJN.05320513.
12. Hetzel, D., Strauss, W., Bernard, K., Li, Z., Urboniene, A., & Allen, L. F. (2014). A Phase III, randomized, open-label trial of ferumoxytol compared with iron sucrose for the treatment of iron deficiency anemia in patients with a history of unsatisfactory oral iron therapy. *American Journal of Hematology*, 89(6), 646–650. https://doi.org/10.1002/ajh.23712
13. Chertow, G. M., Mason, P. D., Vaage-Nilsen, O., & Ahlmén, J. (2006). Update on adverse drug events associated with parenteral iron. *Nephrology Dialysis Transplantation*, 21(2), 378–382. https://doi.org/10.1093/ndt/gfi199.
14. Michael, B., Coyne, D. W., Fishbane, S., Folkert, V., Lynn, R., Nissenson, A. R., Agarwal, R., Eschbach, J. W., Fadem, S. Z., Trout, J. R., Strobos, J., & Warnock, D. G. (2002). Sodium ferric gluconate complex in hemodialysis patients: Adverse reactions compared to placebo and iron dextran. *Kidney International*, 61(5), 1830–1839. https://doi.org/10.1046/j.1523-1755.2002.00328.x.
15. Spinowitz, B. S., Kausz, A. T., Baptista, J., Noble, S. D., Sothinathan, R., Bernardo, M. V., Brenner, L., & Pereira, B. J. (2008). Ferumoxytol for treating iron deficiency anemia in CKD. *Journal of the American Society of Nephrology*, 19(8), 1599–1605. https://doi.org/10.1681/ASN.2007101156.
16. Balakrishnan, V. S., Rao, M., Kausz, A. T., Brenner, L., Pereira, B. J. G., Frigo, T. B., & Lewis, J. M. (2009). Physicochemical properties of ferumoxytol, a new intravenous iron preparation. *European Journal of Clinical Investigation, 39*(6), 489–496. https://doi.org/10.1111/j.1365-2362.2009.02130.x
17. Auerbach, M., & Macdougall, I. (2017). Ferumoxytol for the treatment of iron deficiency anemia: A review of the structure, pharmacokinetics, and safety profile. *Journal of Blood Medicine, 8*, 49–61. https://doi.org/10.2147/JBM.S138881
18. Philipp, A., et al. (2022). Criticality of surface characteristics of intravenous iron–carbohydrate nanoparticle complexes: Implications for pharmacokinetics and pharmacodynamics. *Pharmaceutics, 14*(10), 2011. https://doi.org/10.3390/pharmaceutics14102011
19. Wang, Y., et al. (2022). Polyelectrolyte Coating of Ferumoxytol Differentially Impacts the Labeling of Inflammatory and Steady-State Dendritic Cell Subtypes. *Biomedicines, 10*(12), 3137. https://doi.org/10.3390/biomedicines10123137
20. Weissleder, R., et al. (2005). Unveiling the next generation of MRI contrast agents: Current insights and perspectives on ferumoxytol-enhanced MRI. *National Science Review, 11*(5), nwae057. https://doi.org/10.1093/nsr/nwae057
21. Schiller, B., Bhat, P., & Sharma, A. (2014). Safety and effectiveness of ferumoxytol in hemodialysis patients at 3 dialysis chains in the United States over a 12-month period. *Clinical Therapeutics*, 36(1), 70–83. https://doi.org/10.1016/j.clinthera.2013.09.028.
22. West Bengal Chemical Industries Limited. (n.d.). *Iron*. Retrieved April 9, 2025, from https://www.wbcil.com/product-type/api-fine-chemicals-nutraceutical/iron/.
23. CN105597105A. (2016). *Method for preparing ferumoxytol*. Retrieved April 9, 2025, from https://patents.google.com/patent/CN105597105A/en.
24. Das, M., & Yang, C. (2018). *Synthesis of Ferumoxytol by ordinary chemical co-precipitation method*. *Nanoscale*, *10*(9), 4565–4572. Retrieved April 9, 2025, from https://www.rsc.org/suppdata/c8/nr/c8nr00736e/c8nr00736e1.pdf.
25. Feraheme® (ferumoxytol injection) prescribing information. (2022). AMAG Pharmaceuticals, Inc. Retrieved April 9, 2025, from https://www.accessdata.fda.gov/drugsatfda_docs/label/2022/022180s025lbl.pdf.