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REVIEW

Recent Advances in Vitiligo Treatment

Ye Qiu, Xiangxi Su, Jingru Chen, Shaojing Jiang, Xinrui Tang, Yurong He, Fang Liu

Department of Dermatology, Beijing Chaoyang Hospital, Capital Medical University, Beijing, People's Republic of China

Correspondence: Fang Liu, Department of Dermatology, Beijing Chaoyang Hospital, Capital Medical University, Beijing, People's Republic of China, Email roseliufang@qq.com

Purpose: This review systematically summarizes breakthrough advances in vitiligo treatment from 2020 to 2025 to provide the latest evidence-based insights for clinical practice.

Patients and Methods: We searched ClinicalTrials.gov and PubMed for literature and clinical trials published within this period. Inclusion criteria encompassed randomized controlled trials (RCTs), Phase II and above clinical trial results, and fundamental research with clear clinical translational value.

Results: Our analysis identified that JAK inhibitors achieved significant repigmentation by blocking the IFN-γ/JAK-STAT signaling pathway, while novel agents such as IL-15 inhibitors selectively eliminated pathogenic $CD8^+$ T cells, suppressing immune-mediated damage at its source. The combination of 308 nm excimer laser with JAK inhibitors or platelet-rich plasma (PRP) increased repigmentation rates in acral lesions to 56.1%, and vitamin D adjunct therapy demonstrated synergistic effects. For stable disease, ReCell technology combined with narrowband UVB (NB-UVB) emerged as an effective option, whereas miniature punch grafting further optimized surgical outcomes. Additionally, repurposed traditional drugs and antioxidant strategies expanded the available clinical arsenal.

Conclusion: Vitiligo treatment has entered an era of precision immune modulation, with JAK inhibitors establishing themselves as first-line therapy and novel biologics showing significant promise. Combined phototherapy and cellular therapy innovations markedly enhance repigmentation efficiency, and drug repurposing continues to enrich the therapeutic landscape.

Keywords: vitiligo, targeted therapy, JAK inhibitors, IL-15 inhibitors, combined phototherapy

Introduction

Vitiligo is a chronic autoimmune disorder characterized by the destruction and loss of skin melanocytes, with a global prevalence of approximately 0.5%-2%.[1] Conventional treatment modalities,[2] including phototherapy, topical calcineurin inhibitors, corticosteroids, systemic hormone therapy, and surgical transplantation techniques—exhibit significant limitations: long-term corticosteroid use frequently leads to skin atrophy, telangiectasia, and steroid dependence; phototherapy requires frequent interventions (2–3 sessions per week) and demonstrates suboptimal efficacy in acral regions; while surgical approaches carry the risk of donor-site scarring. There exists an urgent clinical need for safer and more effective innovative treatments.

Recent years have witnessed transformative advances in our understanding of vitiligo's immunopathogenesis, particularly through elucidation of core mechanisms such as aberrant activation of the JAK/STAT pathway and $CD8^+$ T cell-mediated melanocyte damage. These breakthroughs have catalyzed the development of targeted immunomodulatory therapies, innovative phototherapy technologies, and novel cellular treatment strategies, collectively providing unprecedented directions for clinical translation.

Current Research on Vitiligo Treatment

Pathogenesis

The pathogenesis of vitiligo results from the interplay between autoimmune dysregulation and oxidative stress, with the central pathogenic mechanism being the melanocyte-specific destruction mediated by autoreactive $CD8^+$ T cells.[3] This

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process initiates with danger-signal-triggered immune system activation: $CD8^+$ T cells recognize melanocyte surface antigens and launch cytotoxic attacks, while simultaneously secreting interferon-gamma (IFN-γ). IFN-γ activates the JAK/STAT signaling pathway, inducing keratinocytes and melanocytes to overexpress chemokines CXCL9/10. These chemokines further recruit $CXCR3^+$ $CD8^+$ T cells to infiltrate lesional skin, establishing a self-perpetuating cycle of amplified immune attack.[4]

Oxidative stress plays a central initiating role in the pathogenesis of vitiligo: the high metabolic activity of melanocytes leads to excessive generation of reactive oxygen species (ROS), while functional defects in the skin's antioxidant system result in ROS accumulation, directly triggering mitochondrial dysfunction, endoplasmic reticulum stress, and apoptosis. Simultaneously, ROS promote the release of inflammatory cytokines by activating the NF-κB pathway and stimulate melanocytes to release exosomes enriched with HSP70i, which activate dermal dendritic cells (cDC1) via the JAK1/TYK2-STAT signaling axis, initiating antigen presentation. The oxidative stress environment also upregulates interferon-stimulated genes such as ISG15, promoting sustained secretion of IFN-γ by $CD8^+$ T cells; IFN-γ, in turn, induces keratinocytes to highly express CXCL9/CXCL10 through the JAK-STAT pathway, recruiting more autoreactive $CD8^+$ T cells and forming a vicious cycle of "oxidative stress-immune attack" (Figure 1).

Furthermore, tissue-resident memory T cells (Trm) persist long-term with the support of IL-15 (signaling dependent on the JAK-STAT pathway), leading to disease recurrence and stubborn relapse; matrix metalloproteinase (MMP)-mediated degradation of E-cadherin disrupts melanocyte anchoring, while the local inflammatory microenvironment

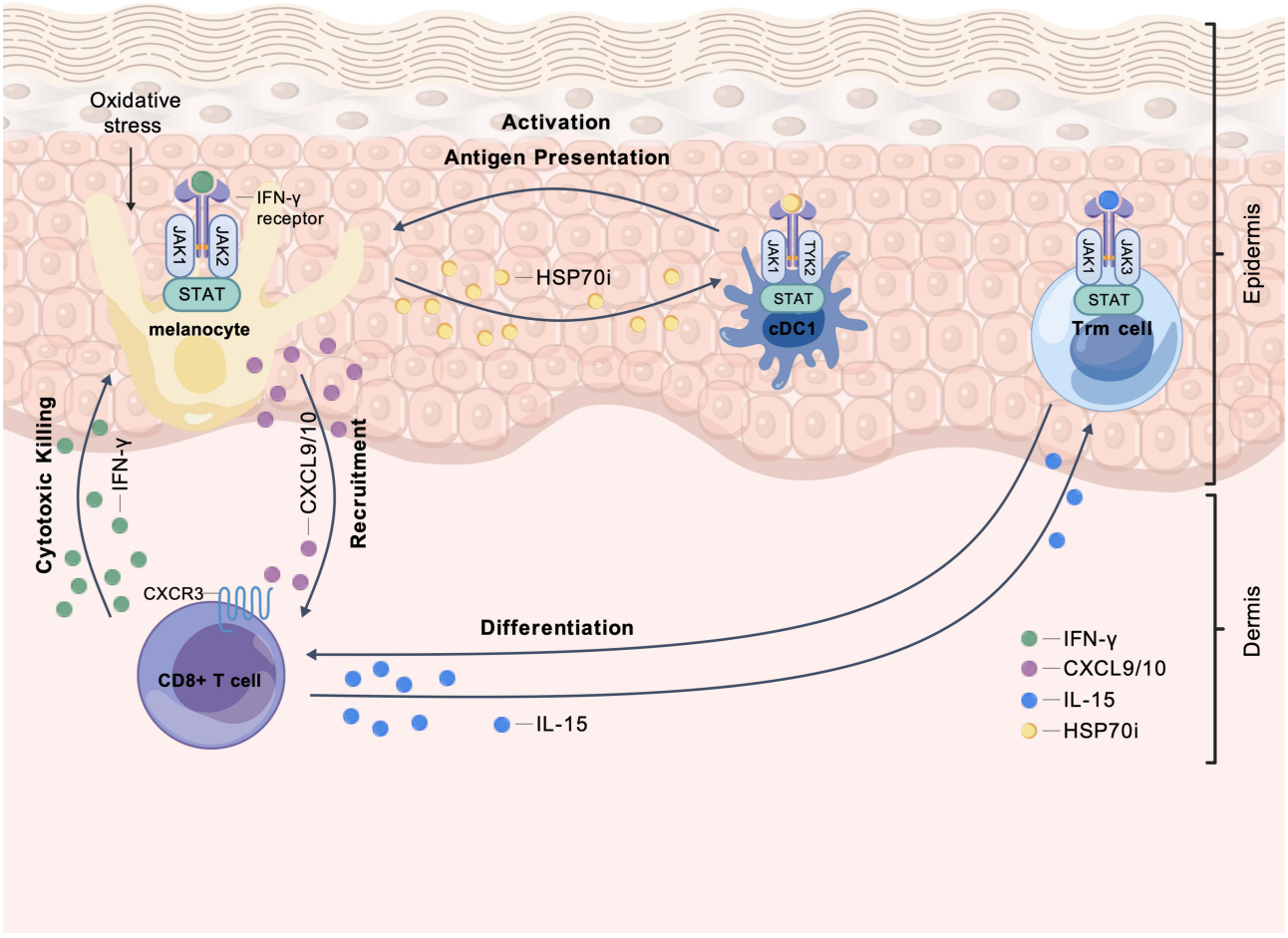

Figure 1 Pathogenesis of vitiligo. The schematic illustrates the core autoimmune mechanisms driving melanocyte destruction. Key processes include: $CD8^+$ T cell activation following antigen presentation by cDC1; cytotoxic killing of melanocytes and IFN-γ secretion; JAK-STAT pathway activation by IFN-γ in melanocytes, inducing chemokine (CXCL9/10) production and recruiting additional T cells; and persistence of Trm cells maintained by IL-15 signaling via JAK-STAT, enabling disease recurrence.
Abbreviations: cDC1, conventional type 1 dendritic cell; Trm, tissue-resident memory T cell.

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suppresses Treg function and weakens immune tolerance. These mechanisms, together with the JAK-STAT pathway, form a network that drives disease progression.[5,6]

Current Therapies[2]

Phototherapy remains the cornerstone of vitiligo management. Narrowband UVB (NB-UVB) is widely recommended as a first-line treatment for non-segmental vitiligo, typically administered 2–3 times per week. While effective for truncal and facial lesions, its efficacy is notably lower in acral areas (repigmentation rates <30%) and treatment often requires 6–12 months or longer. The 308nm excimer laser/light offers targeted phototherapy with potentially faster onset of repigmentation, but its accessibility and cost can be limiting factors.

Topical immunomodulators are first-line for facial and intertriginous areas. Calcineurin inhibitors (tacrolimus, pimecrolimus) are preferred over corticosteroids for sensitive areas to avoid skin atrophy. Topical corticosteroids are effective but their long-term use is restricted by risks of atrophy, telangiectasia, and steroid dependence.

Systemic immunomodulators are utilized for active or rapidly progressive disease. Oral corticosteroid minipulse therapy (eg, betamethasone/dexamethasone on 2 consecutive days per week) can halt disease progression. Conventional immunosuppressants like methotrexate, azathioprine, cyclosporine, and mycophenolate mofetil are also employed, albeit with varying levels of evidence and requiring monitoring for potential adverse effects.

Surgical interventions, including autologous skin grafting, suction blister epidermal grafting, and non-cultured epidermal cell suspensions, are reserved for stable, refractory vitiligo. Success depends on careful patient selection, as variable repigmentation and donor-site scarring remain challenges.

Combination therapy has long been a cornerstone of vitiligo management to enhance efficacy. Established regimens include the combination of phototherapy (NB-UVB) with topical calcineurin inhibitors or corticosteroids, and oral corticosteroid minipulse therapy combined with NB-UVB to concurrently suppress disease activity and stimulate repigmentation.[7]

Recent Advances (2020-2025)

Targeted Immunomodulation

JAK Inhibitors

Mechanism: The JAK family (JAK1-3, TYK2) are key molecules in cytokine signal transduction.[8] In vitiligo, IFN-γ binds to receptors associated with JAK1/JAK2 to initiate signaling. Under oxidative stress, melanocyte-derived exosomes release HSP70, which activates plasmacytoid dendritic cells via JAK1/TYK2 to produce type I IFNs, inducing keratinocytes to express CXCL9/10. Dermal fibroblasts' sensitivity to IFN-γ also contributes to the recruitment of $CD8^+$ T cells. JAK inhibitors block the JAK1/2/3 pathway, suppressing immune responses mediated by proinflammatory cytokines such as IFN-γ and IL-15.[9]

Advances

Ruxolitinib

A JAK1/JAK2 inhibitor. Phase II trials of its cream formulation have demonstrated significant repigmentation in adults with vitiligo.[10] The pivotal Phase III trials (TRuE-V1/V2) confirmed the efficacy and safety of ruxolitinib cream, leading to its regulatory approval.[11] A separate Phase II study (NCT05247489) had explored its combination with phototherapy.[12] Studies on its application in genital areas (NCT05750823) are ongoing.[13]

Baricitinib

A selective JAK1/JAK2 inhibitor.[14,15] Its Phase II trial combined with phototherapy (NCT04822584) first confirmed efficacy in generalized vitiligo,[16] providing evidence for combination therapies.[17]

Tofacitinib

Inhibits JAK1/JAK3 and partially JAK2/TYK2 activity. Oral administration of 510 mg twice daily achieves satisfactory repigmentation, with enhanced effects when combined with sunlight or NB-UVB therapy.[18]

Upadacitinib

A highly selective JAK1 inhibitor. Phase II studies showed that the 22 mg group had a significantly higher rate of vitiligo improvement (11.6%) compared to placebo (0%), along with a notable reduction in dermatology life quality index scores.[19] Phase III trials (NCT06118411) are ongoing.[20]

Ritlecitinib

An irreversible JAK3/TEC kinase inhibitor[21] that suppresses IL-2/IL-15induced cytotoxicity in Trm cells.[22] In Phase IIb trials, the 50 mg daily group (with a loading dose of 200 mg/day for 4 weeks) achieved a 21.2% reduction in F-VASI at 24 weeks, significantly outperforming placebo. Phase III trials (NCT05583526) are ongoing.[23]

SHR0302 Gel

A highly selective JAK1 inhibitor with excellent Phase III data for atopic dermatitis.[24] It is currently in early-stage clinical trials for vitiligo (NCT04774809)[25] and is expected to become China's first topical JAK inhibitor.

Additionally, novel JAK pathway-targeting drugs such as ICP-332 (with prior efficacy in AD)[26] and VC005 have advanced to Phase II trials for vitiligo,[27] indicating a forthcoming expansion of the therapeutic landscape.

IL-15 inhibitor

The novel drug AMG714 suppresses T cell activation by blocking IL-15 signaling, thereby reducing immune attacks on melanocytes at the source.[28] Its phase IIa randomized controlled trial (NCT04338581) is currently evaluating the achievement rate of Facial-Vitiligo Area Scoring Index ≥35 (F-VASI35) after 24 weeks of treatment.[29]

PDE4 Inhibitors

Roflumilast and crisaborole inhibit inflammation and promote melanocyte proliferation via the cAMP pathway. Crisaborole development has been paused due to corporate strategy adjustments, while 0.3% roflumilast cream applied once daily has shown efficacy in repigmenting refractory facial vitiligo in children with good tolerability.[30]

Other Targeted Agents

Abatacept (CTLA4 fusion protein): Suppresses T cell activation. Phase I trials (NCT02281058) are ongoing.[31]

Afamelanotide (α-MSH analog): Activates MC1R to promote melanogenesis. Phase III trials (NCT06109649) are comparing its efficacy in combination with NB-UVB versus NB-UVB monotherapy.[32]

Rapamycin (mTOR inhibitor): Modulates Treg function. Phase II trials (NCT05342519) are evaluating topical rapamycin cream (0.1%/0.001%).[33]

Metformin: Regulates immunometabolism via the AMPK pathway. Phase II trials (NCT05607316) are exploring its clinical value.[34]

Optimization of Phototherapy (308nm Excimer Laser)

Combination with JAK Inhibitors

Baricitinib combined with phototherapy significantly improves both the speed and extent of repigmentation.[17]

Combination with Platelet-Rich Plasma (PRP)

Increased repigmentation rates in acral lesions from 26.8% with phototherapy alone to 56.1%,[35] likely due to growth factors in PRP promoting melanocyte survival.

Combination with Vitamin D Supplementation

Oral vitamin D enhances the repigmentation effect of excimer laser, possibly through immunomodulatory synergy.[36]

Cellular Therapy and Surgical Innovations

Non-Cultured Cellular Grafting

Autologous cellular grafting has revolutionized the surgical repigmentation of stable vitiligo by transplanting melanocyte-rich suspensions. The most established technique is the non-cultured epidermal cell suspension (NCES, often

referred to as "ReCell" technology), which involves applying a suspension of melanocytes and keratinocytes onto dermabraded depigmented skin. A prospective multicenter study is evaluating the repigmentation efficacy of transplanting autologous skin cell suspensions combined with home-based NB-UVB phototherapy for stable depigmented lesions,[37] highlighting the trend of combining surgical and light-based modalities. Beyond standard NCES, evolving strategies aim to harness additional melanocyte reservoirs to enhance outcomes, particularly in challenging cases.

Combined Epidermal and Follicular Cell Suspension

For patients with stable yet refractory vitiligo, particularly in difficult-to-treat areas such as acral sites, bony prominences, and regions with leukotrichia, a significant surgical advance is the combined transplantation of non-cultured epidermal cell suspension (NCES) and follicular cell suspension (FCS). This integrated strategy synergistically utilizes the two primary reservoirs of melanocytes and their precursors: the interfollicular epidermis and the melanocyte stem cell (MelSC)-rich outer root sheath of hair follicles.

The clinical superiority of this combined approach over NCES alone has been established by randomized controlled trials. In a seminal study, the NCES + FCS combination demonstrated significantly better outcomes in extent of repigmentation (76% vs 57%), repigmentation rapidity, color match, and patient satisfaction. The enhanced efficacy is attributed to the combined suspension containing a higher proportion of MelSCs and exhibiting upregulated expression of key growth factors (eg, basic fibroblast growth factor and stem cell factor), which are crucial for melanocyte proliferation and survival.[38]

Recent comparative studies have further validated this strategy. One study reported that 65% of patients in the combined (NCES+FCS) group achieved >75% repigmentation at 4 months, compared to 30% in the NCES-only group, with significantly higher patient satisfaction in the combined group.[39] Another study demonstrated that after 6 months, the combination of FCS with mini-punch grafting (a tissue-cellular hybrid approach) yielded significantly better repigmentation than either technique alone, highlighting the additive benefit of incorporating follicular-derived cells.[40]

This integrated technique, which merges cellular sources from both the epidermis and hair follicles, is now recognized in surgical consensus as a first-line or valuable option for stable, refractory vitiligo. It represents a strategic evolution in cellular therapy, moving beyond single-source grafts towards a combinatorial, physiology-driven approach aimed at achieving more robust, uniform, and durable repigmentation, especially in challenging cases that are resistant to conventional therapies.

Innovations in Tissue Grafting Tools and Techniques

Parallel to advances in cellular grafting, significant refinements have been made in traditional tissue grafting methods to improve cosmetic outcomes and reduce morbidity. Instrument innovation is key; for instance, customized, small-diameter electric micro-punches enable mini-punch grafting (MPG) with minimal donor-site trauma, making it particularly suitable for exposed areas like the face and forearms while reducing scarring risk.[41] Furthermore, technical modifications such as the transverse incision technique in MPG have been reported to further reduce scar formation and accelerate repigmentation,[42] showing particular efficacy in anatomically nuanced areas like the hairline.[43] These continuous improvements in precision tools and surgical methods enhance the versatility and patient acceptance of tissue-based grafts for stable vitiligo.

Novel Applications of Traditional Drugs

Total Glucosides of Paeony (TGP)

Combined with NB-UVB and corticosteroid pulse therapy, significantly improves lesion area and disease activity in non-segmental vitiligo.[44]

Oral Compound Glycyrrhizin (OCG)

When combined with phototherapy in pediatric progressive vitiligo, effectively controls disease progression and accelerates repigmentation.[45]

Emerging Targets and Technologies

Biomarkers

Serum S100B levels significantly correlate with disease activity and may serve as objective indicators for monitoring and treatment evaluation.[46]

Psychological Intervention

Vitiligo patients often experience depression and anxiety, leading to low self-esteem and social isolation.[47] Psychotherapy can improve emotional state and treatment compliance, with ongoing efficacy evaluation trials (NCT05991596).[48]

Novel Strategies for Promoting Melanocyte Repigmentation

Antioxidant Therapy

Vitamin E/C and α-lipoic acid protect melanocytes by neutralizing ROS, enhancing repigmentation efficiency when combined with phototherapy.[49,50]

Melanocyte Activators

Wnt/β-catenin pathway activators promote melanocyte stem cell differentiation, while PGE2 analogs enhance melanocyte migration.[51]

Growth Factor Applications

Basic fibroblast growth factor (bFGF) and stem cell-conditioned medium promote melanocyte survival and regeneration via local injection or microneedle delivery.[52,53]

Physicochemical Adjuvant Techniques

Microneedling enhances drug penetration, while mild chemical peels accelerate epidermal renewal to improve local treatment outcomes.[54]

Traditional Chinese Medicine and Natural Compounds

Psoralen plus UVA (PUVA) induces repigmentation through photosensitization, while resveratrol exerts adjuvant effects via anti-inflammatory mechanisms.[55]

Summary of Clinical Evidence

The recent advances discussed above are supported by a robust pipeline of clinical research. Table 1 summarizes key findings from pivotal published trials, while Table 2 provides an overview of the status and scope of notable ongoing studies registered on ClinicalTrials.gov.

Summary and Future Perspectives

Summary

Vitiligo treatment has entered the era of "precision immunomodulation": JAK inhibitors, with the approval of topical ruxolitinib cream marking a new epoch in targeted therapy, have become important treatment options and are increasingly used in clinical practice; novel therapies like IL-15 inhibitors block the source of immune attacks by eliminating pathogenic T cells; optimized phototherapy combinations and advancements in cellular therapy have significantly enhanced repigmentation efficiency; while the innovative use of traditional medications and antioxidant therapies has further diversified the therapeutic arsenal.

However, a critical analysis reveals a clear distinction between theoretical promise and established clinical evidence. JAK inhibitors, particularly topical ruxolitinib, currently possess the most robust data from large-scale Phase 3 trials, solidifying their real-world position. In contrast, the promise of IL-15 inhibitors and several other novel agents remains largely theoretical, pending confirmation from larger and longer-term studies. Furthermore, the current evidence base has notable limitations: many trials have relatively short follow-up periods, obscuring long-term safety and durability of

Table 1 Key Published Clinical Trials in Vitiligo (2020–2025)

Intervention	Phase	Subjects	Trial Design	Significance/Key Findings
Ruxolitinib cream	2	157	Randomized, double-blind, vehicle-controlled trial	The primary endpoint was met: a significantly higher proportion of patients achieved ≥50% improvement in facial-VASI (F-VASI50) with ruxolitinib cream versus vehicle at 24 weeks (45% vs 13%, p<0.001).[10]
Ruxolitinib cream	3	674	Two replicate, randomized, double-blind, vehicle-controlled trials (TRuE-V1 /V2)	Met both co-primary endpoints: a significantly higher proportion of patients achieved F-VASI75 with ruxolitinib cream versus vehicle at 24 weeks (29.8% vs 7.4% in TRuE-V1; 30.9% vs 11.4% in TRuE-V2; p<0.001 for both). Led to FDA approval.[11]
Baricitinib + Phototherapy	2	49	Academic, multicenter, double-blind, noncomparative randomized clinical trial	The primary endpoint (change in T-VASI at week 36) was not statistically greater than the predefined threshold. However, a post hoc analysis revealed a significantly greater reduction in T-VASI with baricitinib + NB-UVB vs placebo + NB-UVB (−44.8% vs −9.2%; P=0.02), alongside improved quality of life and a comparable safety profile.[17]
Upadacitinib	2	185	Multicentre, randomised, double-blind, placebo-controlled, dose-ranging study	The primary endpoint was met: at week 24, the 11 mg and 22 mg doses demonstrated statistically significant, dose-dependent improvements in F-VASI versus placebo (LSMD: −21.27%, p=0.0051 and −19.60%, p=0.0132, respectively). Repigmentation continued through week 52. The 22 mg group had higher discontinuation and serious TEAE rates, with no new safety signals identified.[19]
Ritlecitinib	2b	364	Randomized, double-blind, placebo-controlled, Phase 2b trial	The primary endpoint was met: at week 24, the 50 mg dose (with or without loading dose) and the 30 mg dose achieved statistically significant, superior improvement in F-VASI versus placebo (eg, 50 mg: −21.2% vs +2.1%; P<0.001). Accelerated repigmentation continued through the extension period, with no dose-dependent safety concerns over 48 weeks.[21]
Roflumilast 0.3% cream	N/A (Case Report)	4 (Pediatric)	Single-case report	A case series of four pediatric patients with refractory facial vitiligo demonstrated that treatment with topical roflumilast 0.3% once daily led to repigmentation after previous treatments (including topical corticosteroids, ruxolitinib, and phototherapy) had failed.[30]
Total glucosides of paeony (TGP) + NB-UVB + Corticosteroid pulse	N/A (Retrospective)	117	Retrospective cohort study	This retrospective study suggested that adding TGP to oral minipulse corticosteroid (OMP) and NB-UVB therapy was associated with a superior effective rate (85.7% vs 60.7%, p=0.004) and greater reduction in disease activity (VIDA score), particularly for head/neck lesions, without increasing adverse events.[44]

(*Continued*)

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Table 1 (Continued).

Intervention	Phase	Subjects	Trial Design	Significance/Key Findings
Oral compound glycyrrhizin (OCG) + Phototherapy	N/A (Clinical study)	86	Prospective clinical study	This randomized trial demonstrated that OCG followed by phototherapy was non-inferior to oral prednisone (OP) + phototherapy in halting disease progression in pediatric vitiligo at 24 weeks (80% vs 84%, p>0.99) and achieved comparable repigmentation at 52 weeks, albeit with a slower onset of action than OP.[45]

Table 2 Key Clinical Trials for Vitiligo (2020–2025)

NCT Number	Intervention	Phase	Subjects	Study Type	Status	Results	Significance/Primary Outcome
NCT05247489	Ruxolitinib cream + Phototherapy	2	55	Interventional	Completed	This Phase II trial specifically evaluated the safety and efficacy of combining ruxolitinib cream with phototherapy.[12]	To explore the potential synergistic effect of a topical JAK inhibitor combined with phototherapy.[12]
NCT05750823	Ruxolitinib cream (genital)	2	49	Interventional	Completed	Results not posted	To evaluate the efficacy and safety of ruxolitinib cream in adults with vitiligo affecting the genital region.[13]
NCT04822584	Baricitinib + Phototherapy	2	49	Interventional	Completed	Baricitinib + phototherapy achieved superior repigmentation vs phototherapy alone (primary endpoint met)[17]	To evaluate the efficacy of combination therapy with an oral JAK1/JAK2 inhibitor and phototherapy.[17]
NCT06118411	Upadacitinib	3	614	Interventional	Active, not recruiting	Results not posted	To evaluate the safety and efficacy of upadacitinib in adults with vitiligo.[20]
NCT05583526	Ritlecitinib	3	592	Interventional	Active, not recruiting	Results not posted	To evaluate the efficacy and safety of ritlecitinib in active nonsegmental vitiligo.[23]
NCT04774809	SHR0302	2/3	75	Interventional	Terminated	Results not posted	To evaluate the efficacy and safety of SHR0302 ointment in subjects with vitiligo.[25]
NCT07047612	ICP-332 (Oral JAKi)	2/3	603 (Est).	Interventional	Recruiting	Results not posted	A pivotal phase 2/3 trial evaluating a novel JAK inhibitor (ICP-332) for non-segmental vitiligo.[26]
NCT07172347	VC005 Tablets (Oral JAKi)	2	120 (Est).	Interventional	Not yet recruiting	Results not posted	To evaluate the efficacy and safety of a novel JAK inhibitor (VC005) in non-segmental vitiligo.[27]

(*Continued*)

Table 2 (Continued).

NCT Number	Intervention	Phase	Subjects	Study Type	Status	Results	Significance/Primary Outcome
NCT04338581	AMG 714	2	60	Interventional	Completed	Results not posted	To evaluate the efficacy and safety of AMG 714 (anti-IL-15 mAb) in vitiligo.[29]
NCT05342519	Topical Rapamycin	2	20	Interventional	Active, not recruiting	Results not posted	To evaluate the safety and efficacy of topical rapamycin in vitiligo.[33]
NCT05607316	Metformin	2	0	Interventional	Withdrawn	Results not posted (N/A)	To explore the clinical value of metformin in vitiligo.[34]
NCT05971381	ReCell	N/A	109	Interventional	Completed	Results not posted	To study the Recell System for the treatment of vitiligo.[37]
NCT05991596	Psychodrama Therapy	N/A	7	Interventional	Completed	Results not posted	To evaluate the effect of a psychological intervention on adults with vitiligo.[48]

Abbreviations: i, inhibitor; mAb, monoclonal antibody.

response, especially for systemic immunomodulators. There is also a scarcity of head-to-head trials comparing novel therapies against each other or against optimized conventional combinations, making it difficult to establish a definitive treatment hierarchy. Finally, the high efficacy rates reported in structured clinical trials may not fully translate to routine practice, where patient adherence, comorbidities, and access to advanced therapies like cellular grafting can significantly impact outcomes.

Future Directions

Safety Studies

Long-term monitoring is required to assess the late-onset safety profiles of JAK inhibitors and IL-15 inhibitors, particularly regarding infection risks and potential oncogenic effects.

Combination Therapy Development

Future efforts should focus on investigating multimodal synergistic approaches combining immunomodulators, phototherapy, and cellular therapies, while developing personalized treatment strategies tailored to disease stages and lesion locations.

Technological Innovation

Develop precision treatment decision-making models based on biomarkers such as serum S100B and HLA typing;[46] explore the feasibility of using CRISPR-Cas9 gene editing technology to repair melanocyte functional defects, thereby advancing vitiligo treatment from symptom control to targeting root causes.[51]

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The author(s) report no conflicts of interest in this work.

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