

Estrogen and Metabolism: Navigating Hormonal Transitions from Perimenopause to Postmenopause

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ABSTRACT

Estrogen is a key hormone that influences metabolism, health, and overall well-being throughout a woman's life. Its levels fluctuate across different reproductive stages: perimenopause, menopause, and postmenopause – each bringing unique physiological changes. During perimenopause, estrogen helps regulate insulin production, glucose metabolism, and fat distribution. However, as levels become unstable in this phase, women may experience increased insulin resistance, shifts in fat storage, and a greater risk of metabolic disorders such as diabetes. Given its widespread effects, proactive lifestyle interventions are essential. A balanced diet rich in phytoestrogens, regular physical activity, and maintaining a healthy body weight can help manage hormonal shifts. Advancing research in molecular endocrinology and personalized medicine offers the potential for targeted strategies that deepen our understanding of estrogen's tissue-specific effects. By personalizing interventions to individual hormonal transitions, we can improve women's health outcomes and quality of life.

KEYWORDS: Estrogen, hormonal fluctuations, hormone therapy, perimenopause, women's health

INTRODUCTION

The health of families and communities is often linked to the well-being of women. Enhancing women's health is mandatory for advancing gender equality and promoting societal progress.^[1] The World Health Organization (WHO) defines natural menopause as the “permanent stopping of menstruation resulting from the loss of ovarian follicular activity,” typically diagnosed after 12 consecutive months of amenorrhea.^[2] The menopausal transition, which typically begins 5–10 years prior to a woman's final menstrual period, is marked by variability in menstrual cycles and significant fluctuations in reproductive hormone levels.^[3] Menopause typically occurs between the ages of 45 and 55 years in women. The menopausal transition is categorized into three stages: perimenopause (menopausal transition), menopause, and postmenopause.^[4] When menopause happens before the age of 45 years, it is classified as early menopause, while menopause before the age of 40 years is called as premature ovarian insufficiency.^[1] Currently, India has approximately 43 million women undergoing

menopause, a figure expected to double by 2026, reaching around 103 million. This trend emphasizes the urgent need for the healthcare sector to give attention to the unique health challenges faced by this expanding human population.^[5] Enhancing awareness about health issues associated with menopause can play a crucial role in improving how women understand and manage their health during the menopausal transition phase.^[6]

The female reproductive cycle is regulated by a complex interplay of hormones collectively referred to as the female hormonal system.^[7] The irregular changes in the menstrual cycle during perimenopause and menopause are largely due to the diminished responsiveness of the hypothalamic–pituitary axis to both the negative and positive feedback signals from ovarian hormones. This disruption contributes to many of the biological changes

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observed in these transitional phases. With advancing age, ovarian function gradually decreases, leading to a declining production of estrogen and progesterone, which in turn results in a deterioration in fecundity. As estrogen levels decline, follicle-stimulating hormone (FSH) and luteinizing hormone (LH) begin to fluctuate significantly, leading to hormonal imbalances that contribute to various menopausal symptoms. These hormonal fluctuations lead to an overall increase in the androgen-to-estrogen ratio, which can contribute to various physiological and symptomatic changes such as hot flashes, night sweats, sleep disturbances, vaginal dryness or atrophy, incontinence, increased risk of osteoporosis, and heart disease.^[8,9] These hormonal changes significantly impact the physical, emotional, and social well-being of females, often resulting in clinical symptoms resembling those observed during menopause.^[10-12]

This review highlights a critical yet often overlooked phase in women's health. The perimenopausal transition is a distinct 2–4-year period marked by hormonal fluctuations, altered body composition, and increased risks of insulin resistance, dyslipidemia, and cardiovascular disease. Unlike the extensively studied postmenopausal stage, perimenopause represents a “metabolic transition window” with unique physiological and clinical challenges that demand early recognition and proactive intervention. By introducing the concept of the “perimenopausal hormonal transition,” this review underscores the importance of addressing metabolic health during this period, not merely managing traditional menopausal symptoms. It synthesizes current evidence on estrogen's metabolic influence and provides clinicians with practical, evidence-based strategies for identifying at-risk women and implementing targeted interventions, including lifestyle modifications, phytoestrogen use, and hormone therapy (HT). In doing so, it advocates for a refined medical approach that positions perimenopause as a pivotal opportunity to optimize long-term metabolic outcomes in women.

METHODOLOGY

This clinically focused review employed a systematic search strategy, specifically targeting perimenopause-related metabolic dysfunction and evidence-based interventions. We conducted comprehensive searches of PubMed, Google Scholar, Scopus, and ScienceDirect databases for articles published between 2000 and 2025, using targeted keywords including “perimenopause,” “estrogen decline,” “metabolic transition,” “insulin resistance prevention,” and “lifestyle interventions.” Priority was given to

clinical trials, longitudinal studies, and meta-analyses, specifically examining perimenopausal women, with particular emphasis on studies providing quantifiable intervention outcomes and clinical decision-making tools. We included original research articles, systematic reviews, and clinical practice guidelines that offered practical applications for healthcare providers managing metabolic health during the perimenopausal transition. The synthesis focused on extracting clinically actionable evidence that could be directly implemented in primary care and specialty practice settings.

ROLE OF ESTROGEN IN INSULIN RESISTANCE

Insulin resistance is a pathological condition characterized by the impaired ability of circulating insulin to effectively regulate glucose uptake and utilization in insulin-sensitive tissues and organs. In the presence of insulin resistance, it leads to increased hepatic glucose production and reduced glucose uptake in muscle, liver, and adipose tissue. Paradoxically, individuals with insulin resistance exhibit both enhanced hepatic glucose production and elevated insulin secretion, contributing to or exacerbating hyperglycemia.^[13,14]

Estrogen plays a crucial regulatory role in metabolic processes during reproductive years, with significant changes during menopausal transitions. In premenopausal women, estrogen contributes to pancreatic β -cell survival by moderating inflammatory responses, an effect that diminishes during the menopausal transition.^[15] Estrogen's protective effects on glucose homeostasis include enhancing hepatic insulin sensitivity and supporting pancreatic function,^[16] as shown in Figure 1.

Their effects are mediated through estrogen receptors (ERs), including ER alpha (ESR1) and ER beta (ESR2), encoded by the ESR1 and ESR2 genes, respectively. A decline in circulating 17 β -estradiol (E2) and progesterone, whether due to natural or surgical menopause, extends beyond reproductive health, significantly influencing metabolic homeostasis in women.^[17] Adipose tissue plays a pivotal role in maintaining metabolic homeostasis, functioning both as an endocrine organ and an energy reservoir. Its regulatory actions are influenced by factors such as nutrient availability, hormonal fluctuations, and stress.^[18] According to the findings of Ahmed *et al.*, ESR1 gene expression remains comparable between premenopausal and postmenopausal women, whereas ESR2 expression is elevated in postmenopausal women.^[19] Selective deletion of ESR1 (ER1)/ER α in skeletal muscle has been shown to result in significant insulin resistance in female mice and cultured myotubes. This finding underscores the critical role of ER α in regulating insulin sensitivity

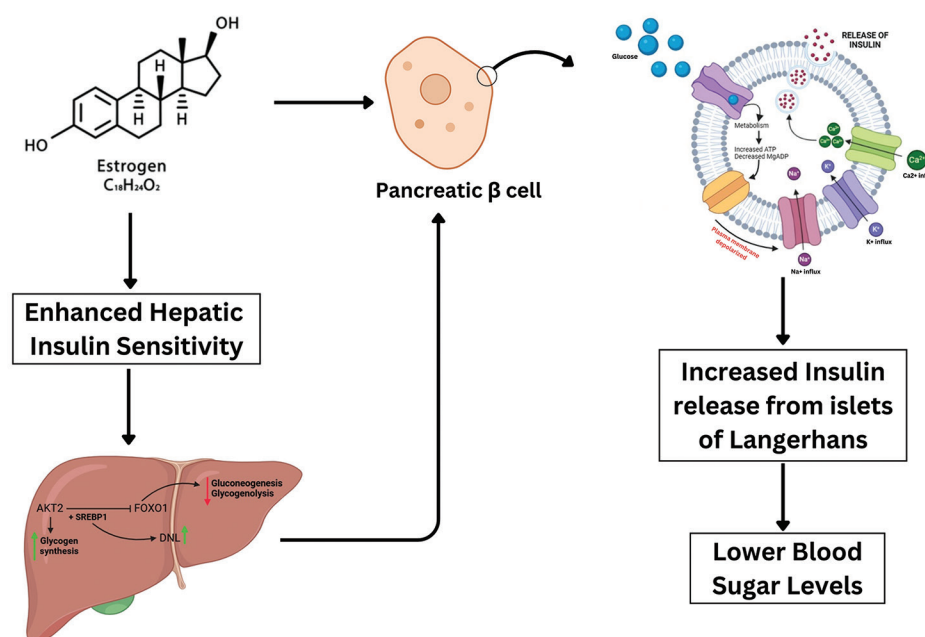


Figure 1: Estrogen-mediated modulation of pancreatic β -cells and insulin secretion: Estrogen exerts significant regulatory effects on pancreatic β -cells, including modulation of ATP-sensitive potassium (K^{ATP}) channels, influencing membrane depolarization, calcium ion influx, and insulin secretion. The figure highlights the estrogen's role in enhancing insulin secretion through inhibition of K^{ATP} channels, triggering action potentials through voltage-gated ion channels, and increasing intracellular Ca^{2+} levels

within skeletal muscle tissue.^[20] Postmenopausal ovaries produce progressively lower levels of E2. According to Park *et al.* suggest that the risk of diabetes during midlife is more closely associated with premenopausal estradiol levels rather than the rate of change in estradiol during the menopausal transition. In addition, the rate of change in FSH during the early stages of the menopausal transition, rather than premenopausal levels or changes in FSH during late perimenopause, is linked to the risk of developing diabetes.^[21]

ROLE OF ESTROGEN IN LIPID METABOLISM DURING PERIMENOPAUSE

During a woman's reproductive years, estrogen levels typically range between 100 and 250 pg/mL, but drop to around 10 pg/mL after menopause. This decline in estrogen is linked to a higher risk of cardiovascular disease due to its impact on lipid metabolism. The Study of Women's Health Across the Nation (SWAN), which tracked over 3300 women from 1996 to 2017, provides critical insight into the metabolic and cardiovascular changes that occur during the menopausal transition. In addition, the study reported a significant rise in apolipoprotein B, low-density lipoprotein cholesterol (LDL-C), total cholesterol (TC), triglycerides (TGs), and lipoprotein (a) levels during late perimenopause and early postmenopause. Although high-density lipoprotein cholesterol (HDL-C) levels initially increased, they tended to plateau in later

postmenopause. Other studies support the association of elevated LDL-C, TGs, and TC with menopause, although findings regarding HDL-C remain inconsistent; some report stable or slightly reduced levels. More importantly, emerging evidence suggests that the quality and function of HDL, including decreased HDL2 subfractions and increased oxidized HDL, may offer a clearer picture of cardiovascular risk than HDL-C levels alone. Therefore, assessing only serum HDL-C may overlook key indicators of atherogenic risk during and after menopause.^[16,22]

As women go through menopause transition, the drop in estradiol levels can significantly affect how HDL (the "good" cholesterol) is processed and functions in the body. Lower estradiol levels boost the activity of enzymes that break down larger HDL particles into smaller, less protective ones. Normally, estradiol helps clear cholesterol from blood vessel cells, so its decline may reduce this beneficial effect. The hormonal shifts that come with ovarian aging can also lead to a buildup of risk factors that promote chronic inflammation, which in turn can alter the makeup and function of HDL. On top of that, menopause often brings changes in how body fat is stored, which can increase the chances of developing insulin resistance and metabolic syndrome. These conditions are closely tied to oxidative stress and inflammation, both of which further disrupt HDL metabolism.^[23] Beyond its effects on circulating lipoproteins, estrogen plays a critical intracellular role in regulating lipid metabolism, as shown in Figure 2,

through modulation of key enzymes involved in *de novo* lipogenesis. Estrogen influences enzymes such as malonyl-CoA decarboxylase, acetyl-CoA carboxylase, and fatty acid synthase, reducing malonyl-CoA availability and long-chain fatty acid synthesis. This results in decreased *de novo* lipogenesis, reduced ectopic lipid accumulation in insulin-sensitive tissues, and ultimately better insulin sensitivity. These changes improve glucose homeostasis and reduce the risk of insulin resistance and type 2 diabetes.^[24]

ROLE OF ESTROGEN ON OBESITY IN PERIMENOPAUSE

Obesity represents a significant global health challenge with relevance during menopausal transitions. Weight gain affects 60%–70% of middle-aged women during the menopausal transition, with the WHO reporting that 55% of women globally were classified as overweight or obese as of 2016.^[25] The menopausal transition correlates with significant changes in body composition and fat distribution patterns. While premenopausal women typically exhibit gynoid fat distribution (femoral–gluteal regions), the perimenopausal period marks a clinical shift toward central adiposity.^[26,27] These changes are clinically significant as they are associated with increased cardiometabolic risk compared to peripheral fat accumulation. This redistribution pattern is illustrated in Figure 3, demonstrating how hormonal shifts influence central appetite regulation and adipose tissue metabolism. Clinical studies have demonstrated that the perimenopausal transition is associated with decreased energy expenditure and altered appetite regulation. Van Pelt *et al.* found that these metabolic changes include reductions in resting metabolic rate, declines in spontaneous physical activity, and increases in caloric intake.^[28] These functional changes have direct clinical implications for weight management strategies during this life stage.

Body composition analyses of perimenopausal women reveal not only increased adiposity but also decreased lean body mass. This unfavorable shift in body composition, as shown in Figure 3, contributes to reduced basal metabolic rate and decreased capacity for energy expenditure, creating a physiological environment that promotes weight gain. Clinical assessments consistently show that these changes often precede the cessation of menses, suggesting that metabolic adaptations begin during the perimenopausal phase rather than after established menopause.^[9] From a clinical perspective, understanding these metabolic changes during perimenopause provides opportunities for targeted interventions.

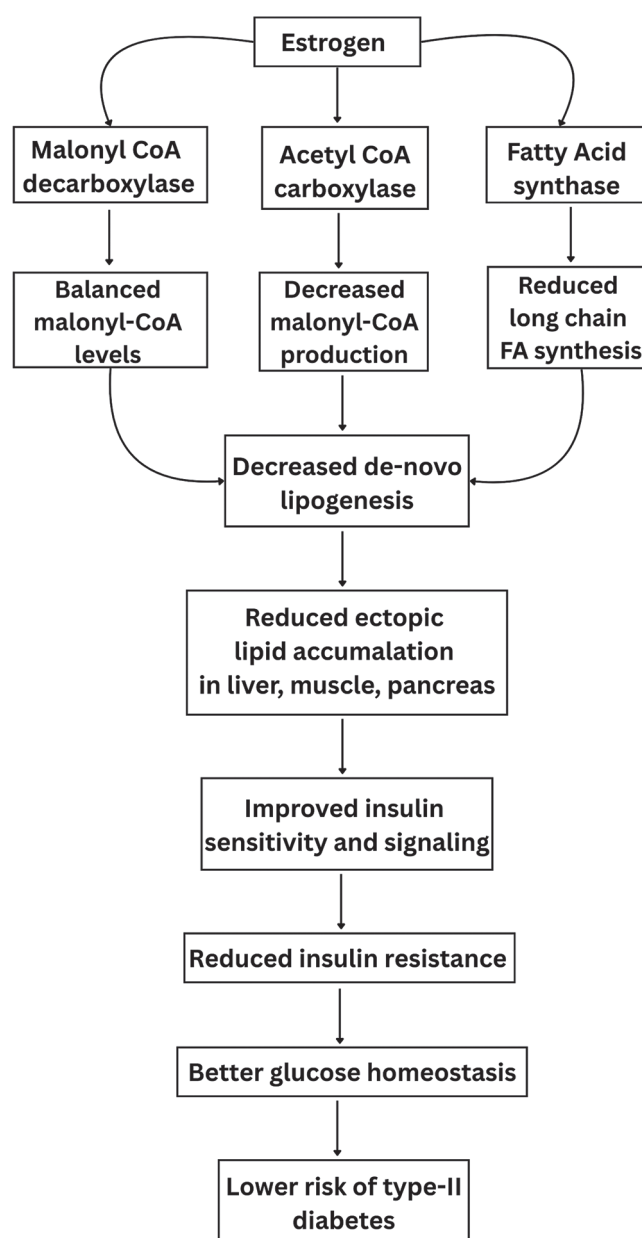


Figure 2: Proposed mechanism of estrogen-mediated regulation of lipid metabolism and insulin sensitivity: Estrogen modulates key enzymes involved in lipid metabolism, including malonyl-CoA decarboxylase, acetyl-CoA carboxylase, and fatty acid synthase. This leads to balanced malonyl-CoA levels, decreased malonyl-CoA production, and reduced long-chain fatty acid synthesis, collectively resulting in decreased *de novo* lipogenesis. The downstream effects include reduced ectopic lipid accumulation in the liver, muscle, and pancreas, which contributes to improved insulin sensitivity and signaling. Consequently, this cascade reduces insulin resistance, enhances glucose homeostasis, and lowers the risk of developing type 2 diabetes

EFFECT OF UNHEALTHY LIFESTYLE FACTORS IN PERIMENOPAUSE

The perimenopausal transition represents a period of increased vulnerability where unhealthy lifestyle factors can exacerbate metabolic and cardiovascular risk profiles. Clinical studies demonstrate that

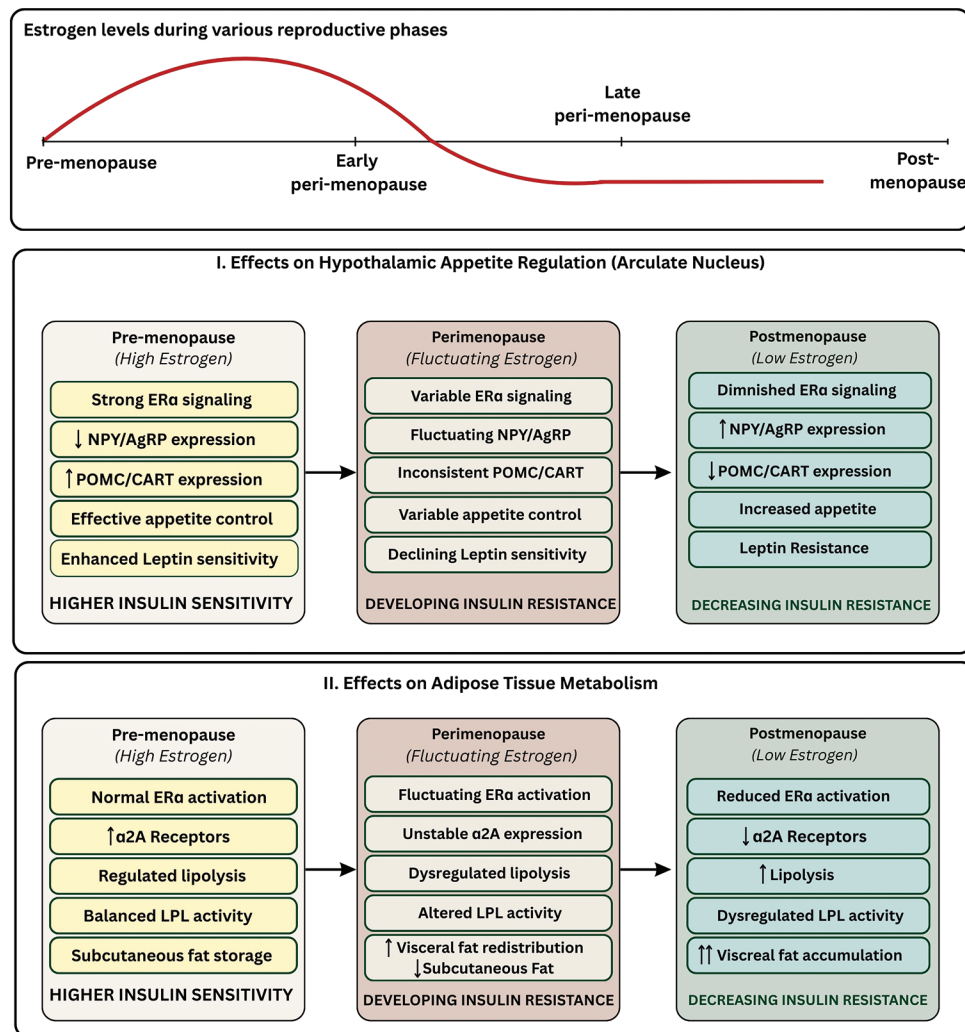


Figure 3: Estrogen's effects on metabolic regulation during reproductive transitions: This figure illustrates the dynamic relationship between estrogen levels and metabolic regulation across reproductive stages. The top panel displays estrogen's trajectory from high levels in premenopause through fluctuating patterns during perimenopause to consistently low levels in postmenopause. The middle panel demonstrates estrogen's impact on hypothalamic appetite regulation, showing how declining estrogen progressively alters estrogen receptor α signaling pathways, neuropeptide expression (neuropeptide Y/Agouti-related protein [appetite-stimulating] and pro-opiomelanocortin/cocaine- and amphetamine-regulated transcript [appetite-suppressing]), and leptin sensitivity. These changes contribute to the transition from effective appetite control and high insulin sensitivity during premenopause to increased appetite and insulin resistance in postmenopause. The bottom panel depicts how these hormonal shifts affect adipose tissue metabolism, with premenopausal estrogen promoting subcutaneous fat storage and regulated lipolysis, while perimenopausal fluctuations and postmenopausal deficiency lead to visceral fat redistribution, dysregulated lipolysis, altered lipoprotein lipase activity, and worsening insulin resistance. Together, these panels demonstrate how estrogen's decline fundamentally reshapes metabolic function through both central and peripheral mechanisms. ER: Estrogen receptor, NPY/AgRP: Neuropeptide Y/Agouti-related protein (appetite-stimulating), POMC/CART: Pro-opiomelanocortin/cocaine- and amphetamine-regulated transcript (appetite-suppressing), LPL: Lipoprotein lipase, α 2A: alpha-2A adrenergic receptor

smoking, alcohol consumption, and physical inactivity significantly impact women's health outcomes during this critical transition.^[29] During the challenging transition of perimenopause, heavy cigarette use seems to affect women's mental health. One study found that women who smoked more than a pack a day were much more likely to experience depression during this time in their lives, showing how our daily habits can significantly impact our emotional well-being during hormonal changes. The same connection appears with drinking habits. Research has shown clear links between how much alcohol women consume and their risk

of depression, both during and after the menopausal transition.^[30] These findings highlight the importance of addressing multiple lifestyle factors simultaneously when developing clinical approaches to perimenopausal health management.

ADOPTING HEALTHY LIFESTYLE

Lifestyle medicine (LM) offers a relevant approach for addressing the complex metabolic changes occurring during perimenopause. As an emerging medical specialty, LM integrates evidence-based lifestyle practices into conventional medicine to reduce chronic

disease risk factors and complement existing treatment approaches.^[31] This integrated approach is particularly valuable during perimenopause when multiple body systems undergo significant adaptations.

During the transition, physiological changes affect skeletal muscle, liver, pancreas, and intestinal function. These changes, illustrated in Figure 4, have direct possible clinical effects for metabolic health, including alterations in muscle mass maintenance, glucose regulation, and mitochondrial function. Clinical evidence demonstrates that unhealthy lifestyle habits exacerbate these physiological changes, while positive interventions can mitigate their impact.^[32] Furthermore, research indicates that adopting a healthy lifestyle can reduce the severity of perimenopausal symptoms.

A meta-analysis of middle-aged women found that walking at least 6000 steps daily was associated with a significant reduction in cardiovascular and metabolic risk factors, independent of menopausal status. This threshold is clinically practical and has been incorporated into preventive guidelines due to its feasibility and consistency with improved glucose tolerance, lipid profile, and inflammatory markers.^[31,33] For weight management during perimenopause, clinical evidence supports creating a modest energy deficit of 500–1000 kcal/day (approximately 25 kcal/kg/day), leading to a sustainable weight loss of 0.5–1 kg weekly. Protein intake of 1–1.2 g/kg/day (or 20% of

total energy) combined with resistance exercise has demonstrated clinical efficacy in preserving muscle mass during weight loss.^[34] The mechanisms behind protein's effectiveness in weight management are shown in Figure 5, highlighting its role in satiety hormone regulation and metabolic function.

Nutritional quality during perimenopause extends beyond macronutrient ratios to include fatty acid composition. Clinical research supports replacing saturated fatty acids with polyunsaturated fatty acids from sources such as seeds, nuts, and vegetable oils to improve metabolic parameters during the menopausal transition.^[22]

Lifestyle modifications during the perimenopausal years play a critical role in addressing social determinants of health, ensuring equitable access to healthcare, and promoting research that considers women's unique needs and experiences. Midlife and perimenopause present a suitable time to emphasize the importance of health screening and risk factor assessment. Perimenopausal women should evaluate their risk factors to implement lifestyle changes that mitigate or reverse adverse health effects. This study utilizes a simple screening questionnaire to assess the lifestyle practices and habits of perimenopausal women.^[33] The time when women are approaching menopause presents a golden opportunity to get ahead of potential health problems. Doctors should use simple questionnaires to understand each woman's unique risks and then

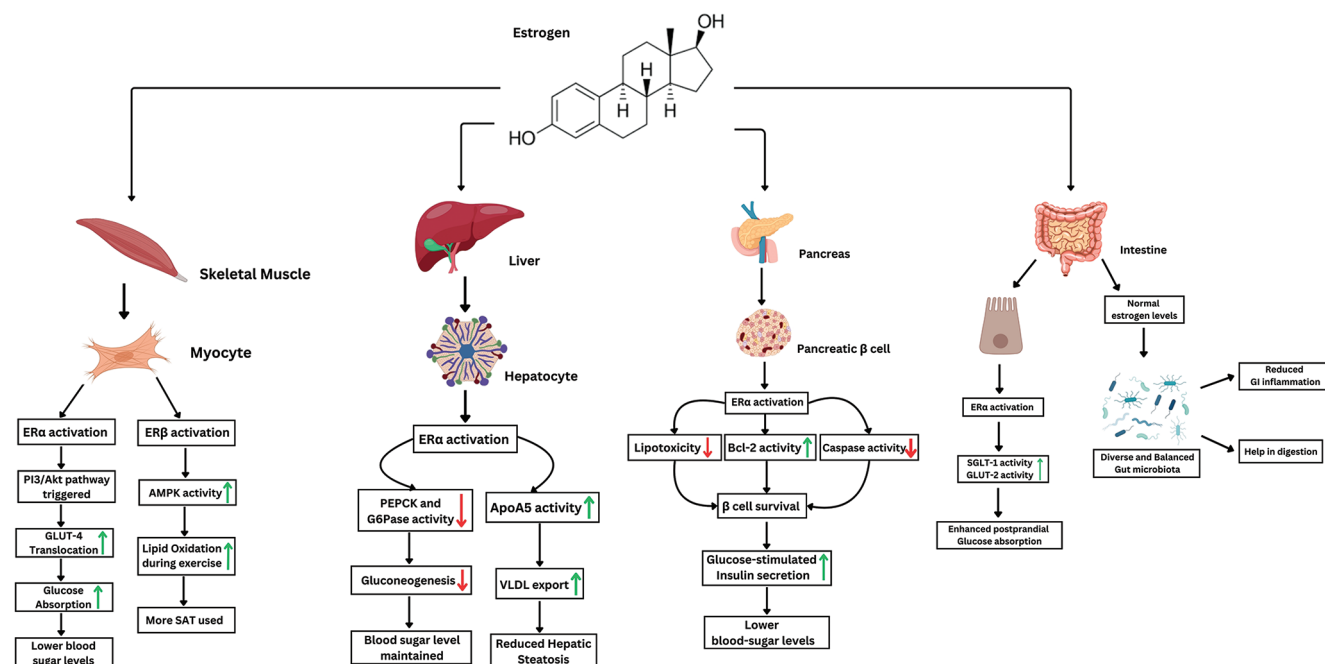


Figure 4: Role of estrogen in metabolic regulation across key organs: This diagram illustrates estrogen's role in glucose and lipid metabolism via estrogen receptor (ER) α and ER β activation in the muscle, liver, pancreas, and intestine. Key mechanisms include PI3K/Akt signaling, GLUT-4 translocation, AMPK activation, β -cell survival, and gluconeogenesis suppression, highlighting estrogen's protective effects against metabolic disorders. ER: Estrogen receptor

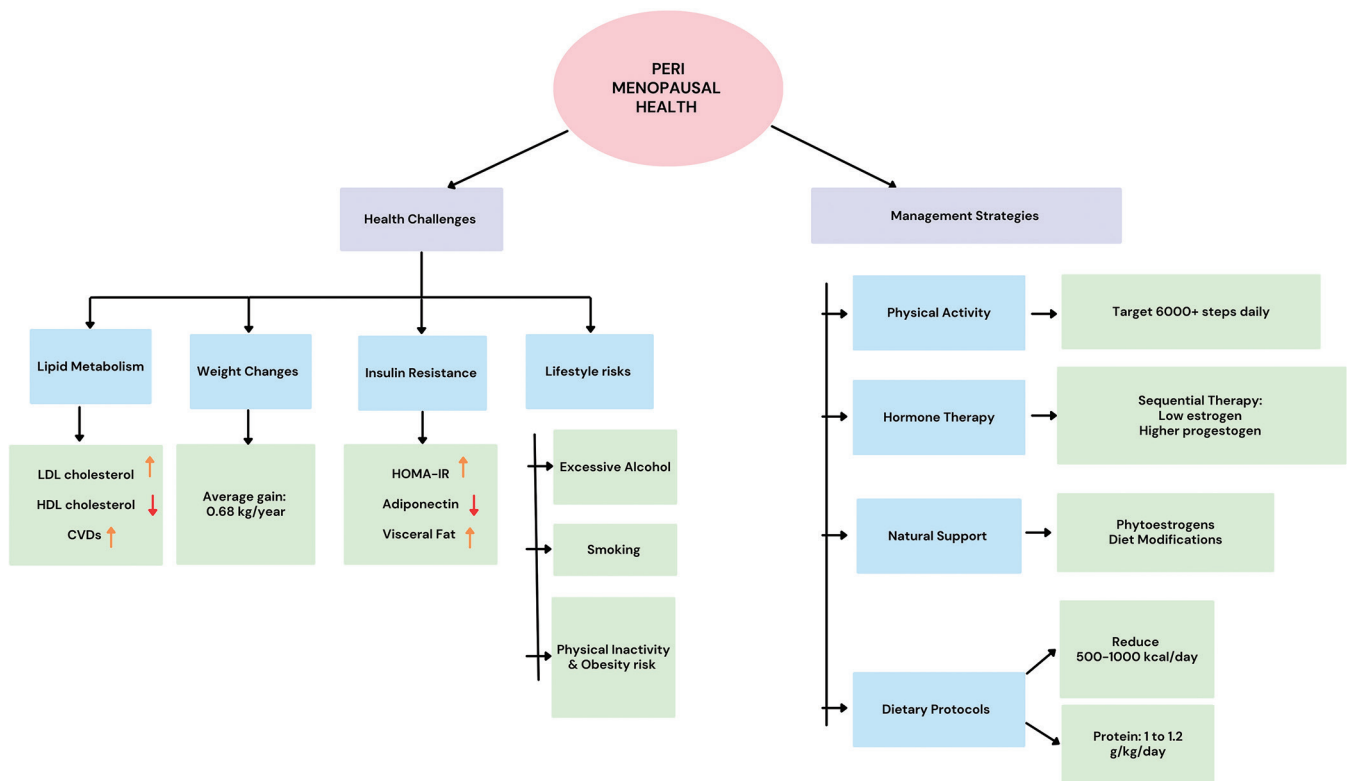


Figure 5: Perimenopausal health: Challenges and management strategies: This diagram outlines health challenges during perimenopause, including weight changes, insulin resistance, lipid metabolism, and lifestyle risks. It highlights management strategies such as physical activity, hormone therapy, phytoestrogens, and dietary modifications to support overall health during the perimenopausal transition. LDL: Low-density lipoprotein, HDL: High-density lipoprotein, HOMA-IR: Homeostatic model assessment for insulin resistance, CVD: Cardiovascular disease

create custom health plans that work for her real life. Going forward, we need more research on personalized approaches and tools that help women stick with healthy changes over time. Community programs designed specifically for women in this life stage could make a real difference, helping prevent age-related health issues while making this transition smoother and more comfortable.

ROLE OF PHYTOESTROGEN IN PERIMENOPAUSE

Recent clinical research demonstrates that dietary components can complement conventional approaches to managing perimenopausal symptoms. Foods rich in phytoestrogens – such as papaya, soybeans, and green tea – have shown clinical utility in alleviating common perimenopausal complaints. These plant-derived compounds interact with hormonal pathways and influence multiple physiological systems during the menopausal transition. The clinical effects of phytoestrogen consumption during perimenopause include improvements in tissue elasticity, favorable changes in vaginal pH, enhanced bone mineral density, and reduced frequency of vasomotor symptoms (VMS). Cognitive function also appears to benefit from regular phytoestrogen consumption, suggesting that multisystem

effects beyond reproductive tissues. Based on these documented benefits, these clinical observations position phytoestrogen-rich foods as valuable components of comprehensive nutritional strategies during the perimenopausal transition.^[35]

HORMONAL THERAPY FOR PERIMENOPAUSE

Menopausal HT (MHT) has received FDA approval for four clinical indications in menopausal women: the management of VMSs, prevention of osteoporosis, treatment of premature hypoestrogenism, and alleviation of moderate-to-severe vulvovaginal symptoms.^[36] Importantly, HT is part of an overall management strategy for menopausal women that includes lifestyle measures aimed at promoting and maintaining good health, which include smoking cessation, a diet low in sugar and fat, regular physical activity (e.g., brisk walking), moderate alcohol consumption, and weight management (body mass index <30 mg/m²).^[37] In perimenopausal women, sequential HT should be administered with a relatively low dose of estrogen and a higher dose of progestogen. Our analysis of HT reveals important clinical correlations between estrogen formulations and therapeutic outcomes across menopausal

transitions. For perimenopausal women, continuous systemic estrogen can be paired with an intrauterine device that steadily releases progestin to protect the uterus, offering contraception and typically causing little to no vaginal bleeding, though symptoms from fluctuating ovarian function may still occur. Women more than a year past their last period with an intact uterus are generally given a continuous combined HT (MHT) of estrogen and progestogen, with advice that breakthrough bleeding is common in the first 3–6 months. In women without a uterus, estrogen-only MHT is usually recommended, except in cases of subtotal hysterectomy or severe active endometriosis.^[38] Standard-dose estrogen therapy (2 mg oral estradiol or 0.625 mg conjugated equine estrogens) provides robust symptom relief but with increased thromboembolism risk compared to lower doses.^[39] Low-dose formulations (0.5–1 mg estradiol) offer an optimal balance of efficacy and safety for most women, while ultra-low-dose preparations (0.25 mg estradiol) maintain bone protection with minimal endometrial stimulation. Route of administration further influences outcomes, with transdermal delivery systems demonstrating reduced thrombotic risk compared to oral formulations at equivalent dosages.^[40] This approach accounts for the fact that endogenous ovarian estradiol production may remain elevated during this transitional phase.^[41,42] A comprehensive understanding of the risks and benefits of MHT concerning outcomes such as cancer, cardiovascular diseases (including coronary heart disease and stroke), cognitive decline, venous thromboembolism, and osteoporosis is essential.

CLINICAL IMPLEMENTATION: EVIDENCE-BASED METABOLIC MANAGEMENT DURING PERIMENOPAUSE

The clinical management of metabolic health during perimenopause requires a systematic, evidence-based approach that recognizes this phase as a critical intervention window.^[43] Healthcare providers should implement structured screening protocols that include baseline metabolic assessments at the onset of irregular menstrual cycles, with follow-up evaluations every 6 months during active perimenopause. Key metabolic markers for monitoring include homeostatic model assessment for insulin resistance, fasting glucose, lipid panels, and waist circumference measurements, as these parameters often show significant changes before overt diabetes develops.^[44,45] The clinical approach should emphasize personalized interventions based on individual risk profiles, hormonal status, and patient preferences, moving beyond the traditional

“one-size-fits-all” approach to menopausal care.^[46] This proactive approach recognizes that metabolic changes during perimenopause often precede traditional diagnostic criteria for metabolic syndrome or diabetes, emphasizing the importance of early detection and intervention during this critical transition period.^[11]

CONCLUSION

The gradual decline of estrogen during perimenopause disrupts key metabolic processes, contributing to increased insulin resistance and a heightened risk of diabetes. These physiological changes emphasize the importance of personalized health strategies, including balanced nutrition, regular physical activity, and avoidance of harmful habits. While hormone therapies, particularly ultra-low-dose formulations, show promise, there remains a significant lack of research focused specifically on their use during perimenopause. Addressing this gap through interdisciplinary research that combines molecular endocrinology, metabolic science, and personalized medicine could lead to more effective, targeted interventions. Such efforts are crucial for advancing women's health and ensuring that the unique challenges of the perimenopausal transition are appropriately managed.

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Conflicts of interest

There are no conflicts of interest.

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