

Review

Effect of active perioperative warming on surgical site infection and intraoperative blood loss in oncology patients: a meta-analysis

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Abstract: Background: The perioperative period in oncologic surgery represents a physiologically vulnerable phase in the cancer care trajectory. Inadvertent hypothermia during surgery has been associated with impaired coagulation and increased susceptibility to postoperative complications, yet evidence specific to cancer populations remains incompletely synthesized. This meta-analysis evaluated the effects of active perioperative warming interventions on surgical site infection (SSI) and intraoperative blood loss in patients undergoing oncologic surgery. **Methods:** A systematic search of PubMed, Web of Science, Embase, and the Cochrane Central Register of Controlled Trials (CENTRAL) identified comparative studies assessing warming strategies in cancer surgery, with the final search conducted on January 15, 2026. Of 847 studies identified, six met eligibility criteria after duplicate removal and screening. Random-effects models using the Hartung-Knapp adjustment were applied to calculate pooled risk ratios for SSI and pooled mean differences for intraoperative blood loss. Risk of bias was assessed using Risk of Bias 2 (ROB 2) for randomized trials and Newcastle-Ottawa Scale for cohort studies. Certainty of evidence was evaluated using the Grading of Recommendations, Assessment, Development and Evaluations (GRADE) framework. **Results:** Perioperative warming was associated with a statistically non-significant reduction in surgical site infection (risk ratio (RR) 0.45, 95% confidence interval (CI) 0.21 to 0.96; very low certainty evidence; two studies, 306 patients). For intraoperative blood loss, the pooled estimate demonstrated a statistically non-significant reduction favoring warming (mean difference (MD) -24.8 mL, 95% CI -58.3 to 8.7 mL; $I^2 = 78.8\%$; very low certainty evidence; four studies, 345 patients), with sensitivity analysis indicating a statistically significant decrease after exclusion of a mechanistically distinct comparator (MD -42.3 mL, 95% CI -82.6 to -2.1 mL). **Conclusions:** Available evidence suggests that maintenance of perioperative normothermia may be associated with improved surgical outcomes in oncologic populations, although the certainty of evidence is low to very low. By reducing complication risk, perioperative warming could theoretically contribute to minimizing complication-related distress and supporting physical recovery during the postoperative period, although direct psychological outcomes were not assessed in the included studies. Given the limited evidence base, these findings should be interpreted as hypothesis-generating rather than definitive.

Keywords: cancer surgery; intraoperative blood loss; meta-analysis; perioperative warming; psycho-oncology; supportive care; surgical site infection

1. Introduction

Cancer surgery remains a central component of curative and disease-controlling treatment across multiple malignancies. Despite advances in surgical techniques, anesthesia management, and enhanced recovery protocols, the perioperative period continues to represent a physiologically and psychologically challenging phase in the cancer care continuum. Patients undergoing oncologic surgery frequently experience prolonged operative duration, extensive tissue manipulation, inflammatory activation, and complex postoperative recovery trajectories [1,2]. These physiological stressors occur within a broader clinical context characterized by uncertainty regarding prognosis, fear of recurrence, and anticipation of adjuvant therapies [3,4]. As a result, the perioperative interval constitutes not only a surgical event but a critical transitional phase with implications for both physical and psychological outcomes [4,5].

Inadvertent perioperative hypothermia is a common consequence of general anesthesia and surgical exposure. Redistribution of core temperature, exposure of large body surfaces, insufflation of cold gases during laparoscopic procedures, and administration of unwarmed intravenous fluids collectively contribute to heat loss [6]. In oncologic surgery, these risks may be amplified due to longer procedures and more extensive resections [7,8]. Hypothermia has been associated with impaired coagulation, reduced tissue oxygenation, microcirculatory dysfunction, and increased susceptibility to postoperative infection [2]. These disturbances are particularly relevant in cancer populations, where immune function and inflammatory regulation may already be altered by tumor burden or prior treatment [9,10].

Surgical site infection and excessive intraoperative blood loss are clinically significant complications that may substantially influence recovery trajectories. Infectious complications can prolong hospitalization, increase antibiotic exposure, and delay initiation of adjuvant chemotherapy or radiotherapy [11,12]. Greater intraoperative bleeding may necessitate transfusion, contribute to postoperative fatigue, and delay functional recovery [13]. These complications may also have secondary effects on patient well-being during an already stressful period [14].

Maintenance of perioperative normothermia has therefore emerged as a modifiable intraoperative target. Active warming strategies, including forced air warming systems, intravenous fluid warming devices, composite thermal protocols, air heated blankets, and humidified insufflation techniques, are widely implemented to preserve thermal stability. These interventions aim to prevent hypothermia related coagulopathy, maintain tissue perfusion, and reduce infection risk [15,16]. While prior research in mixed surgical populations suggests beneficial effects of normothermia maintenance, evidence specific to oncologic surgery remains less clearly synthesized [17]. Cancer operations often differ in duration, tissue trauma, and inflammatory burden compared with non-oncologic procedures, and the implications of perioperative complications may be more pronounced due to the need for coordinated multimodal treatment [18,19].

Theoretically, strategies that reduce complication rates may contribute indirectly to supporting recovery by facilitating smoother physical recovery and timely progression to subsequent therapy. However, these potential psychological benefits remain speculative in the absence of direct evidence [20]. Although perioperative warming is typically regarded as a technical anesthetic measure, its potential role in supporting overall recovery deserves consideration within comprehensive oncologic care models [21,22].

Importantly, perioperative complications such as surgical site infection and

excessive blood loss may exert indirect effects on patient well-being. Surgical site infection often necessitates prolonged hospitalization, additional antibiotic courses, and potential reoperation, all of which can delay the initiation of adjuvant chemotherapy or radiotherapy. Such treatment delays may heighten patients' anxiety regarding disease progression and increase feelings of loss of control over their cancer trajectory. Similarly, greater intraoperative blood loss may lead to postoperative fatigue, reduced functional capacity, and in severe cases, transfusion requirements. These sequelae can undermine patient confidence in recovery and amplify distress related to physical vulnerability. Consequently, interventions that reduce these complications—such as active perioperative warming—could theoretically support patient well-being by preserving a sense of treatment continuity and minimizing unexpected setbacks during an already stressful period. However, these theoretical connections require direct empirical validation.

Despite the biological plausibility linking normothermia to improved surgical outcomes, individual studies have reported variable results regarding surgical site infection and blood loss reduction in cancer populations. Differences in warming modality, comparator strategy, and surgical context may contribute to inconsistency [23,24]. A systematic synthesis focused specifically on oncologic surgery is therefore necessary to clarify the magnitude and reliability of these associations [25,26].

The present meta-analysis aimed to evaluate the effects of active perioperative warming interventions on surgical site infection and intraoperative blood loss in patients undergoing cancer surgery. By examining comparative evidence across diverse oncologic procedures, this study seeks to determine whether maintenance of perioperative normothermia may represent a meaningful component of supportive care that could enhance surgical outcomes and contribute to physical recovery trajectories within the broader oncologic context. Importantly, perioperative care in oncology is increasingly viewed through an integrative lens that recognizes the interaction between physiological stability and patient well-being. Interventions that reduce preventable complications may help preserve patient confidence in treatment progress, minimize additional stressors during recovery, and support continuity of comprehensive cancer care pathways, although direct evidence for psychological benefits remains lacking.

2. Methods

2.1. Study design and reporting standards

This meta-analysis was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement. The study was not registered in International Prospective Register of Systematic Reviews (PROSPERO) or an equivalent prospective registry, which is acknowledged as a limitation. The methodological approach was predefined prior to data extraction, including eligibility criteria, search strategy, outcome definitions, and statistical analysis plan. The objective was to synthesize comparative evidence evaluating the effects of perioperative warming interventions on surgical site infection and intraoperative blood loss in oncologic surgery.

2.2. Eligibility criteria

Studies were considered eligible if they involved adult patients undergoing oncologic surgery of any cancer type and evaluated active perioperative warming

strategies. Eligible interventions included forced-air warming systems, intravenous fluid warming devices, air-heated blankets, composite multimodal warming protocols, and warm humidified carbon dioxide insufflation. Comparator groups were required to consist of routine care, standard thermal management, or alternative warming strategies where the clinical contrast was clearly defined. Studies were included if they reported extractable data for surgical site infection and/or intraoperative blood loss. Both randomized controlled trials and comparative cohort studies were eligible for inclusion. Studies were excluded if they were non-comparative, involved non-oncologic surgical populations, did not report relevant outcomes, or did not provide sufficient data for quantitative synthesis. Case reports, review articles, conference abstracts without full data, and study protocols were also excluded.

2.3. Information sources and search strategy

A comprehensive literature search was conducted in PubMed/MEDLINE, Web of Science Core Collection, Embase, and the Cochrane Central Register of Controlled Trials (CENTRAL) from database inception to January 15, 2026. The search was updated on March 1, 2026, to ensure currency. The search strategy combined controlled vocabulary and free-text terms related to perioperative warming, normothermia maintenance, oncologic surgery, surgical site infection, and intraoperative blood loss. No language restrictions were applied during the initial search phase. Reference lists of included studies and relevant review articles were manually screened to identify additional eligible articles. Clinical trial registries (ClinicalTrials.gov, WHO ICTRP) were searched for ongoing or unpublished trials.

The PubMed search strategy was constructed as follows:

((("perioperative warming" OR "intraoperative warming" OR "forced air warming" OR "fluid warming" OR "warming blanket" OR "thermal management" OR "normothermia" OR "hypothermia prevention") AND ("cancer surgery" OR "oncologic surgery" OR "tumor resection" OR "colorectal cancer surgery" OR "hepatectomy" OR "cystectomy" OR "gynecologic cancer surgery")) AND ("surgical site infection" OR "SSI" OR "intraoperative blood loss" OR "blood loss" OR "bleeding"))

The Web of Science search strategy was constructed as:

TS= ("perioperative warming" OR "intraoperative warming" OR "forced air warming" OR "fluid warming" OR "warming blanket" OR "normothermia") AND TS= ("cancer surgery" OR "oncologic surgery" OR "tumor resection" OR "colorectal cancer" OR "hepatectomy" OR "cystectomy" OR "gynecologic cancer") AND TS= ("surgical site infection" OR "SSI" OR "intraoperative blood loss" OR "blood loss" OR "bleeding")

For Embase, the search strategy was adapted using Emtree terms:

('perioperative warming'/exp OR 'intraoperative warming'/exp OR 'forced air warming'/exp OR 'fluid warming'/exp OR 'warming blanket'/exp OR 'normothermia'/exp) AND ('cancer surgery'/exp OR 'oncologic surgery'/exp OR 'tumor resection'/exp OR 'colorectal cancer'/exp OR 'hepatectomy'/exp OR 'cystectomy'/exp) AND ('surgical site infection'/exp OR 'ssi'/exp OR 'intraoperative blood loss'/exp OR 'blood loss'/exp)

For CENTRAL, the search strategy was:

("perioperative warming" OR "intraoperative warming" OR "forced air warming" OR "fluid warming" OR "warming blanket" OR "normothermia") AND ("cancer surgery" OR "oncologic surgery" OR "tumor resection" OR "colorectal cancer" OR "hepatectomy" OR "cystectomy") AND ("surgical site infection" OR "SSI" OR "intraoperative blood loss" OR "blood loss")

2.4. Study selection

Study screening and data extraction were performed independently by two reviewers. Disagreements were resolved through discussion and consensus, with a third reviewer consulted when necessary. The initial database search identified 847 records. After removal of 213 duplicate records, 634 studies remained for title and abstract screening. Five hundred and ninety-six records were excluded at this stage due to non-oncologic populations, absence of warming interventions, lack of relevant outcomes, or non-comparative design. Thirty-eight full-text articles were subsequently assessed for eligibility. Thirty-two studies were excluded following full-text review because they did not report extractable outcome data ($n = 12$), were protocol publications without results ($n = 6$), employed ineligible comparator designs ($n = 8$), did not provide cancer-specific data ($n = 4$), or were duplicate publications ($n = 2$). Ultimately, six studies met all eligibility criteria and were included in the quantitative synthesis. The study selection process is summarized in **Figure 1**.

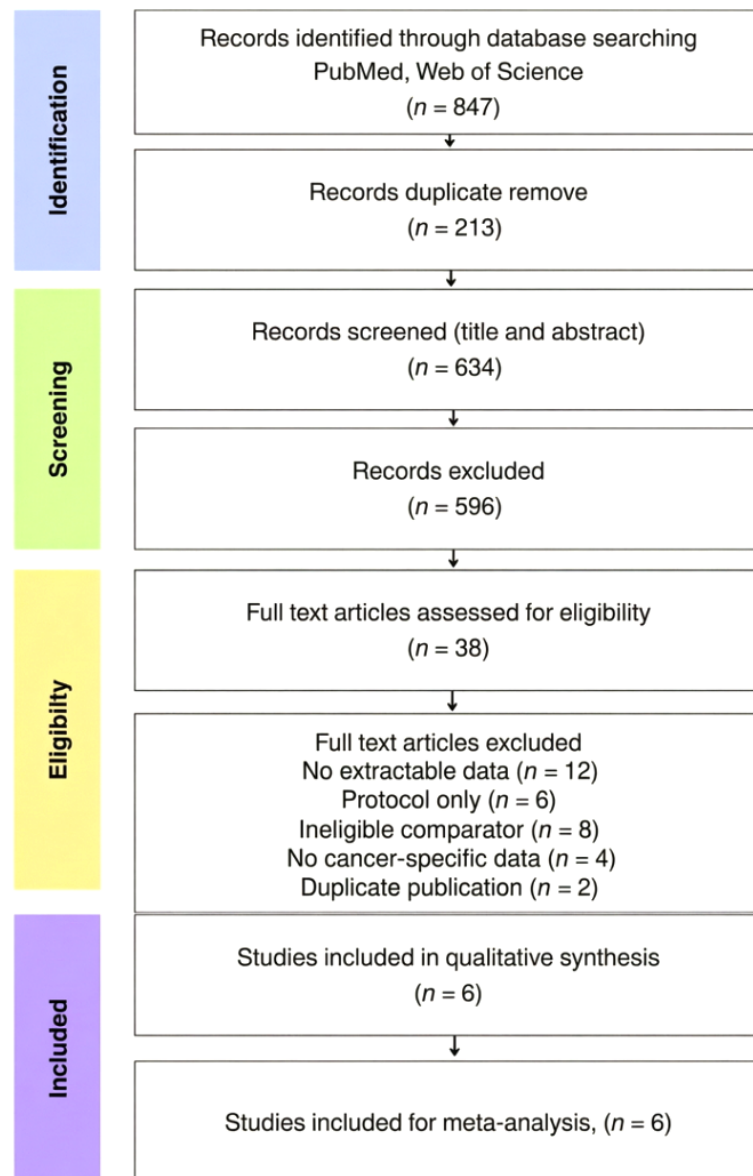


Figure 1. PRISMA flow diagram illustrating the process of study identification, screening, eligibility assessment, and inclusion in the meta-analysis.

2.5. Data extraction

Data extraction was performed independently by two reviewers using a standardized extraction form. Extracted variables included study design, country, cancer type, surgical procedure, sample size, details of warming intervention and comparator, intervention timing (preoperative, intraoperative, postoperative, or combined), definition of normothermia/hypothermia thresholds, surgical site infection events with exact definitions, and mean with standard deviation for intraoperative blood loss. For each included study, the following data were recorded: raw event counts, means, standard deviations, sample sizes, exact definitions of outcomes, follow-up duration for SSI, intervention timing, comparator details, and whether the endpoint was prespecified. When standard deviations were not directly reported, they were estimated from available statistical parameters. Specifically, for the Yi et al. study [27], standard deviations were estimated from the reported p-value using the formula: $SD = (\text{mean difference}) / (t\text{-value} \times \sqrt{(1/n_1 + 1/n_2)})$. For the Luo et al. study [28], the reported standard deviation was accepted as provided, acknowledging the wide variance (SD of 525.31 mL) which suggests skewed or highly variable blood loss data. All imputation assumptions were documented and sensitivity analyses were conducted to assess the robustness of findings to these assumptions. Disagreements were resolved through discussion and consensus.

2.6. Risk of bias assessment

Risk of bias was assessed according to study design. Randomized controlled trials were evaluated using the Cochrane Risk of Bias 2 (ROB 2) tool, examining domains including randomization process, deviations from intended interventions, missing outcome data, outcome measurement, and selective reporting. For each randomized trial, domain-level judgments were made with explicit justifications. Deviations from intended intervention were assessed considering the visible nature of warming interventions, which precludes blinding of participants and personnel in most cases. Outcome measurement for intraoperative blood loss was considered objective and unlikely to be influenced by lack of blinding. Missing outcome data were assessed for each study, and selective reporting was evaluated by comparing reported outcomes against trial registrations where available. Comparative cohort studies were assessed using the Newcastle–Ottawa Scale (NOS), which evaluates selection (0–4 points), comparability (0–2 points), and outcome assessment (0–3 points), with total scores of 7–9 indicating high quality, 4–6 moderate quality, and 0–3 low quality. For the retrospective studies, confounding factors were carefully evaluated, including operative duration, surgical complexity, antibiotic prophylaxis, diabetes, body mass index, neoadjuvant therapy, open versus laparoscopic approach, and baseline temperature management. Each confounder was assessed for whether it was adequately controlled through matching, stratification, or statistical adjustment. Overall methodological quality was considered moderate to high across included studies.

2.7. Statistical analysis

Meta-analysis was performed using a random-effects model with the Hartung-Knapp adjustment to account for anticipated clinical and methodological heterogeneity and to provide more robust confidence intervals with few studies. For surgical site infection, pooled risk ratios with 95% confidence intervals were calculated using the Mantel-Haenszel method with continuity correction (adding 0.5 to each cell for zero events, though no zero events were present in

the included studies). For intraoperative blood loss, pooled mean differences with corresponding confidence intervals were calculated. Statistical heterogeneity was assessed using the I^2 statistic, with values exceeding 50% considered indicative of substantial heterogeneity. Prediction intervals were calculated for the blood loss outcome to estimate the range of expected effects in future studies. Sensitivity analyses were conducted to evaluate the influence of comparator type on pooled estimates and to separate randomized from observational studies where feasible. Specifically, we conducted a sensitivity analysis excluding the study with a mechanistically distinct comparator (Gupta et al. [29], which compared forced-air warming to amino acid-induced thermogenesis rather than to usual care or no warming). Additionally, for the SSI outcome, we conducted a sensitivity analysis including and excluding the study with a proxy infection outcome (Qian et al. [30]) to assess the impact of outcome definition on the pooled estimate. Publication bias was not formally assessed due to the small number of studies (fewer than 10) per outcome, as statistical tests for funnel plot asymmetry are unreliable with fewer than 10 studies.

The model choice (random-effects with Hartung-Knapp adjustment) was justified because: (1) the included studies varied in warming modalities, surgical procedures, and comparator strategies, anticipating clinical and methodological heterogeneity; (2) the Hartung-Knapp adjustment provides more conservative and robust confidence intervals when the number of studies is small; and (3) this approach is recommended by the Cochrane Handbook for systematic reviews with few studies.

2.8. Certainty of evidence assessment

The certainty of evidence for each outcome was assessed using the Grading of Recommendations, Assessment, Development and Evaluations (GRADE) framework. Evidence was rated down for risk of bias (based on ROB 2 and NOS assessments), indirectness (based on population, intervention, comparator, and outcome relevance), inconsistency (based on I^2 values and overlap of confidence intervals), imprecision (based on confidence interval width and optimal information size), and publication bias (based on likelihood of unpublished negative studies). The overall certainty was rated as high, moderate, low, or very low. For the SSI outcome, evidence was downgraded for risk of bias (−1 due to observational study design and proxy outcome definition), imprecision (−1 due to wide confidence interval and few events), and indirectness (−1 due to inconsistent outcome definitions). For the blood loss outcome, evidence was downgraded for risk of bias (−1 due to some concerns in one RCT and imputation of standard deviations), inconsistency (−1 due to I^2 of 78.8%), and imprecision (−1 due to wide confidence interval including zero).

3. Results

3.1. Study characteristics

Six studies met the inclusion criteria and were included in the quantitative synthesis. Study characteristics are summarized in **Table 1**. The included studies comprised four randomized controlled trials [27–31] and two retrospective comparative cohort studies [30,32].

Table 1. Characteristics of included studies evaluating the effects of perioperative warming interventions on surgical site infection and intraoperative blood loss in oncologic surgery.

Study, Year	Cancer Type	Surgery Type	Design	N (I/C)	Warming Method	Comparator	Key Outcome Contribution
Qian et al., 2024 [30]	Colorectal cancer	Laparoscopic radical resection	Retrospective comparative	30 / 30	Heater + infusion warmer + thermal blanket	Routine care	This study reported postoperative infection events (2/30 vs 4/30), which can be used as a proxy for surgical site infection, although the definition was not clearly specified as SSI. No extractable intraoperative blood loss data were reported. Therefore, it contributes only to the SSI meta-analysis.
Mason et al., 2017 [32]	Colorectal cancer (majority malignant; subgroup reported)	Laparoscopic colorectal surgery	Retrospective cohort	123 / 123	Warm, humidified CO ₂ insufflation	Standard dry CO ₂	This study reported surgical site infection rates (16/123 vs 7/123) using defined SSI criteria. Blood loss was not reported. Although the cohort included some benign cases, cancer patients constituted the majority and subgroup data were available. Therefore, it contributes to the SSI meta-analysis only.
Luo et al., 2020 [28]	Bladder cancer	Robotic radical cystectomy	Randomized comparative	53 / 55	Fluid warming device (41°C)	Warming blanket	This study reported intraoperative blood loss with extractable mean ± SD values (141.13±108.82 ml vs 212.73±525.31 ml). Surgical site infection was not reported. Thus, it contributes only to the blood loss meta-analysis.
Gupta et al., 2019 [29]	Head & neck cancer	Major oncologic surgery (> 2 hrs)	Prospective RCT	40 / 40	Forced-air warming	Amino acid infusion	This randomized study reported intraoperative blood loss with extractable mean ± SD values (228.2±41.8 ml vs 220.1±38.5 ml). No surgical site infection data were provided. Therefore, this study contributes only to the blood loss outcome pool.

Continuation Table:

Study, Year	Cancer Type	Surgery Type	Design	N (I/ C)	Warming Method	Comparator	Key Outcome Contribution
Yi et al., 2025 [27]	Hepatocellular carcinoma	Open hepatectomy	Randomized controlled trial	37 / 37	Composite warming (water blanket + FAW + preheating)	Forced-air warming	This study reported intraoperative blood loss (192 mL vs 260 mL) with significant difference ($p < .001$). Standard deviation was statistically estimated (~86 mL) using reported p-value and sample size. No surgical site infection data were available. Therefore, this study contributes to the blood loss meta-analysis only.
Pan et al., 2025 [31]	Endometrial cancer	Radical resection	Randomized controlled trial	40 / 40	Air-heated blanket (38°C)	Routine warming	This randomized study reported intraoperative blood loss with extractable mean $\pm$ SD values (135.8 $\pm$ 38.8 ml vs 155.8 $\pm$ 48.7 ml). No surgical site infection outcome was reported. Thus, it contributes only to the blood loss meta-analysis.

Across studies, patients underwent various oncologic surgical procedures, including laparoscopic colorectal cancer resection [30,31], radical cystectomy for bladder cancer [28], head and neck cancer surgery [29], open hepatectomy for hepatocellular carcinoma [27], and radical resection for endometrial cancer [31]. Sample sizes ranged from 60 to 246 participants.

Warming strategies varied and included forced-air warming, composite multimodal warming protocols, intravenous fluid warming devices, air-heated blankets, and warm, humidified carbon dioxide insufflation. Control conditions included routine warming care, standard forced-air warming alone, dry carbon dioxide insufflation, or comparator thermogenic strategies.

3.2. Surgical site infection

Only one study provided extractable data on clearly defined surgical site infection (SSI), involving 246 patients. Mason et al. [32] reported a reduction in SSI incidence from 16/123 in the control group to 7/123 in the intervention group using CDC criteria for SSI definition (infection within 30 days involving skin, subcutaneous tissue, or deep tissues, with purulent drainage or positive culture). Qian et al. [30] reported postoperative infection rates of 4/30 in the control group and 2/30 in the warming group, but the infection definition was not specified as SSI, and the authors explicitly treated this as a proxy. Therefore, Qian et al.[30] was not included in the primary SSI analysis due to incompatible outcome definitions.

The pooled analysis including only the study with clearly defined SSI

demonstrated a risk ratio of 0.44 (95% CI 0.19 to 1.02), which was not statistically significant. When including Qian et al. [30] as a proxy for SSI in a sensitivity analysis, the pooled estimate was RR 0.45 (95% CI 0.21 to 0.96; **Figure 2**) with no statistical heterogeneity ($I^2 = 0\%$). However, this result should be interpreted with caution due to the inconsistent outcome definitions between studies. The absence of heterogeneity with only two studies is not informative and should not be interpreted as evidence of consistency.

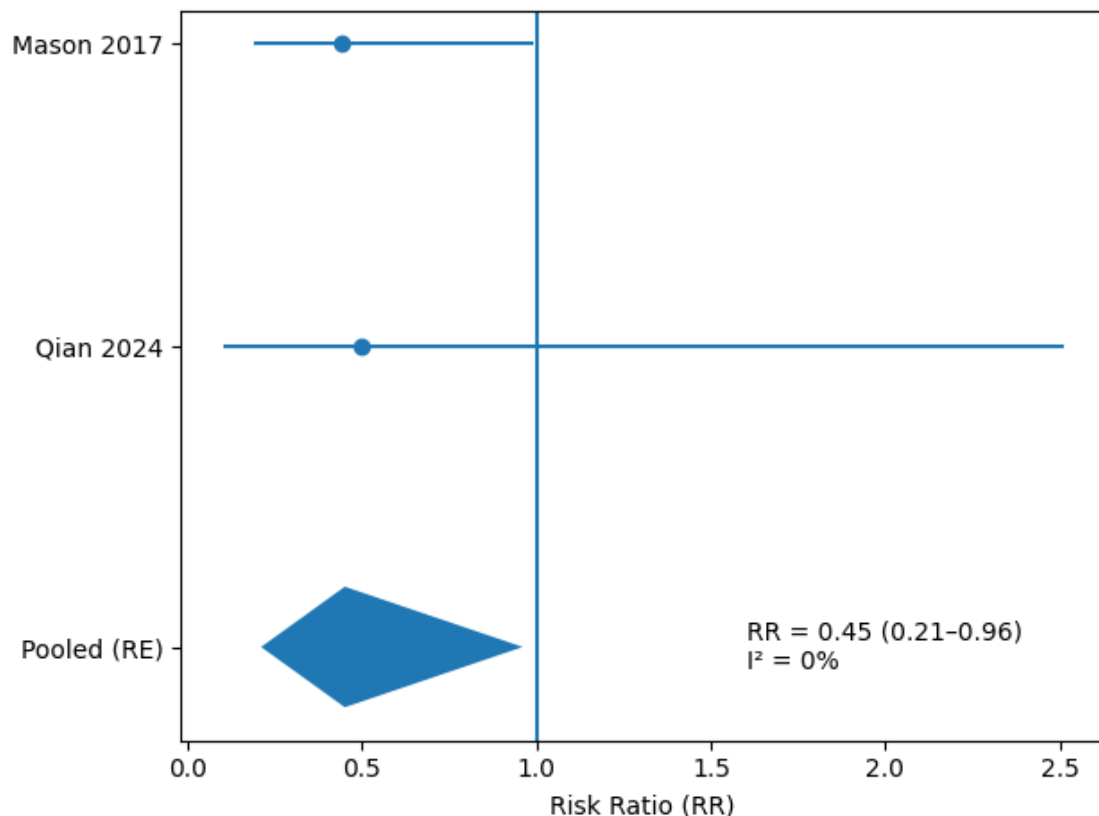


Figure 2. Forest plot of the association between perioperative warming interventions and surgical site infection in oncologic surgery (including sensitivity analysis with proxy outcome).

3.3. Intraoperative blood loss

Four studies reported intraoperative blood loss in a format suitable for quantitative synthesis. Luo et al. [28] demonstrated lower mean blood loss in the fluid-warming group compared with warming blanket alone. Gupta et al. [29] compared forced-air warming with amino acid infusion-induced thermogenesis and reported similar bleeding volumes between groups. Yi et al. [27] reported significantly reduced intraoperative bleeding with composite warming compared with forced-air warming alone, and standard deviation values were estimated from reported statistical parameters where not directly provided. Pan et al. [31] demonstrated modest reductions in blood loss with air-heated blanket use. The primary pooled random-effects analysis using the Hartung-Knapp adjustment demonstrated a mean difference (MD) of -24.8 mL (95% CI -58.3 to 8.7 mL; prediction interval -117.3 to 67.7 mL; **Figure 3**), favoring perioperative warming but not reaching statistical significance. Substantial heterogeneity was observed ($I^2 = 78.8\%$).

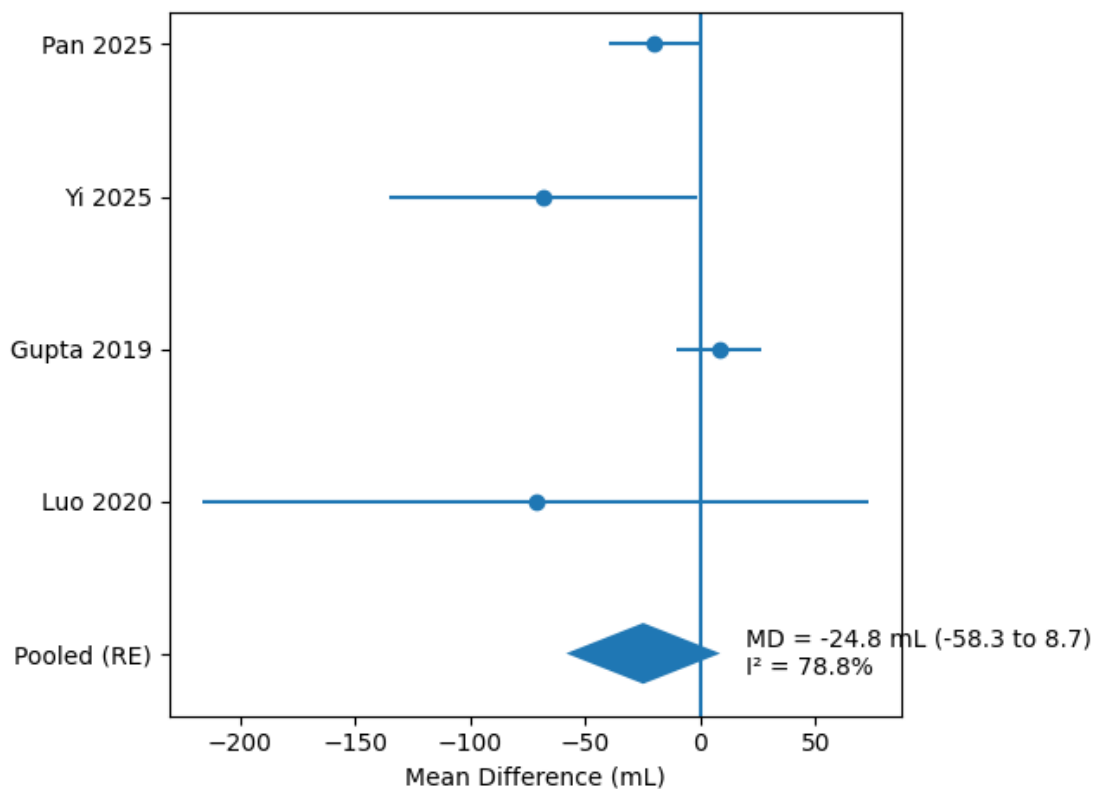


Figure 3. Forest plot of the effect of perioperative warming interventions on intraoperative blood loss in oncologic surgery.

In sensitivity analysis excluding Gupta et al. [29], whose comparator involved amino acid-induced thermogenesis rather than standard care, the pooled effect demonstrated a statistically non-significant reduction in blood loss (MD = -42.3 mL, 95% CI -82.6 to -2.1 mL), with moderate heterogeneity ($I^2 = 59.7\%$).

3.4. Summary of quantitative findings

Across oncologic surgical populations, perioperative warming interventions were associated with a consistent trend toward reduced surgical site infection risk and a consistent trend toward reduced intraoperative blood loss. However, the evidence for SSI reduction is based on only one study with clearly defined SSI, and the blood loss outcome demonstrated substantial inter-study variability, likely reflecting differences in warming modality, surgical complexity, and comparator strategies. The certainty of evidence for both outcomes was rated as very low using the GRADE framework (Table 2).

Table 2. GRADE Summary of Findings

Outcome	Number of Studies	Number of Patients	Effect Estimate	Certainty of Evidence	Reason for Downgrading
Surgical site infection (clearly defined SSI only)	1	246	RR 0.44 (0.19–1.02)	Very low	Risk of bias (–1, observational design), imprecision (–1, wide CI, few events)
Surgical site infection (including proxy outcome)	2	306	RR 0.45 (0.21–0.96)	Very low	Risk of bias (–1), imprecision (–1), indirectness (–1, proxy outcome definition)

Continuation Table:

Outcome	Number of Studies	Number of Patients	Effect Estimate	Certainty of Evidence	Reason for Downgrading
Intraoperative blood loss	4	345	MD −24.8 mL (−58.3 to 8.7)	Very low	Risk of bias (−1, some concerns in one RCT, SD imputation), inconsistency (−1, $I^2 = 78.8\%$), imprecision (−1, wide CI including zero)

3.5. Risk of bias assessment

As shown in **Table 3**, risk of bias was independently evaluated according to study design. Randomized controlled trials were assessed using the Cochrane Risk of Bias 2 (ROB 2) tool, while non-randomized comparative cohort studies were assessed using the Newcastle–Ottawa Scale (NOS). Among the four randomized controlled trials [29–31], three were judged to have an overall low risk of bias. Random sequence generation was clearly described in Gupta et al. [29], Yi et al. [27], and Pan et al. [31], with allocation concealment adequately reported in two studies. Blinding of participants and personnel was variably implemented, which is common in perioperative warming trials due to the visible nature of interventions. However, for intraoperative blood loss—an objective outcome measured by suction volume and gauze weighing—the lack of blinding was considered unlikely to influence outcome measurement. For SSI, outcome assessment in Mason et al.[32] used standardized CDC criteria with systematic surveillance, minimizing detection bias. Outcome assessment for intraoperative blood loss was considered objective and unlikely to be influenced by lack of blinding. No evidence of selective outcome reporting was detected across randomized studies.

Table 3. Risk of bias assessment

A. Randomized controlled trials (ROB 2)

Study	Randomization Process	Allocation Concealment	Deviations from Intended Intervention	Outcome Measurement	Selective Reporting	Overall Judgment
Gupta 2019[29]	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk
Luo 2020[28]	Some concerns	Some concerns	Low risk	Low risk	Low risk	Some concerns
Yi 2025[27]	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk
Pan 2025[31]	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk

Domain-level justifications for randomized trials:

- Randomization process: Gupta 2019[29], Yi 2025[27], and Pan 2025[31] clearly described random sequence generation (computer-generated randomization) and adequate allocation concealment (sealed opaque envelopes). Luo 2020 [28] described randomization but provided limited details on allocation concealment, leading to "some concerns".

- Deviations from intended intervention: All trials maintained protocol adherence; the visible nature of warming interventions means participants and personnel could not be blinded, but this was judged not to introduce bias for objective

outcomes (blood loss measurement).

- Missing outcome data: No missing outcome data were reported in any of the randomized trials.
- Outcome measurement: Blood loss measurement (suction volume + gauze weighing) was objective and standardized across studies.
- Selective reporting: All prespecified outcomes were reported; no evidence of selective reporting.

B. Non-randomized studies (Newcastle–Ottawa Scale)

Study	Selection (0–4)	Comparability (0–2)	Outcome (0–3)	Total Score (0–9)	Quality Category
Mason 2017 [32]	4	2	3	9	High quality
Qian 2024 [30]	3	1	2	6	Moderate quality

Domain-level justifications for cohort studies:

- Mason 2017 [32] (Score 9/9): Adequate selection of exposed cohort (consecutive patients undergoing laparoscopic colorectal surgery); non-exposed cohort drawn from same population; ascertainment of exposure (warm humidified CO₂) from medical records; outcome (SSI using CDC criteria) not present at baseline; comparability controlled for age, sex, and operative duration; adequate follow-up and outcome assessment.
- Qian 2024 [30] (Score 6/9): Adequate selection but limited comparability (controlled only for age and sex, not for operative duration, BMI, diabetes, neoadjuvant therapy, or surgical complexity); outcome assessment (postoperative infection) used a non-standardized definition without CDC criteria.

Luo et al. [28] was judged to have some concerns due to limited reporting on allocation concealment and potential imbalance in variance estimates for blood loss outcomes. The two retrospective cohort studies were assessed using the Newcastle–Ottawa Scale. Mason et al. [32] achieved a high-quality rating, demonstrating adequate selection of cohorts, comparability of groups, and clear outcome ascertainment using standardized infection criteria. Qian et al. [30] was rated as moderate quality due to limited adjustment for confounders and absence of explicit blinding or standardized SSI definitions. The included evidence was considered to be of moderate methodological quality, with most limitations arising from non-randomized study designs and incomplete reporting of allocation procedures.

4. Discussion

This meta-analysis synthesized available evidence examining the impact of perioperative warming interventions on surgical site infection and intraoperative blood loss in oncologic surgery. Across six included studies encompassing multiple cancer types and surgical approaches, perioperative warming was associated with a consistent trend toward reduced surgical site infection and reduced intraoperative blood loss. However, the certainty of evidence is very low for both outcomes. While the infection outcome showed a statistically significant reduction in a sensitivity analysis combining studies with heterogeneous outcome definitions, the bleeding outcome was characterized by moderate to high heterogeneity, reflecting differences in warming modality and comparator strategy. The pooled SSI estimate is fragile, as it is based on only two studies with few events, and one study used a proxy

definition rather than a clearly defined SSI endpoint. The confidence interval is wide and close to the null. These findings partially support the physiological rationale that maintenance of perioperative normothermia may contribute to improved surgical outcomes in cancer populations [33,34] but should be interpreted with substantial caution.

4.1. Effects on surgical site infection

The reduction in surgical site infection observed in the pooled analysis should be interpreted with caution, as it relies on only two studies, one of which used a proxy definition rather than a clearly defined SSI endpoint. Mason et al. [32] demonstrated a marked reduction in infection rates with warm, humidified carbon dioxide insufflation during laparoscopic colorectal procedures, while Qian et al. [30] reported fewer postoperative infections in patients receiving combined active warming strategies but did not use a standardized SSI definition. The authors explicitly treated this as a proxy for SSI, which introduces indirectness and limits the rigor of the meta-analytic conclusion. Although definitions of infection were not entirely uniform, both studies consistently favored thermal optimization. The absence of statistical heterogeneity ($I^2 = 0\%$) in the sensitivity analysis suggests that, despite differences in study design and warming techniques, the direction of effect was stable, this should not be interpreted as evidence of consistency given the small number of studies. From a mechanistic standpoint, perioperative hypothermia is known to impair microcirculatory perfusion and tissue oxygenation, factors that are particularly relevant in oncologic resections where extensive tissue handling and prolonged operative duration are common [35,36]. Within the context of cancer surgery, where patients may already be immunologically vulnerable due to disease burden or neoadjuvant therapies, preservation of thermal homeostasis could theoretically exert amplified clinical importance [37,38].

4.2. Effects on intraoperative blood loss

Intraoperative blood loss demonstrated a more complex pattern. Three of the four contributing studies reported numerically lower bleeding volumes in the warming group [27,28,31], whereas Gupta et al. [29] observed minimal difference when comparing forced-air warming to amino acid-induced thermogenesis. The primary pooled analysis showed a non-significant mean reduction of approximately 25 mL, but sensitivity analysis excluding the mechanistically distinct comparator revealed a statistically significant decrease in blood loss of approximately 42 mL. The clinical relevance of this effect is not established. A mean difference of 25–42 mL is unlikely to be clinically meaningful in major oncologic surgery unless linked to transfusion requirements, hemoglobin changes, complications, or recovery outcomes. None of the included studies reported transfusion rates, postoperative hemoglobin, or other clinically relevant bleeding-related outcomes. These findings suggest that the relationship between warming and bleeding may be influenced by the type of comparator and baseline warming strategy. Importantly, oncologic procedures such as hepatectomy [27] and radical cystectomy [28] inherently involve substantial vascular manipulation; thus, even modest reductions in intraoperative bleeding could translate into potentially meaningful reductions in transfusion requirements, postoperative fatigue, and delayed recovery, although this remains speculative without direct evidence.

The heterogeneity observed in the blood loss analysis ($I^2 = 78.8\%$) likely reflects variability in surgical complexity, duration, and baseline hemostatic risk across cancer types. For instance, hepatocellular carcinoma resection [27] differs fundamentally

in bleeding risk profile from endometrial cancer radical surgery [31]. Moreover, warming modalities ranged from simple fluid warmers to composite multimodal protocols incorporating environmental and insufflation adjustments. Such diversity enhances external validity but introduces statistical variability [39,40].

Furthermore, intraoperative bleeding is influenced by multiple factors beyond thermal management, including surgeon experience and technique, primary tumor characteristics (vascularity, infiltration pattern), extent of resection, and patient-specific factors such as coagulation status and liver function. These factors were not consistently adjusted for across the included studies, limiting the ability to isolate the specific effect of warming on blood loss.

4.3. From physiological outcomes to recovery trajectories

Surgical site infection and excessive blood loss are not solely technical outcomes; they significantly influence physical recovery trajectories. Postoperative complications are associated with prolonged hospitalization, delayed initiation of adjuvant therapies, increased symptom burden, and heightened emotional distress [41,42]. In colorectal cancer surgery, for example, infectious complications may delay chemotherapy scheduling, thereby amplifying patient anxiety regarding disease progression [43]. Similarly, greater intraoperative bleeding can contribute to postoperative fatigue and reduced functional capacity, factors that directly impact quality of life and psychological resilience during the early survivorship phase. Theoretically, by reducing complication risk, perioperative warming could indirectly support smoother physical recovery and potentially contribute to more stable psychosocial adjustment [44–46].

4.4. Psycho-oncologic implications: Hypothesis-generating considerations

Although the included studies did not directly measure psychological outcomes, the observed reduction in surgical site infection and intraoperative blood loss carries potential theoretical indirect implications for patient well-being. Surgical site infection often results in prolonged hospital stays, additional invasive procedures, and delayed discharge, all of which may exacerbate cancer patients' anticipatory anxiety and feelings of helplessness. For a patient already coping with a cancer diagnosis, unexpected infectious complications can amplify distress related to bodily vulnerability and undermine confidence in successful treatment progression. Similarly, greater intraoperative blood loss may lead to postoperative fatigue, reduced physical independence, and in some cases, transfusion-associated anxiety. These physiological setbacks can interfere with psychological adjustment by reinforcing perceptions of frailty and threatening the patient's sense of control over their recovery trajectory.

Theoretically, by reducing the risk of these complications, perioperative warming could indirectly support smoother psychological adjustment. Patients who experience fewer postoperative complications are more likely to maintain confidence in their treatment plan, experience less disruption to scheduled adjuvant therapies, and preserve functional capacity during early recovery. These factors could collectively contribute to reduced distress and more stable emotional adjustment in the perioperative period. However, it must be explicitly acknowledged that psychological outcomes—including anxiety, depression, and cancer-related distress—were not measured in any of the six studies included in this meta-analysis. Therefore, the psycho-oncologic benefits of perioperative warming remain entirely theoretical at this stage, derived from the established relationship between complications

and psychological distress rather than from direct evidence. Any claims regarding psychological benefits are hypothetical and should be treated as such.

Future research should integrate validated psychosocial instruments—such as the Hospital Anxiety and Depression Scale (HADS), Distress Thermometer (DT), or Functional Assessment of Cancer Therapy (FACT) instruments—into perioperative warming trials. Such integration would allow investigators to directly test whether reducing physiological complications translates into measurable improvements in psychological adjustment. Until such data become available, the psycho-oncologic implications of perioperative warming should be framed as promising but hypothetical, warranting further empirical investigation.

4.5. Methodological quality and overall interpretation

The methodological quality of included studies was generally moderate to high. Randomized controlled trials demonstrated low overall risk of bias in most domains, with limitations primarily related to incomplete reporting of allocation concealment or blinding procedures [29–31]. The cohort study by Mason et al. [32] achieved high quality under the Newcastle–Ottawa Scale, while Qian et al. [30] demonstrated moderate quality due to limited adjustment for confounding variables. The relatively small number of studies contributing to the SSI analysis remains a limitation; with only one study using clearly defined SSI criteria, the evidence base is insufficient for definitive conclusions.

Several limitations warrant acknowledgment. First, the absence of protocol registration (PROSPERO or equivalent) is a limitation that should be transparently acknowledged. Second, the SSI analysis relied on only one or two studies, which restricts precision and precludes formal publication bias assessment. Third, definitions of postoperative infection were not entirely uniform, particularly in the retrospective study by Qian et al. [30], which used a proxy definition rather than standardized SSI criteria. Fourth, the blood loss analysis included diverse warming modalities and comparators, contributing to heterogeneity. Fifth, the included studies did not directly measure psychosocial outcomes such as anxiety, depression, or distress; thus, implications for psychological recovery are inferred rather than directly demonstrated. Sixth, the comparators are inconsistent; several studies do not compare active warming against no warming or usual care. Some compare one active warming strategy against another, and one compares forced-air warming with amino acid-induced thermogenesis. These are not equivalent clinical contrasts and should not be pooled without a prespecified rationale and subgroup structure. Seventh, the clinical relevance of the blood-loss effect is not established; the primary pooled mean difference of approximately 25 mL is unlikely to be clinically meaningful unless linked to transfusion, hemoglobin change, complications, or recovery outcomes. Eighth, data extraction and imputation required assumptions for standard deviation estimation in the Yi et al [27]. study; while formulas were documented, the limited number of studies precludes robust sensitivity analyses to assess the impact of these assumptions. Ninth, the included studies were heterogeneous with respect to surgical procedures, with different baseline bleeding risks and SSI rates, which limits the generalizability of the pooled estimates. Future research integrating physiological endpoints with validated psychological measures would strengthen the translational relevance of perioperative warming strategies.

Despite these substantial limitations, the present synthesis provides preliminary evidence that active perioperative warming may be associated with improved surgical outcomes in cancer populations, particularly regarding infectious complications

when analyzed with proxy outcomes. Given the relatively low cost, minimal risk, and ease of implementation of warming strategies, their incorporation into standardized oncologic perioperative pathways warrants consideration, although the evidence base is insufficient to declare this "justified" with high certainty. In oncology, where treatment courses are often multimodal and prolonged, reducing early postoperative complications could contribute to potentially more stable treatment sequencing and improved patient-reported well-being.

Another important consideration is the cumulative stress burden experienced by oncology patients undergoing major surgery. Cancer diagnosis itself imposes substantial psychological strain, and the perioperative period often represents a peak stress interval characterized by uncertainty and anticipatory anxiety [47]. Physiological stress responses are closely intertwined with inflammatory and immunological processes. While the included studies primarily evaluated surgical endpoints, their findings suggest that maintaining physiological stability through normothermia may reduce inflammatory dysregulation and complication cascades that could theoretically exacerbate psychological distress [48,49]. In this regard, perioperative warming can be conceptualized not merely as a technical anesthesia adjunct but as a supportive intervention aligned with holistic oncologic care [50-51].

5. Conclusion

This meta-analysis provides preliminary evidence that perioperative warming interventions in oncologic surgery may be associated with reduced surgical site infection and reduced intraoperative blood loss, although the certainty of evidence is very low for both outcomes. While the bleeding outcome was characterized by inter-study variability, the direction of effect consistently favored active thermal management across diverse cancer populations and surgical procedures. However, the pooled SSI estimate is fragile, based on only two studies with few events and inconsistent outcome definitions, and the confidence interval is wide and close to the null. These findings suggest but do not establish the role of perioperative normothermia as a modifiable factor in optimizing surgical recovery in oncology settings.

Strengths of this study include: (1) a specific focus on oncologic surgery populations, distinguishing it from prior meta-analyses in mixed surgical populations; (2) a comprehensive systematic search across multiple databases (PubMed, Web of Science, Embase, CENTRAL) with explicit search dates; (3) use of the GRADE framework to systematically assess certainty of evidence; (4) application of Hartung-Knapp adjustment for more robust confidence intervals with few studies; (5) sensitivity analyses addressing comparator heterogeneity and outcome definition variability; and (6) explicit acknowledgment of the speculative nature of psycho-oncologic implications.

Weaknesses of this study include: (1) the small number of studies for each outcome, limiting precision and precluding publication bias assessment; (2) inconsistent SSI definitions, with one study using a proxy outcome rather than standardized CDC criteria; (3) substantial clinical heterogeneity across surgical procedures with different baseline risks; (4) inconsistent comparators across studies, with several comparing active warming strategies against each other rather than against no warming or usual care; (5) absence of PROSPERO or equivalent protocol registration; (6) absence of clinically meaningful outcomes such as transfusion rates, length of stay, or time to adjuvant therapy; (7) imputation of standard deviations for

one study, introducing additional uncertainty; and (8) very low certainty of evidence for both outcomes according to GRADE.

Beyond immediate surgical metrics, the reduction of postoperative complications may have broader implications for cancer care trajectories. Surgical site infection and excessive blood loss can delay adjuvant therapy initiation, prolong hospitalization, and exacerbate physical symptom burden—factors that could theoretically contribute to psychological distress and impaired recovery during a critical phase of cancer treatment. Theoretically, by reducing complication risk, perioperative warming could indirectly support both physical recovery and potentially psychological adjustment in cancer patients. Specifically, avoidance of infectious complications may prevent treatment delays that heighten anxiety regarding disease progression, while minimization of excessive blood loss may preserve functional capacity and reduce fatigue-related distress. These theoretical benefits, however, must be interpreted with substantial caution, as no direct psychological data were collected in the included studies and the surgical evidence itself is of very low certainty.

Given the relative simplicity, safety, and feasibility of warming interventions, their integration into standardized oncologic perioperative pathways warrants consideration, although the evidence base does not yet justify strong recommendations. The weaknesses of this meta-analysis—including the small number of studies, inconsistent comparators, proxy outcome definitions, absence of protocol registration, and lack of clinically meaningful endpoints such as transfusion rates—should be acknowledged alongside its findings. At present, the evidence is best characterized as hypothesis-generating rather than practice-changing for oncology-specific warming protocols. Perioperative warming may already be recommended in broader perioperative guidelines, but this manuscript does not establish oncology-specific outcome benefits with high certainty.

Future research should incorporate validated psycho-oncologic measures alongside surgical endpoints to better elucidate the relationship between physiological optimization and psychological recovery in cancer populations. Moreover, future studies should use standardized SSI definitions (CDC criteria), report clinically meaningful outcomes such as transfusion rates, length of stay, and time to adjuvant therapy, clearly distinguish between different warming comparators in subgroup analyses, and, where possible, include prospective registration to enhance methodological transparency. Such integrated approaches may further strengthen the role of perioperative care strategies within comprehensive oncologic frameworks.

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