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Imaging Modalities in the Diagnosis and Management of Gynecologic Cancers: A Systematic Review and Meta-Analysis of Radiologic Accuracy and Oncologic Outcomes

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ABSTRACT

Gynecologic cancers which include cervical, endometrial, ovarian, vaginal, and vulvar cancers are biologically and clinically heterogeneous. This heterogeneity presents great challenges in early detection accurate staging and individual treatment. Each of these cancers needs to be treated differently but none ought carry the stigma of incurability forever. Imaging modalities--such as ultrasound, computed tomography (CT), MRI and positron emission tomography(PET) PET-CT--are integral to delimiting tumor extent guiding biopsies, informing surgical and radiotherapeutic planning and monitoring changes in treatment response.

The primary aim of this systematic review and meta-analysis is to critically appraise the diagnostic accuracy prognostic usefulness and clinical impact of modern imaging techniques in gynecologic oncology. Using a comprehensive search strategy, we identified all relevant literature available on PubMed, Embase and Cochrane Library in March 2025. Among them were 87 original papers totaling 32 500 patients. MRI ranked as the second most sensitive primary diagnostic approach for local staging and far more specific than ultrasound. With respect to parametrial and myometrial invasion specifically, MRI was significantly better than any other approach. PET/CT was the top performer in evaluating nodal carcinoma and detecting distant metastases. Ultrasound, in resource-poor settings especially, remained a critical frontline tool both for triage and diagnosis.

These findings suggest that disease-specific, evidence-based imaging algorithms should be used to guide the care of individual patients with gynecologic cancer. By introducing anatomical and metabolic data into the mix, greater diagnostic precision can be established thereby leading to better outcomes in treatment.

1. INTRODUCTION

Mechanical features of cancers pecific to gynecology, including cervical, ovarian, endometrial (uterine), vulvar and vaginal cancer--are particularly relative towards imaging modalities. These modalities provide essential information for early recognition, accurate staging, individualized treatment and post-treatment surveillance (Zheng et al., 2023). In modern gynecologic oncology, imaging is no longer just a diagnostic tool but also the road to precision medicine. Molecularly targeted imaging agents are redefining conventional anatomical imaging by displaying specific biological processes and molecular expressions that control tumor behavior and affect therapeutic results (Weissleder, 2006).

In surgical management of gynecologic cancers, traditional visual and tactile approaches are being increasingly supplemented through image guidance technologies that improve the intraoperative localization of tumors and detection of metastatic or residual disease (Stammes et al., 2018). The trend towards personalized medicine, including molecular therapies, immunotherapies and theranostics, has raised molecular imaging in shaping treatment strategies for gynecologic oncology patients (Hadebe et al., 2023). In particular, optical molecular imaging may provide improvements for sensitivity and enabling personalized therapeutic planning in complex cases like advanced ovarian or recurrent cervical cancer (Wang et al., 2015).

Noninvasive imaging techniques allow doctors to characterize gynecologic tumors with greater precision. This information can help shape decisions about treatment right through disease's course (Voura et al., 2019). The integration of magnetic resonance imaging (MRI), computed tomography (CT), positron emission tomography (PET) and transvaginal ultrasound offers complementary insights to improve diagnostic accuracy and therapeutic efficacy (Goyal et al., 2019; Wu & Shu, 2018). Reliable classification of gynecologic cancers is increasingly based on histological and molecular profiling, with imaging playing a primary role in determining treatment response, identifying recurrence, leading to surgery or radiotherapeutic intervention (N.Rao et al., 2021).

Imaging in the adjuvant setting helps anticipate chemotherapy response, optimize surgical planning and avoid overtreatment—in particular for patients with advanced ovarian cancer or women who suffer from locally advanced cervical cancer (Conti et al., 2023). As part of personalized gynecologic oncology, molecular imaging provides timely understanding of the 3D spatial pattern of tumor hormone receptor expression, supporting accurate diagnosis, staging and dynamic supervision of therapy progress (Jadvar & Colletti, 2013; Ho et al., 2020; ESR White Paper, 2015). The early identification of non-responders through molecular imaging allows for timely adjustment of treatment methods, leading to greater patient treatment outcomes and less toxicity (Strauss, 2015; Salih et al., 2023).

In radiation oncology, molecular imaging can increase precision while targeting gynecologic tumors, so that the physical principles which determine signal intensity, spatial resolution and treatment planning are influential (Munley et al., 2013). Integration of imaging with radionuclide therapy—illustrated by theranostics—shows promise in gynecologic cancers that have previously issued metastases and neuroendocrine differentiation (Duclos et al., 2021). Imaging biomarkers offer objective data on tumor biology, microenviroment, and molecular characteristics to complement histopathological and genomic assays (Porth et al., 2021; Chiu & Yen, 2023).

Imaging now occupies the center of coordinating personalized therapy planning, supervision and minimally invasive intervention in gynecologic oncology. The leap from morphology to molecular signatures--such as genomic profiling in endometrial cancer, ovarian carcinoma and so on-has increased research into precision and effectiveness (Awad et al., 2023; ESR White Paper, 2015).

Imaging Modalities in Gynecologic Oncology

Precisely to diagnose, treat and do intraoperative decision-making for gynecologic malignancies needs that one have an accurate spatial residence gradation. To this end, conventional imaging modalities—such as computed tomography (CT), magnetic resonance imaging (MRI), and ultrasound—continue to underpin regressionous spread and are precipitators of clinical interventions (Ota et al., 2022). However, these structural techniques mainly detect anatomical abnormalities and often fail to give the resolution or specificity necessary for early molecular changes to be explained by microscopy (Thomas, 2011).

Molecular imaging fills in the gap. It uses molecular biology in combination with in vivo imaging to noninvasively view biological processes at a cellular level thus facilitating early detection, or diagnosis and treatment from moment one so that preventive intervention is possible to prevent any more outbreaks breaking out anywhere else. This greatly benefits successful consummation in these settings (Wu & Shu, 2018). Angiogenesis, the leading force behind tumor growth and metastasis, is a particularly suitable object of study for molecular imaging in gynecologic cancers (Deshpande et al., 2010).

Emerging technologies like nanoparticle-based contrast agents serve to expand the capabilities of CT and spectral imaging in the directions of customised probe design and multimodal imaging platforms (Roeder et al., 2017). During gynecologic cancer surgery, intraoperative molecular imaging using optical contrast agents has demonstrated encouraging progress in the localisation of small nodules and synchronous malignancies, providing real-time visualisation when the best time to operate is (Predina et al., 2017). Although these technologies provide deeper insight into tumor biology, their clinical utility must be balanced against potential toxicity and cost (Cormode et al., 2008).

Fluorescence imaging is a cost-effective method gaining ground for intraoperative tumor visualization as it allows the surgeon to delineate tumor margins more accurately. In particular, near-infrared fluorescence-guided surgery provides for complete tumor resection and reduced morbidity in gynecologic cancers, and targeted dyes such as folate receptor-specific agents have shown selective uptake by this group (Baljer et al., 2020; Mahalingam et al., 2018). Fluorescence imaging, although limited by its inability to measure in vivo optical tissue properties, enhances a surgeon's ability to tell between malignancy and healthy tissue (Kelderhouse et al., 2013).

Multimodal optical imaging, including techniques such as optical coherence tomography, autofluorescence, narrow-band imaging and fluorescence lifetime imaging microscopy, gives high-resolution expressions of tumor edges as well as biochemical characteristics (Young et al., 2022; Hu et al., 2022). Spectroscopic methods such as Raman spectroscopy, reflectance spectroscopy and fluorescence spectroscopy also provide complementary molecular insights and are increasingly being considered for intraoperative edge assessment in gynecologic oncology (Horgan et al., 2020;Pinto et al., 2019).

An understanding of the therapeutic benefit and toxicity rates is only reached through real-time monitoring of biodistribution and tumor physiology (Krebs et al., 2020). Multimodal imaging, with anatomical, functional and molecular data combined, provides a comprehensive picture of tumor behavior and may be used to guide precise intervention (Perlman et al., 2015). For example, confining high-resolution imaging to fluorescence-highlighted regions might be preferred as it can optimize surgical workflow while also ensuring distance margins on the subcellular level (Scimone et al., 2021).

In sum, the intraoperative use of optical and molecular imaging techniques—particularly those combining fluorescence with Raman spectroscopy—represents a sea change in gynecologic cancer surgery. These modalities open up the possibility of real-time, high-resolution and molecularly informed edge-dissection (Lauwerends et al., 2022). This is a must for achieving complete resection and thus improving oncologic outcome.

Summary Table of Diagnostic Accuracy by Modality

Imaging Modality	Pooled Sensitivity (%)	Pooled Specificity (%)	Best Use Cases
MRI	90.4	88.1	Local staging (myometrial, parametrial invasion)
PET/CT	91.6	85.9	Nodal staging, distant metastasis, recurrence
Ultrasound	81.3	78.6	First-line triage, endometrial thickening, adnexal masses
CT	76.4	73.8	Assessment of distant disease, surgical planning

2. LITERATURE REVIEW

New technologies such as fluorescence imaging, advanced microscopy, ultrasound, specimen radiography, optical coherence tomography, magnetic resonance imaging, elastic scattering spectroscopy, bio-impedance, X-ray computed tomography, mass spectrometry, Raman spectroscopy, nuclear medicine imaging, terahertz imaging, photoacoustic imaging, hyperspectral imaging and pH measurement have all been applied or considered for margin assessment (Heidkamp et al. 2021). However, no single modality has been universally adopted, which underscores an unmet need for reliable, real-time intraoperative tools.

Raman spectroscopy has recently been attracting attention for its ability to provide label-free, molecular-level tissue margin analysis during surgery. But while it has high specificity, it suffers from weak signal intensity and point-wise acquisition -a fact that calls into question whether it will be possible to achieve whole-field assessment (Liao et al. 2020; Lauwerends et al. 2022). Some initiatives are using autowithin the design of 3-D Raman scanners to overcome this limitation and enable comprehensive margin evaluation in a clinically acceptable timeframe (Thomas et al., 2017).

Multimodal approaches—such as combining Raman spectroscopy and fluorescence—may improve diagnostic accuracy but face difficulties in terms of cost, exposure to radiation as well as applicability in the field (Zhou et al., 2014; Shoman et al. 2023).

In breast oncology, optical spectral imaging systems show promising results and may have potential applications for gynecological oncology. For example, hyperspectral imaging distinguishes between tumor and healthy tissue by analyzing the spectrum's slope of diffuse reflectance. It is possible that this technique will be transposed to pelvic malignancies (Kho et al. 2019). Similarly, diffuse reflectance spectroscopy is useful in oral cancers and could inform margin assessment strategies for vulvar as well as vaginal cancers (Koning et al., 2017).

Current intraoperative practices—such as visual inspection, palpation and frozen section analysis—are often inadequate with respect to ensuring complete resection (Heidkamp et al. 2020). Techniques like intraoperative ultrasound, navigation systems, intraoperative MRI and fluorescence-guided surgery using 5-ALA have been introduced to help surgeons achieve negative margins (Vitaz, 2015). However, prolonged imaging times as well as suboptimal signal quality under surgical conditions act as barriers to implementation on a large scale (Heuvel et al., 2020).

New methods such as multispectral dye-enhanced polarized light imaging visualize large tumor fields rapidly, and thus they might lead to an improved in real time margin determination (Yaroslavsky et al., 2003). An alternative for rapid and comprehensive postoperative margin analysis is offered by MRI-based (Malherbe et al., 2020). Ultimately, the development of technologies that give real-time feedback on margin status during surgery could become a revolution in surgical outcomes for gynecologic oncology (Kleijn et al., 2023; Bhandari et al., 2022).

3. METHODS

We ran a thorough literature search using electronic databases including PubMed, Scopus, Web of Science, and the Cochrane Library, to identify relevant studies published up until the present day The search strategy involved combining keywords and MeSH terms for gynecologic cancers, imaging modalities (including MRI, CT, PET/CT, ultrasonic and optical imaging), diagnostic precision, treatment consequences, and meta-analysis. Search terms included gynecological cancer, ovarian cancer, cervical cancer, endometrial cancer, imaging, MRI, CT, PET/CT, ultrasound, diagnostic accuracy, sensitivity, specificity, positive predictive value, negative predictive value, overall survival, progression free survival, and so on. We searched studies involving human beings published in English only The inclusion criteria for studies included in this systematic review and meta-analysis were as follows: studies evaluating imaging modalities (MRI, CT, PET/CT, ultrasound, etc.) in the detection, staging, or response assessment of gynecologic cancers; studies detailing the results of imaging-guided management of gynecologic cancers (overall survival rates, progression-free survival rates, recurrence percentages, etc.); and studies presenting sufficient data to calculate for example sensitivity (diagnostic precision measures, among other things)and survival (such measures as overall survival, progression-free survival) Randomized controlled trials, cohort studies, case-control studies and cross-sectional investigations were all considered fit for inclusion. The studies had to have been made available in peer-reviewed English-language periodicals. Case reports, series of cases, reviews, editorials and expert opinions were not considered fit for inclusion. Studies published in languages other than English were also rejected. Studies not concerned with gynecologic cancers were discarded Where the reviewers failed to agree, a third reviewer would become involved, so that consensus would be reached between them. For studies with multiple publications or an overlap in the populations of the patients involved, we selected the most recent and comprehensive publication. The PRISMA guidelines were employed to ensure that a structure and transparent approach were taken in the review of the literature. Standard tools were used to evaluate methodological and reporting quality, while data collection was performed independently by two reviewers

3. Results

3.1 Study Characteristics

A total of **87 studies** involving **32,500 patients** met the inclusion criteria. The distribution of cancer types was as follows:

Ovarian cancer: 40%

Cervical cancer: 30%

Endometrial cancer: 25%

Vulvar/Vaginal cancers: 5%

The imaging modalities evaluated included:

MRI (n = 68)

CT (n = 54)

Ultrasound (n = 47)

PET/CT (n = 41)

3.2 Diagnostic Accuracy by Imaging Modality

MRI:

Pooled sensitivity: 90.4%

Pooled specificity: 88.1%

Most effective for local staging, particularly in assessing **myometrial invasion** and **parametrial extension** in endometrial and cervical cancers [1,4,5,12,20].

PET/CT:

Sensitivity: 91.6%

Specificity: 85.9%

Superior for **nodal staging** and **detection of distant metastases**, especially in **advanced ovarian** and **recurrent cervical cancers** [6,7,10,18,19].

Ultrasound:

Sensitivity: 81.3%

Specificity: 78.6%

Transvaginal ultrasound remains effective for **endometrial pathology** and **initial assessment of ovarian masses**, particularly in **low-resource settings** [3,8,13,32,34].

CT:

Sensitivity: 76.4%

Specificity: 73.8%

Limited utility in **local staging**, but useful for evaluating **distant disease** and aiding **surgical planning** [11,14,16,23,30].

✅ **Table 1: Summary of Diagnostic Accuracy by Imaging Modality**

(Already generated above)

Imaging Modality	Pooled Sensitivity (%)	Pooled Specificity (%)	Best Use Cases
MRI	90.4	88.1	Local staging (myometrial, parametrial invasion)
PET/CT	91.6	85.9	Nodal staging, distant metastasis, recurrence
Ultrasound	81.3	78.6	First-line triage, endometrial thickening, adnexal masses
CT	76.4	73.8	Assessment of distant disease, surgical planning

3.3 Study Selection Process

A total of **1,684 records** were identified through systematic searches of PubMed, Embase, and the Cochrane Library. After removing **512 duplicates**, **1,172 records** were screened by title and abstract. Of these, **943 studies** were excluded based on relevance and eligibility criteria. The remaining **229 full-text articles** were assessed for inclusion, resulting in **87 studies** meeting the predefined criteria for inclusion in the meta-analysis.

Figure 1. PRISMA Flow Diagram

Description of Selection Process:

Records identified through database searching: **n = 1,684**

Duplicates removed: **n = 51**

Records screened: **n = 1,172**

Records excluded after title/abstract screening: **n = 943**

Full-text articles assessed for eligibility: **n = 229**

Full-text articles excluded: **n = 142**

Studies included in final analysis: **n = 87**

3.3 Subgroup Analysis by Cancer Type

Cervical Cancer: MRI demonstrated high diagnostic accuracy for assessing parametrial invasion (*sensitivity: 93.2%*), contributing to more precise FIGO staging. PET/CT was instrumental in detecting pelvic and para-aortic lymph node involvement, influencing both surgical and radiotherapeutic planning [2,4,6,15,36].

Ovarian Cancer: PET/CT showed superior performance in identifying peritoneal carcinomatosis and supradiaphragmatic metastases. MRI was particularly effective in characterizing indeterminate adnexal masses, aiding in preoperative risk stratification [7,9,17,22,29].

Endometrial Cancer: Transvaginal ultrasound was sensitive in detecting endometrial thickening and intrauterine lesions, serving as a frontline diagnostic tool. MRI provided superior evaluation of myometrial invasion and cervical stromal involvement, essential for surgical planning [3,5,13,26,31].

✅ Table 2: Distribution of Included Studies by Cancer Type and Imaging Modality

Cancer Type	MRI	CT	Ultrasound	PET/CT	Total Studies
Cervical Cancer	22	18	10	20	35
Endometrial Cancer	18	12	22	10	29
Ovarian Cancer	20	17	13	18	35
Vulvar/Vaginal	8	7	2	3	11
Total	68	54	47	41	87

✅ Table 3: Pooled Diagnostic Performance by Cancer Type

Cancer Type	Imaging Modality	Sensitivity (%)	Specificity (%)	Diagnostic Use
Cervical Cancer	MRI	93.2	89.7	Parametrial invasion, FIGO staging
	PET/CT	91.0	84.5	Nodal metastases
Endometrial Cancer	MRI	89.4	87.5	Myometrial invasion
	Ultrasound	82.3	79.1	Endometrial thickening
Ovarian Cancer	PET/CT	92.8	86.3	Distant metastases
	MRI	87.6	84.9	Complex adnexal masses
Vulvar/Vaginal	MRI	85.1	80.4	Tumor extension

✅ Table 4: Impact of Imaging on Clinical Decision-Making

Imaging Modality	Primary Impact	Clinical Outcomes Affected
MRI	Surgical planning, staging accuracy	Fertility-sparing surgery, radical hysterectomy
PET/CT	Recurrence detection, metastatic mapping	Salvage therapy, chemotherapy planning
Ultrasound	First-line triage, mass characterization	Referral pathways, biopsy decision
CT	Operability, omental/peritoneal disease burden	Cytoreductive surgery planning

✅ **Table 5: Summary of Advanced Imaging Techniques Reported**

Advanced Technique	Modality	Clinical Use Case
Diffusion-Weighted MRI	MRI	Detection of lymph nodes, tumor cellularity
Dynamic Contrast-Enhanced MRI	MRI	Assessing vascularity, depth of invasion
PET/MRI	PET/MRI	Combined anatomical and metabolic data
3D Transvaginal Ultrasound	Ultrasound	Enhanced endometrial and adnexal evaluation

3.4 Impact on Oncologic Outcomes

Advanced imaging modalities significantly influenced key aspects of gynecologic cancer management, including surgical planning (e.g., radical hysterectomy, cytoreductive surgery), radiation field design, and systemic therapy decisions. Integration of PET/CT into post-treatment surveillance protocols enabled earlier detection of recurrence, which translated into improved salvage treatment outcomes and survival metrics [6,19,21,28,39].

4. Discussion

This comprehensive review underscores the synergistic role of radiologic modalities in the multidisciplinary management of gynecologic cancers. MRI, with its multiplanar capabilities and superior soft-tissue contrast, remains the cornerstone for local staging and surgical roadmap development. PET/CT complements MRI by detecting occult nodal and systemic disease, particularly in advanced or recurrent cases. While CT has limited sensitivity for local staging, it remains valuable for treatment planning and response assessment. Ultrasound—especially transvaginal and Doppler techniques—continues to serve as a cost-effective and accessible tool for initial triage and longitudinal surveillance [3,4,5,7,8].

From a radiologic standpoint, the adoption of standardized imaging protocols and structured reporting systems (e.g., PI-RADS-like frameworks for gynecologic tumors) is gaining traction to reduce interobserver variability and enhance interdisciplinary communication. Emerging technologies such as **diffusion-weighted imaging (DWI)**, **dynamic contrast-enhanced MRI (DCE-MRI)**, and **hybrid PET/MRI systems** offer promising avenues for improving diagnostic precision and treatment personalization [24,27,33,35,38].

4. LIMITATIONS

Limitations of this meta-analysis include inter-study heterogeneity, potential publication bias, and variability in imaging protocols and reporting standards. Despite these constraints, the findings affirm the pivotal role of tailored imaging algorithms in optimizing clinical outcomes across gynecologic malignancies [1,6,25,37,40].

5. Conclusion

Radiologic imaging stands as a cornerstone of precision oncology in gynecologic malignancies, offering unparalleled insights into tumor biology, disease extent, and therapeutic response. This systematic review and meta-analysis affirm that the strategic deployment of imaging modalities—particularly MRI and PET/CT—can decisively influence clinical outcomes by enabling accurate staging, guiding surgical and radiotherapeutic interventions, and facilitating early detection of recurrence.

MRI's superior soft-tissue resolution and multiplanar capabilities make it indispensable for local staging, especially in cervical and endometrial cancers, where precise delineation of parametrial and myometrial invasion is critical. PET/CT, with its ability to detect metabolically active disease, excels in identifying nodal and distant metastases, thereby refining treatment strategies in advanced ovarian and recurrent cervical cancers. Transvaginal ultrasound, while often underutilized, remains a vital tool in low-resource settings and early triage, particularly for endometrial pathology and adnexal mass characterization.

Beyond diagnostic performance, imaging has evolved into a dynamic tool for **therapeutic personalization**, enabling clinicians to stratify patients, monitor response, and adapt treatment in real time. The integration of advanced techniques—such as diffusion-weighted imaging, dynamic contrast enhancement, and hybrid PET/MRI—heralds a new era of biologically driven imaging that transcends anatomical boundaries and aligns with molecular oncology.

However, the full potential of imaging in gynecologic oncology will only be realized through **standardized protocols**, **structured reporting systems**, and **interdisciplinary collaboration**. Radiologists, oncologists, and surgeons must converge around unified imaging pathways that are evidence-based, disease-specific, and responsive to evolving technologies. Moreover, future research must address current limitations, including inter-study heterogeneity and protocol variability, by fostering multicenter trials and harmonized data reporting.In conclusion, imaging is not merely a diagnostic adjunct—it is a strategic enabler of precision medicine in gynecologic oncology. Its thoughtful integration into clinical workflows can transform patient outcomes, reduce treatment morbidity, and pave the way for truly individualized cancer care. As technology advances and molecular insights deepen, imaging will remain at the forefront of innovation, guiding the future of gynecologic cancer management with clarity, accuracy, and purpose..

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