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A Comprehensive Review on the Recent Advances in Prostate and Breast Cancer Research: Overview, Potential Treatment, and Perspectives

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Abstract

The therapeutic limitations of conventional cancer treatments currently deployed are driving the development and creation of new nanodrugs. Significant advances have been made in understanding the biology of various cancers, as well as in the development of imaging technologies and therapeutic approaches. Subsequently, cancer management has evolved rapidly, with profound research undertakings focused on elucidating the genomic landscape and oncogenesis of localized and metastatic cancers. Prostate cancer (PCa) is a prevalent clinical problem in older men with a significant global incidence, with 1.5 million cases reported in 2022. Breast cancer (BC) is also a considerable health burden among women worldwide, with reports showing over 67000 deaths in 2022. Generally, across the world, these cancers have posed a significant health burden due to limited access to treatment options, high incidence rates, and mortality rates occasioned by lifestyle and genetic factors. Accordingly, this review covers a nuanced and insightful overview of the available cancer treatment options, such as radiation therapy, surgery, hormone therapy, chemotherapy, and targeted therapies, focusing on PCa and BC. The current treatment strategies face therapeutic challenges related to accessibility issues, drug resistance, and side effects. The emergence of nanomedicine and artificial intelligence (AI) models in imaging, therapy, and drug delivery seems to offer solutions related to these challenges. Nanomedicine is a growing research hotspot, with an increasing number of publications featuring keywords such as “prodrug,” “cancer nanomedicine,” “cancer immunotherapy,” “artificial intelligence,” and “targeted nanomedicine.” The nanotechnologies utilized in cancer treatment reduce side effects, enhance treatment efficacy, and improve patient outcomes. Combining nanomedicine with conventional therapies holds promise in revolutionizing cancer treatment and addressing the clinical challenges of current therapies.

Keywords: Prostate cancer; breast cancer; oncogenesis; mortality rates; targeted therapies; nanomedicine

1. Introduction

Cancer is a serious illness that poses a grave concern to the health of the global population (Xi & Xu, 2021; Xu et al., 2023). Academic series have described cancer as a cell growth that forms abnormal tissue masses in the body. The National Cancer Institute (NCI) defines cancer as “a disease in which some parts of the body’s cells grow uncontrollably and spread to other parts of the body” (Brown et al.,

2023). Cancer first arises from changes in cells (the growth of tissue mass) to form a tumor. It was first recognized as "a disease of the genes," where the normal cells transform into malignant cells (Brown et al., 2023). The cancer cells undergo epigenetic and genetic changes, adopting a tumorigenic process (metastasis). The more resilient and aggressive cells drive the disease progression and multi-drug resistance. Considering the evolutionary nature of cancer cells by natural selection and genetic and epigenetic changes, Brown et al. (2023) define cancer as "a disease of uncontrolled proliferation by transformed cells subject to evolution by natural selection". The underlying mechanism of heterogenous prostate cancer (PCa) and breast cancer (BC), both genetically and histopathologically, is still uncertain. The mono-therapeutic treatment selection for these malignancies includes chemotherapy, hormonal therapy, surgery, and radiotherapy (Cai & Liu, 2021). Notwithstanding the success of mono-therapeutic selection for cancer treatment, the success of mono-therapies is limited by drawbacks associated with an increase in resistance and damage to healthy growing cells. Therefore, the current research programs focus on targeted therapy by leveraging the existing and vast knowledge in structural and functional characteristics with high specificity on the target protein. Current advances in cancer research are aimed at overcoming chemoresistance mechanisms. They also aim to improve the delivery of treatment regimens selectively to cancer cells without damaging the microenvironment and reduce the toxicity profiles of anticancer agents (Marey et al., 2024). Accordingly, there is a need to leverage the synergistic potential of next-generation technologies and the vast knowledge in structural biology to enhance the early detection of biomarkers, optimize treatment delivery, and develop individualized treatment plans for cancer patients (Marey et al., 2024).

The risks of PCa, BC, colon cancer, and lung cancer hold a prominent place in global health (Cai & Liu, 2021; Siegel et al., 2021). The incidence rates of these cancers increase with age (Harding et al., 2012). However, incidence rates based on age vary widely across countries/regions (Zahed et al., 2024); for instance, BC may occur in young girls in Asian and African countries (Brinton et al., 2014; Leong et al., 2010), while colon cancer has a higher incidence at a young age in West Africa than in the United States (Alatise et al., 2021). The treatment or prevention of cancers diagnosed earlier is more cost-effective than that of those identified at older ages, given the number of lives saved. However, the heterogeneity and plasticity of cancer pose significant treatment challenges (Ottaiano et al., 2023). Besides, cancer develops resistance to anti-cancer medications. Among all cancers, BC and PCa have emerged as the second and third most prevalent types of cancer since 2018, respectively (Auli et al., 2024). There are over 1 million deaths globally due to metastatic PCa and BC (Verbruggen et al., 2024). Precise diagnostics and screening are recommended to determine an appropriate treatment course for PCa and BC. Early detection of these cancers augments the quality of life, overall survival rate, and timely decision-making (Prager et al., 2018). Breast biopsies are a common invasive method used to detect BC potential risks, including bleeding, bruising, infection, and swelling of the biopsy site (Pansa et al., 2023). Furthermore, urinary tract diagnosis using a non-invasive (pain-free) approach can easily detect specific biomarkers, such as microRNAs (miRNAs), which regulate cell metabolism. On the other hand, serum prostate-specific antigen (PSA) is a pivotal biomarker in PCa diagnosis, showing substantial promise in reducing PCa-related mortality (Chen et al., 2023). However, the diagnosis of both cancers has escalated debate as to whether screening does more harm than good, mainly due to the unintended consequences of overtreatment and excessive diagnosis of low-risk cancers (Benson et al., 2023; Hewitt et al., 2020).

As of 2020, PCa was reported as the most common cancer by incidence among men in 112 countries and accounts for 15% of all male cancers. PCa comes second (after lung cancer) as the most common cancer in men globally. In 2022, on a global scale, approximately 1.5 million new cases of PCa were reported by the World Cancer Research Fund (WCRF) (WCRF, 2024b) while 2.3 million new cases of BC were reported in the same year (WCRF, 2024a). BC-related deaths were over 670,000, as reported by WHO (2023), while PCa-related deaths were approximately 397,000 (WCRF, 2024b). The prevalence of these cancers varies widely across countries, with nations like Brazil, China, and the

United States recording the highest prevalence for PCa (WCRF, 2024b). Similarly, North America records the highest incidence rates of BC compared to Sub-Saharan Africa (WCRF, 2024a; WHO, 2023). South Africa and Nigeria recorded the highest number of PCa-related deaths attributed to limited access to healthcare. Across Sub-Saharan Africa, the incidence rates for PCa and BC vary widely across different regions (WCRF, 2024a, 2024b)

Prostate cancer (PCa) and BC occupy a prominent space in the medical sector in the world. BC has been recorded as one of the causes of high mortality rates among women. Most BC incidents are diagnosed at an advanced stage in many countries due to a lack of early screening programs. Conversely, PCa incidence across the world is recorded at advanced stages, contributing to high mortality rates (WCRF, 2024a, 2024b). There is a document proof from the World Health Organization (WHO) that BC and PCa are growing health concerns with significant mortality and incidence rates across different regions. According to the WHO, risk factors such as lifestyle and family history must be understood for timely screening and treatment for these cancers (WCRF, 2024b).

The treatment and management options of PCa and BC depend on the stage and type of cancer (De Silva & Alcorn, 2022). The common treatments for BC include chemotherapy, radiation therapy, surgery, and so forth (Kunkler et al., 2023). PCa patients have also benefited from treatment options, including active surveillance, surgery, chemotherapy, and radiation therapy, among others (Shah et al., 2018). Nevertheless, these treatment options are associated with significant clinical challenges related to drug-related side effects, including cisplatin-induced ototoxicity and nephrotoxicity, anthracycline-induced cardiotoxicity, cardiac and pulmonary injury, and radiation dermatitis (Yang et al., 2023). Nanotechnology has emerged as a promising tool for enhancing cancer treatment through thermal therapy, targeted drug delivery, gene therapy, and diagnostics and imaging. Tracking the latest research advancements is crucial for a deeper understanding of BC and PCa, as well as for enhancing treatment outcomes for cancer patients. The objectives of this review paper are threefold: (1) to assess the epidemiological trends and global burden of BC and PCa, (2) to examine the current therapeutic approaches for BC and PCa, and (3) to provide a concise overview of how nanotechnology and AI-assisted imaging have improved cancer management. Accordingly, the paper offers a concise overview of PCa and BC progression, the synergistic relationship between nanomedicine and conventional cancer treatments, and the prospects of AI-assisted imaging in improving cancer screening and treatment.

2. Methodology

In this review, we collected reviews and studies concerning treatment options currently deployed in BC and PCa management, published from 2001 to the present, in the Scopus, Web of Science, WHO Global Health Library, Google Scholar, medRxiv, and PubMed databases. The keywords used in the literature search were: “prostate cancer”, “breast cancer”, “chemotherapy”, “radiation therapy”, “radical prostatectomy”, “external beam radiation therapy”, “surgery”, “immunotherapy”, “active surveillance”, “brachytherapy”, “hormone therapy”, “nano drugs”, “artificial intelligence”, and “prodrugs”. The literature search was conducted using Boolean “OR” and “AND” operators to connect keywords or main terms. Original and review studies were manually excluded if they were irrelevant to the treatment of BC and PCa. Further, non-English articles were also manually excluded. The search result was imported into EndNote Version X8, Clarivate Analytics, USA. The flowchart methodology used in this review is summarized in Figure 1.

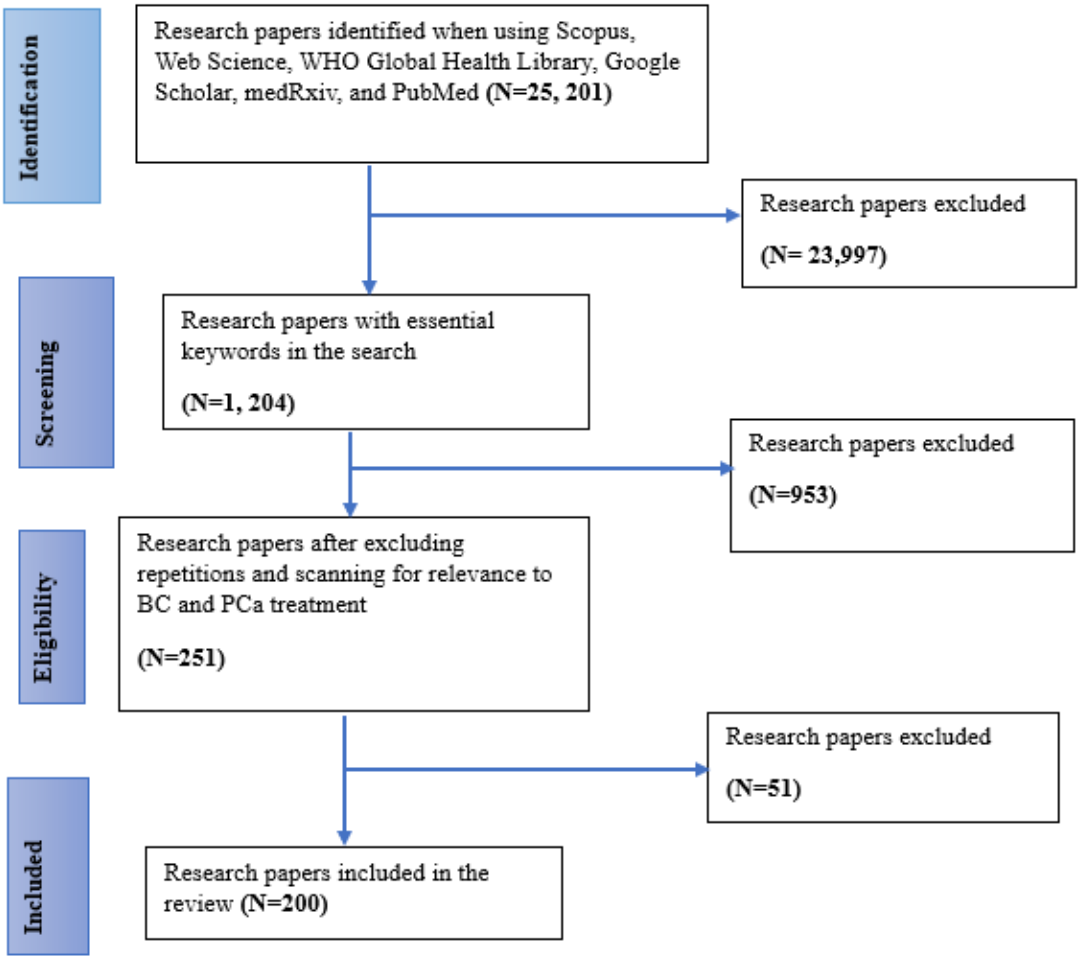

Fig. 1 Flowchart methodology used in this review paper

2.1 Prostate cancer diagnostic pathway

2.1.1 General anatomy of the prostate glands

The prostate gland is a male reproductive organ below the urinary bladder and in front of the rectum. It is a pyramid-shaped organ that surrounds the prostatic urethra, extending superiorly to the base of the bladder and inferiorly to the urogenital diaphragm, measuring approximately 3 × 3 × 5 cm and having a volume of 25 mL (Mahadevan et al., 2024). The prostate size varies with age; it weighs approximately 20 g for males between 20 and 50 years old and 30 g for those between 60 and 80 years old (Mahadevan et al., 2024). Its primary role is to produce fluids that, together with fluids from other glands and sperm cells from the testes, make semen.

The zonal anatomy of the prostate, as established by McNeal segmentation, consists of three glandular zones: peripheral, transition, and central zones, and the anterior fibromuscular stroma, which is non-glandular (Figiel et al., 2023; Laschkar et al., 2022). The central zone lies posterior to the transition zone and surrounds the left and right ejaculatory ducts (Ali et al., 2022). The transition zone surrounds the prostatic urethra. The peripheral zone surrounds the transition, and the central zone is located laterally and posteriorly (Ali et al., 2022). The anterior fibromuscular is anterior to the transition zone and forms the anterior aspect of the prostate. PCa is commonly found in the periphery zone of the prostate (70%) rather than the anterior fibromuscular stroma zone (5%) and the transition zone (25%) (Figiel et al., 2023). On the other hand, benign prostatic hyperplasia mainly affects the transition zone.

This discrepancy is due to the differences in the densities of glandular tissues susceptible to transformation in each zone. Figure 2 illustrates the zones of the prostate, according to McNeal.

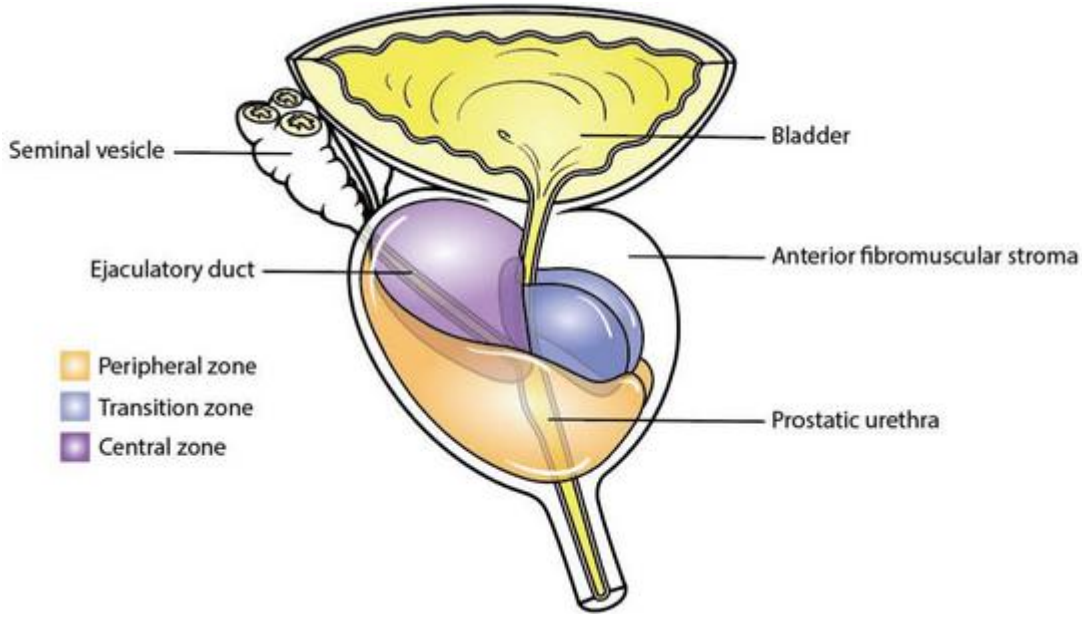

Fig. 2 Anatomical zones of the prostate gland (Figiel et al., 2023)

2.1.2 Prostate Cancer Progression

The first sign of PCa is the inflammation of the prostate gland, which occurs due to rapid and uncontrolled cell division (Oseni et al., 2023). Clinical observations reveal that the damage to the DNA results in uncontrollable cell division. The oxidative stress resulting from prostate gland inflammation may potentially shorten the telomeres of the prostate, leading to the onset of prostate cancer (PCa). Research has shown that several genes, including Transmembrane Protease, Serine 2-ETS-Related Gene (TMPRSS2-ERG), NK3 Homeobox 1 (NKX3.1), phosphatase and Tensin Homolog (PTEN), and myelocytomatosis (MYC) viral oncogene Homolog, are known to initiate PCa (Sekhoacha et al., 2022). In particular, the PMPRSS2-ERG gene fusion is the primary molecular type of PCa (Kobelyatskaya et al., 2023). The reactivation of pathways involved in uncontrollable cell division leads to the metastasis of PCa, resulting in rapid cell proliferation (cf. Figure 3). In high-income countries, early detection is more common, driven by better access to treatment and higher rates of PSA (Zahed et al., 2024). In low- and middle-income countries, PCa is mainly diagnosed at an advanced age when the tumour has metastasis, when the patient has high total serum concentrations, or when the patient already has locally advanced cancer (Zahed et al., 2024). Arguably, early detection translates to lower mortality rates per incident case, particularly in high-income countries. Overtreatment and overdiagnosis cause harm in high-income countries; undertreatment and underdiagnosis lead to different harms in low- and middle-income countries (Shen & Abate-Shen, 2010). Therefore, the opposing issues need an improved understanding of a more refined diagnostic pathway.

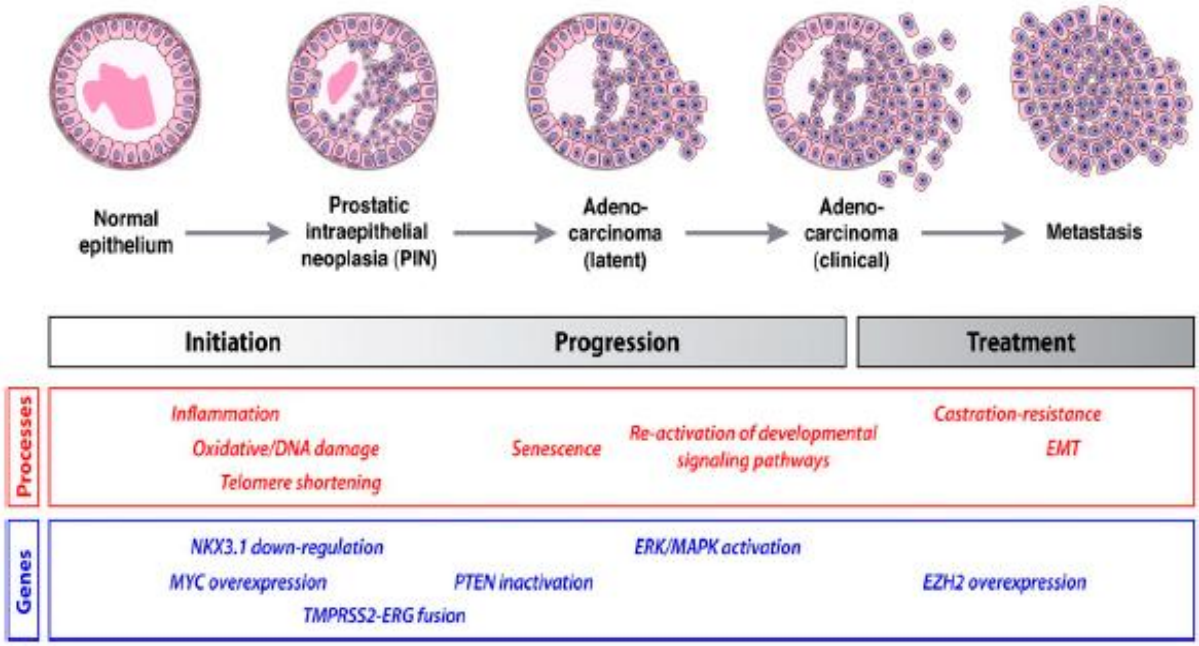

Fig. 3 The development of prostate cancer – processes and genes involved (Sekhoacha et al., 2022; Shen & Abate-Shen, 2010)

The oncogenesis of PCa is linked with complex interactions between acquired somatic gene alterations, inherent germline susceptibility, and micro- and macro-environmental factors (Rehman et al., 2023). It is believed that chronic infection and inflammation due to urinary microbes drive prostate carcinogenesis through oxidative stress and the generation of reactive oxygen species, which damage the DNA and selection of mutated cells. The proliferative inflammatory atrophy (PIA) identified during biopsies is characterized by shrinkage of the glandular tissue (glandular atrophy), rapidly dividing epithelial cells, and chronic inflammation (Oseni et al., 2023). PIA is a precancerous lesion but is susceptible to epigenetic and genetic transformation, eventually leading to prostatic intraepithelial neoplasia (PIN) and, finally, lethal cancer cells (Oseni et al., 2023). PIN can be categorized within the tissue from low-grade to high-grade. In high-grade PIN lesions, the presence of multilayered luminal epithelium is associated with markers of transformation such as cytokeratin 14 (KRT14), cytokeratin 5 (KRT5), cytokeratin 18 (KRT18), basal markers p63 (TP63), and overexpression of methyl acyl-CoA racemase (AMACR) enzyme, which is associated with malignancy in mucus-secreting glands (adenocarcinoma) (Hu et al., 2021; Sandhu et al., 2021).

In PCa, somatic mutations drive cancer progression and affect how these cancerous cells respond to tumours. The commonly mutated genes in PCa include RB1, PTEN, and TP53, while ATM and BRCA1/2 are genes involved in DNA repair (Ghose et al., 2021; Sekhoacha et al., 2022). Genomic classifiers such as the Gleason score and PSA levels are important prognostic biomarkers that predict the likelihood of cancer progression (Oseni et al., 2023). Additionally, androgen receptor splice variant 7 (AR-V7) is a predictive biomarker that predicts tumour resistance to specific hormonal therapies, influencing treatment decisions. TMPRSS2-ERG is the most common genetic alteration in prostate cancer (PCa) and significantly contributes to the tumor's initiation and progression. While this fusion is uncommon among men of Asian heritage, in every 4 of 10 prostate tumours, it is a result of hotpot mutations in CHD1, ZNF292, and FOXA1 (Sandhu et al., 2021; Sekhoacha et al., 2022). Figure 4 depicts various prognostic and predictive biomarkers and somatic mutations in localized and metastatic PCa.

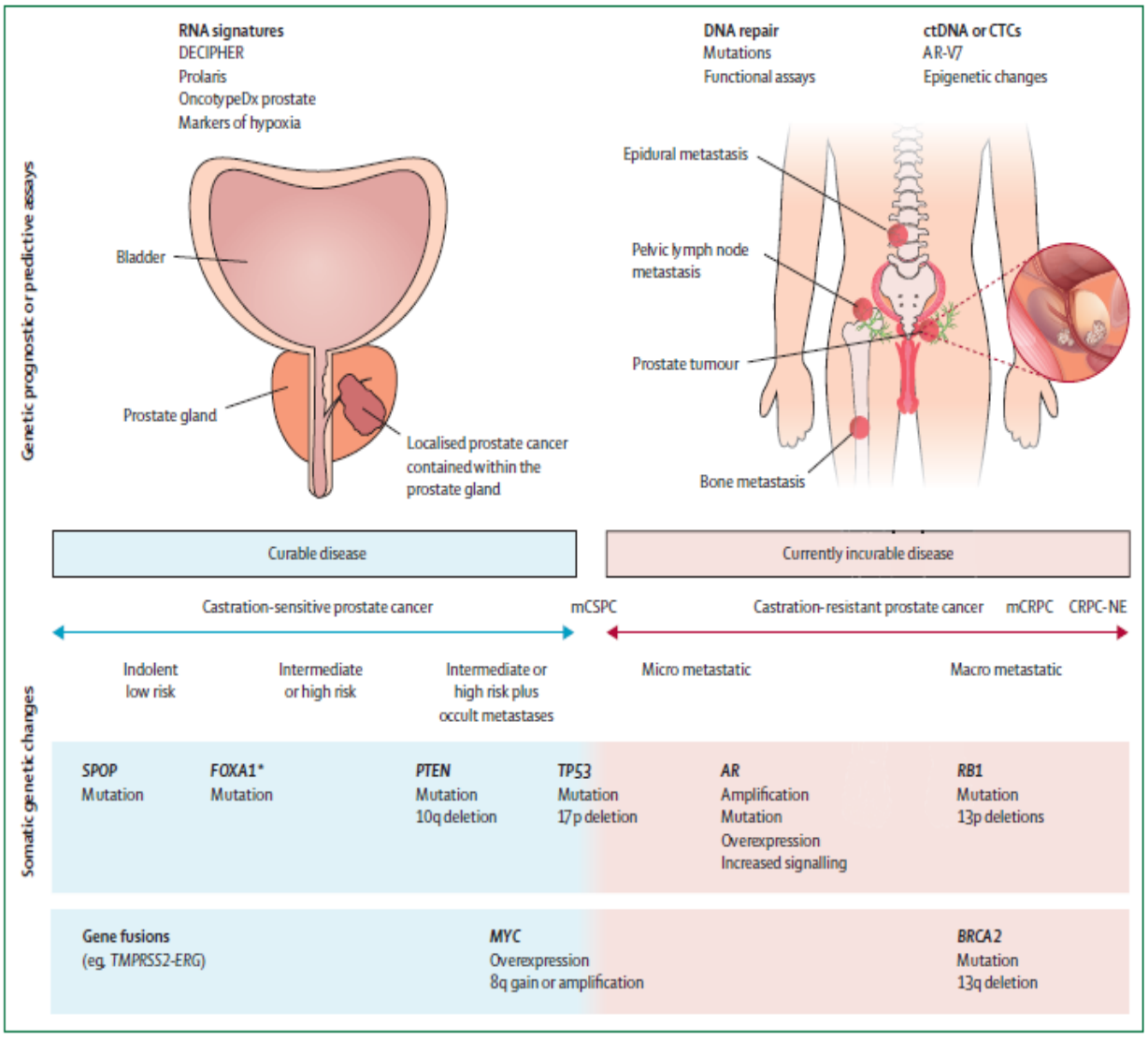

Fig. 4 Prostate cancer genetic prognostic or predictive essay and the somatic genetic challenges (Sandhu et al., 2021)

2.1.3 Prostate Cancer Diagnosis and Treatment

Prostate cancer (PCa) is a malignant growth that affects middle-aged men aged 45 and older (Kraujalis et al., 2022) and accounts for the increased mortality rates globally. The diseases arise from the lining of the epithelium of the prostate gland, ranging from indolent to lethal tumours (Hashemi et al., 2024). Nevertheless, the biology underlying the existence of low-grade tumours that require no treatment for highly lethal cancers is not well understood. The increased mortality rates are due to PCa diagnosis at advanced stages and failure of the therapy. Conventionally, PCa diagnosis by digital rectal examination (DRE) involves the assessment of the size of the prostate gland by inserting a gloved finger into the patient's rectum (Andrews et al., 2024). Health screening, magnetic resonance imaging (MRI), prostate-specific antigen (PSA) testing, and prostate biopsy and analysis have been proposed as screening techniques for PCa (Hugosson et al., 2022). Advanced imaging techniques such as multi-parametric MRI (mp-MRI), PCa gene 3 (PCA3) test, which measures PCA3 gene level, and prostate health index (PHI) that combines various forms of PSA (Li et al., 2024). Additional tests may include the Gleason

score to determine the aggressive nature of PCa [44], a bone scan to monitor cancer cells in the bones [45], and a computed tomography (CT) scan to accurately detect PCa (de Feria Cardet et al., 2021).

The frequently cited risk factors for PCa include obesity, age, ethnicity, and family history, among other environmental factors (Lynch et al., 2020; Zhang & Zhang, 2023). However, there is scientific evidence that gene mutations are the prevalent cause of cancer (Mendiratta et al., 2021). Men younger than 40 have a low risk of developing prostate cancer (PCa), but the risk increases as an individual approaches 50 (Huynh-Le et al., 2020). Academic series show that six out of 10 PCa incidences are in men aged over 65 (Jha et al., 2014). It is also well-established in the literature that African-American men face a high risk of PCa compared to other racial groups (Murphy et al., 2024). Genetic and family history are additional risk factors, particularly if one or more family members have been affected by the condition. Individuals may inherit gene mutations, including those related to BRCA1/BRCA2, and the risk is even higher for men with Lynch syndrome (Cheng et al., 2024). A Westernized lifestyle, characterized by the consumption of high-fat red meat and dairy products, is associated with prostate cancer (PCa) (Castelló et al., 2023). Conversely, diets rich in vegetables or fruits may lower the risk of prostate cancer (PCa). People with obesity and high smokers are also likely to develop aggressive PCa. Research has been ongoing on treatment options for PCa, such as hormonal therapy, active surveillance, radiation therapy, chemotherapy, cryotherapy, and surgery (Sekhoacha et al., 2022). The treatment option for PCa patients depends on various factors, including the potential for recurrence of the malignancy, PSA level, tumor nature, grade, and stage (Sekhoacha et al., 2022). For instance, hormonal therapy is recommended for treating cancers that have reoccurred or have spread beyond the prostate (Merseburger et al., 2022). For low-risk PCa, radiation therapy in conjunction with radical prostatectomy (surgical option) is recommended (Moris et al., 2020).

2.1.4 Treatment Options for Localized Prostate Cancer

Prostate cancer (PCa) management and treatment options are multiple, leading to debate amongst radiation oncologists and urologists over the optimal approach (Reitano et al., 2024). Treatment options for PCa patients are selected based on various factors, including expected outcomes, disease risk categories, potential complications tied to each treatment, and life expectancy (Reitano et al., 2024). Other factors to be considered include patient treatment and the medical ability of the PCa patient to receive general anesthesia and undergo invasive procedures (Shu et al., 2022). Accordingly, selective PCa screening and treatment reduce mortality rates due to cancer cells (McNevin et al., 2021). The risk stratification scheme identifies appropriate PCa treatment options, including pre-treatment PSA, clinical staging with a DRE, and Gleason scores (Sopyllo et al., 2021). Magnetic resonance imaging (MRI) has also proved beneficial in evaluating potential local disease extension (Da Conceição & Dias, 2023). According to the National Comprehensive Cancer Network (NCCN), PCa stratification is fundamental in guiding decisions regarding management and treatment. Typically, cancer confined to the prostate is of very low risk (Gleason score is less than 6) and can be managed by active surveillance to counter its progression (de Vos et al., 2023). Low-risk PCa has slightly higher Gleason scores and PSA levels than very low-risk PCa and can also be treated with active surveillance. Cancer stratified as intermediate risk is aggressive within the prostate with Gleason scores between 7-10 and higher PSA levels. Intermediate cancer may be treated/managed with hormone therapy, radiation therapy, or surgery. High-risk cancer is more aggressive with higher Gleason and PSA levels and is often managed with a combination of chemotherapy, hormone, and radiation therapy. On the other hand, very high-risk PCa is very aggressive with very high Gleason and PSA levels (Gnanapragasam et al., 2016). This cancer spreads widely in the prostate, and options such as surgery, chemotherapy, radiation, and hormone therapy may be recommended. Metastatic is a PCa that has spread beyond the prostate to other body organs. Therefore, treatment options that control its spread, such as immunotherapy, chemotherapy, targeted therapies, and hormone therapy, may be recommended. Table 1 presents a 6-tier stratification ranging from very low to very high risk according to NCCN.

Table 1: Table of NCCN prostate cancer risk stratification criteria (Templeton et al., 2023)

Risk group	Clinical/pathological features		
Very low	It has all the following: T1c Grade Group 1 PSA<10 ng/mL/g Fewer than three prostate biopsy fragments/cores positive, ≤ 50% cancer in each fragment/core PSA density <0.15 ng/mL/g		
Low	Has all of the following, but does not qualify for very low-risk T1-T2a Grade Group 1 PSA<10 ng/mL		
Intermediate	It has all of the following: No high-risk group features No very-high-risk group features	Favorable intermediate	It has all of the following: 1 IRF Grade Group 1 or 2 <50% biopsy cores positive
	Has one or more intermediate risk factors (IRF): T2b-T2c Grade Group 2 or 3 PSA 10-20 ng/mL	Unfavorable intermediate	Has one or more of the following: 2 or 3 RFs Grade Group 3 ≥ 50% biopsy cores positive
High	It has no very-high-risk features and has exactly one high-risk feature T3a OR Grade Group 4 or Grade Group 5 OR PSA>20 ng/mL		
Very high	Has at least one of the following: T3b-T4 Primary Gleason pattern 5 2 or 3 high-risk features >4 cores with Grade Group 4 or 5		

Localized PCa is a prevalent cancer in men, manifesting in old age (Bergengren et al., 2023). Patients and clinicians must weigh conservative versus aggressive options when choosing the appropriate treatment for localized PCa. Localized cancer progresses slowly, and therefore, aggressive options such as robot-assisted laparoscopic radical prostatectomy, intensity-modulated radiotherapy, brachytherapy, and active surveillance or local treatment are recommended for patients with a life expectancy of over 10 years (Knipper et al., 2021). Robust evidence suggests that men diagnosed with intermediate- or low-risk clinically localized PCa can live longer after diagnosis (Zattoni et al., 2024). Typically, patients newly diagnosed with localized PCa choose their initial treatment options based on the low likelihood of dying of PCa, tumour stage, and risks of cancer progression (Knipper et al., 2021). Therefore, detailed consultation with a radio-oncologist and/or urologist is advisable due to the potential adverse effects of treatment options, including chronic infection of the rectum and impairment of continence and erectile function.

2.1.5 Radical Prostatectomy

For healthy men younger than 70 years diagnosed with localized PCa, radical prostatectomy (RP) is recommended (Barakat et al., 2022; Cacciamani et al., 2021). RP involves the removal of the prostate

with the prostatic urethra together with the seminal vesicles. RP is performed using a minimally invasive, nerve-sparing technique with a laparoscopic or robotic-assisted laparoscopic approach (Kumar et al., 2021). Thanks to PSA-based screening, the rate of organ-confined prostate cancer (PCa) at diagnosis has increased, leading to successful surgery. Patients with organ-confined PCa (selected patients with high-risk disease and low- or intermediate-risk disease), younger than 70 years, with a life expectancy of more than 10 years and minimal or no comorbidities, have benefited from this treatment option (Sekhoacha et al., 2022). There are also minimally invasive surgical approaches, such as robotic RP or laparoscopic, that offer shorter recovery times but have not shown promise in controlling cancer tumours and their side effects (Bignante et al., 2024). Figure 5 depicts RP, whereby the whole prostate is removed to eliminate all cancerous tissue to minimize tumor recurrence and prevent the spread of tumor cells (Anene, 2021).

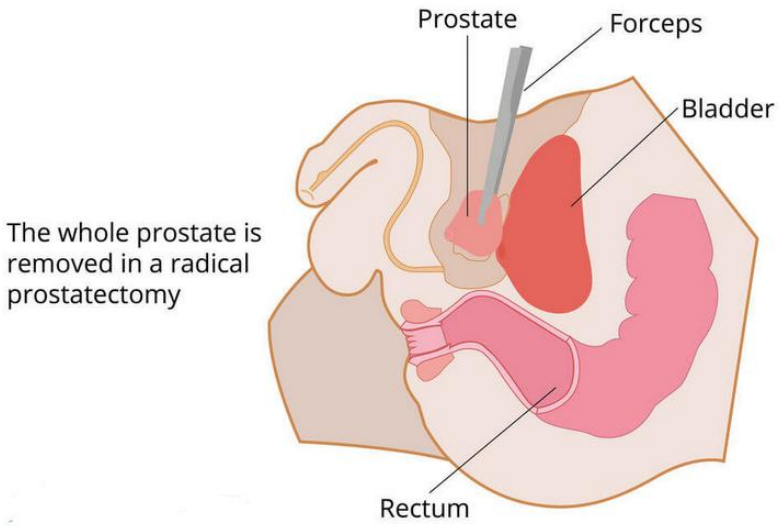

Fig. 5: Radical prostatectomy treatment (Anene, 2021)

2.1.6 External Beam Radiation Therapy

Furthermore, external beam radiation therapy (EBRT) has gained global acceptance due to its versatility, which is combined with other treatments. Therapies combined with EBRT include such therapies as hormonal therapy due to its effectiveness for various PCa stages, and its non-invasive approach (Zou et al., 2024). High-energy beams, such as gamma rays and X-rays, and electron beams from outside the body are directed to the localized prostate cancer (PCa) to kill the cancer cells (Russ et al., 2022). EBRT also utilizes imaging techniques, such as MRI, to target tumors precisely, including 3D conformal radiotherapy (3D-CRT), proton beam therapy (PBT), and stereotactic radiotherapy (Chen, 2020; Ferini & Pergolizzi, 2021). A simulation session is first executed in EBRT to map the tumor's location precisely. Subsequently, an appropriate dose of radiation is determined and suitable angles for hitting the cancer. Normal EBRT sessions usually take six to eight weeks, each lasting approximately 15 minutes (Moghaddam et al., 2024). EBRT is an effective treatment for cancer used in cases where it is a more advanced local disease (Koka et al., 2022). It blocks cancer cell proliferation by inducing cytogenic damage, cell cycle arrest, senescence, apoptosis, and DNA damage in cancer cells (Koka et al., 2022).

Brachytherapy, also known as internal radiation, involves inserting small radioactive sources into the prostate gland using the transperineal approach. [79] This treatment option is the most extreme dose injection, delivered under trans-ultrasound guidance. This technique takes approximately 45 minutes to perform under an epidural or general anesthesia (Petereit et al., 2023). Brachytherapy may be

accomplished using low-dose rate (LDR) techniques, whereby radioactive isotopes such as cesium, palladium, or iodine-125 are permanently placed in the prostate (Banerjee et al., 2020; Sgouros et al., 2021). It may also be delivered through a high-dose rate (HDR) technique, whereby the catheters are temporarily placed in the prostate while the iridium-192 isotope flows down each catheter (Hunt, 2024; Song et al., 2021). HDR and LDR differ only in the speed of radiation dose delivery. In LDR, the dose is delivered over 12-16 weeks via tiny radioactive seeds implanted permanently in the prostate under local anesthesia, while in HDR, the dose is given quickly under anesthesia [85] (cf. Figure 6). This treatment option is preferred because of the delivery of high doses of radiation with minimal effect on the adjacent normal tissues due to the rapid dose fall-off.

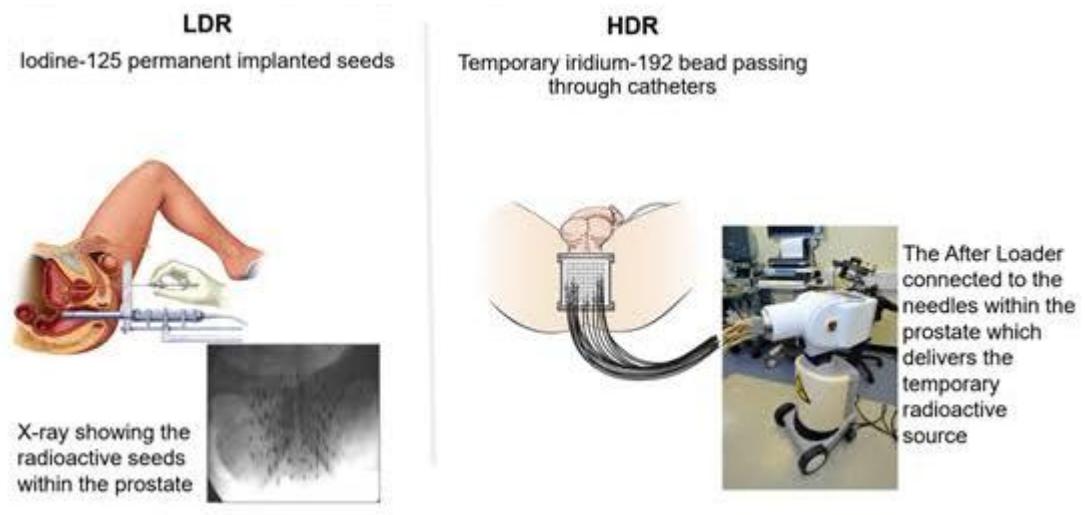

Fig. 6: Types of prostate brachytherapy: low-dose rate (LDR) and high-dose-rate (HDR) (PM, 2024)

2.1.7 Active Surveillance

Since the first publication that coined the term "active surveillance," this treatment option has been subjected to intense scholarly scrutiny regarding which specific men should be under active surveillance and how to monitor them (Manceau et al., 2021). This treatment procedure requires clarification on how overtreatment can be minimized while still maintaining the window of cure. The protocol for this treatment approach includes PSA measurement, regular physical assessment, multiple surveillance prostate biopsies, and multi-parametric MRI no more than once yearly (Bhanji et al., 2022; Liu et al., 2021). The consensus among prominent scholars is that active surveillance can help forgo or delay treatment for PCa patients by monitoring the malignancy while making necessary adjustments, thus mitigating overtreatment (Newcomb et al., 2024). Additionally, active surveillance also involves preserving bowel, urinary, and sexual functions in affected men (Kato & Sugimoto, 2020). According to the American Urological Association (AUA), "Active surveillance is the best available care option for very low-risk localized PCa patients" and "is the preferable care option for most low-risk localized PCa patients.

A comprehensive study by Shah et al. (Shah et al., 2018) delved into treatment-related side effects and cancer-specific survival outcomes among patients with PCa. This study highlighted the benefits of active surveillance, also referred to as conservative management. This treatment modality includes DRE, PSA testing, as well as occasional biopsies, reducing risks of overtreatment among other side effects/complications such as erectile dysfunction. Notably, the study's findings showed that among 10,000 patients with Prostate cancer (PCa), those undergoing active surveillance had lower odds of experiencing treatment-related side effects. However, the study did not report any significant difference in cancer-specific survival between patients undergoing chemotherapy and those undergoing active surveillance, supporting the evidence for using active surveillance in managing patients with localized

Prostate Cancer. The effectiveness of various treatment modalities in managing localized and advanced (metastatic) prostate cancer (PCa), along with potential adverse effects, is summarized in Table 2.

Table 2: Common PCa treatment options and potential adverse effects (Shah et al., 2018)

Treatment Option	Disease Progression	Potential Adverse Effects
Radical prostatectomy	Localized	Urinary incontinence Erectile dysfunction
Active surveillance	Localized	Illness uncertainty
Brachytherapy	Localized	Urinary incontinence Erectile dysfunction Diarrhea, dysuria, proctitis, urinary urgency, and frequency
External beam radiation	Localized and advanced disease	Urinary incontinence Erectile dysfunction Diarrhea, dysuria, proctitis, urinary urgency, and frequency
Hormone therapy	Advanced	Hot flashes and flare effect Hyperlipidemia Insulin resistance Cardiovascular disease Anemia Fatigue Osteoporosis Erectile dysfunction Cognitive deficits
Chemotherapy	Advanced	Peripheral neuropathy Gastrointestinal upset Myelosuppression Hypersensitivity reaction

2.2 Breast Cancer Progression and Treatment

2.2.1 General Anatomy of Breast Cancer

The breast comprises various tissues, including the lobes and lobules, ducts, nipple and areola, stroma, lymphatic system, and blood vessels. Normal breast tissue consists of three layers: myoepithelial cells, epithelial cells, and a basement membrane (Tarighati et al., 2023). At the onset of BC, the organization of these tissues is disrupted, and the normal function of the tissues is impaired. BC progression starts with hyperplastic lesions, which extend to lobular or ductal *in situ,* invasive carcinoma, and metastatic cancers (Tarighati et al., 2023). BC manifests in various forms, including changes in breast size and shape, nipple or breast pain, thickening of lumps, nipple discharge, and skin changes (such as puckering or dimpling) (Abdou et al., 2020). Figure 7 (A) depicts the anatomy of a normal breast, showing the terminal ductal lobular unit (TDLU), where the majority of the tumours arise, and the breast duct tree, which consists of myoepithelial and luminal cells surrounded by stroma that influences carcinogenesis and physiology of the normal breast (Nolan et al., 2023). Figure 7(B) illustrates BC pathogenesis, cell division, and overgrowth in the ductal or lobular epithelium, resulting in carcinoma *in situ* (pre-invasive lesions). Invasive carcinoma is when the tumour cells breach the basement membrane and infiltrate the surrounding stroma (Nolan et al., 2023). These cancers become metastatic following the degradation of the basement membrane and myoepithelial layer, as well as the processes of angiogenesis, stroma cell proliferation, and the invasion of tumorigenic epithelial cells to distant sites (cf. Figure 7). Metastatic cancer cells primarily target sites, including the brain, lungs, liver, and bones (Liang et al., 2020; Park et al., 2022). Clinical research has strongly linked metastatic events to an increase in mortality rates among BC patients.

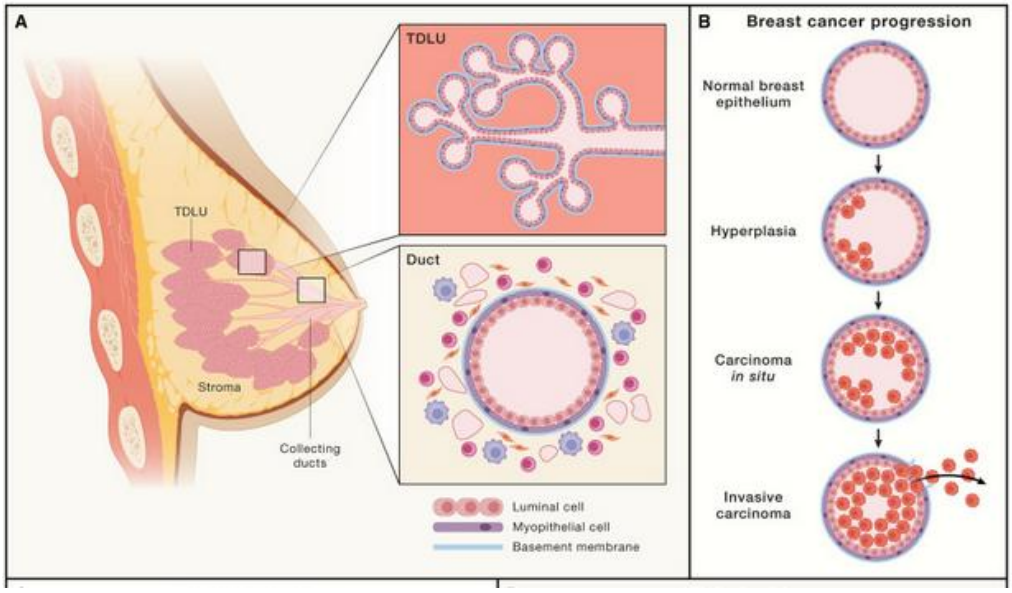

Fig. 7: Breast anatomy and histopathological classification of BC (A) and (B) BC progression from normal breast to invasive carcinoma (Nolan et al., 2023)

2.2.2 Molecular Subtypes of BC and Mechanisms of Therapeutic Resistance

There is a document proof that BC is a constellation of biologically distinct entities. The advances in molecular profiling have enhanced our understanding of breast tumors, including hormone receptor status, gene expression patterns, and clinical behaviors (Lopez-Gonzalez et al., 2024). BC is classified molecularly based on histological features and immunohistochemical expression of progesterone receptor (PR), estrogen receptor (ER), human epidermal growth factor receptor 2 (HER2), and proliferation marker (Ki67) (Tarighati et al., 2023). Accordingly, this classification has revolutionized treatment, prognosis, and diagnosis, depending on the therapeutic opportunities and challenges of each type. Luminal A is characterized by the absence of human epidermal growth factor receptor 2 (HER2) and expression of progesterone receptors (PR), estrogen receptors (ER), and a low Ki-67 proliferation index. Typically, luminal A tumours exhibit indolent clinical behaviour and low-grade histology (Parikh & Shah, 2024). Cancer patients diagnosed with luminal A BC show desirable clinical outcomes when endocrine therapies such as aromatase or tamoxifen inhibitors are used with minimal chemotherapy. Studies have shown that luminal A tumors respond favorably to endocrine therapies, with a low recurrence risk and high survival rates. Unlike the luminal A subtype, the luminal B subtype exhibits high Ki-67 levels and HER2 positivity. These tumours are aggressive and highly proliferative with increased risks of nodal involvement and high-grade histology. As such, to distinguish luminal B tumors, predictive models and multimodal imaging have been employed to guide more aggressive treatment strategies. In addition, the management and treatment of these tumors require a combination of chemotherapy and endocrine therapy.

HER2-enriched BC is characterized by a lack of PR and ER expression and a high expression of HER2 protein. Research indicates that the HER2 molecular subtype has a high metastatic potential and higher rates of proliferation. The currently deployed HER2-targeted therapies, including pertuzumab, trastuzumab, and **Trastuzumab emtansine** agents, have significantly improved the clinical outcomes of patients with HER2-positive tumors (Zhang & Peng, 2025). Conversely, triple-negative BC is unresponsive to HER2-targeted and hormone therapies because it lacks expression of HER2, PR, and ER. It is a highly aggressive tumour affecting younger women with a high propensity for recurrence and metastasis (Atallah, 2024). There is an urgent need for biomarkers and therapeutic strategies that can be used to augment the current plan, such as the use of poly **(ADP-ribose) polymerase** (PARP)

inhibitors and immunotherapy. Basal-like BC falls under the broad category of triple-negative BC typified by a lack of HER2, PR, and ER expression, with expression of growth factor receptor (EGFR), and basal cytokeratin (CK14/CK5/6) (Zhang & Peng, 2025). This tumour is highly aggressive, with high prevalence reported among young women of African descent. Anthracycline-based chemotherapy is a commonly used treatment option for this tumour, and to improve the clinical outcomes for cancer patients with this tumour, as summarized in Table 3. Studies have reported that ER+ tumours account for about 70% of all BCs, where ER+ is defined as greater than or equal to 1%ER-positive cancer cells (Nolan et al., 2023). Molecular subtypes are summarized in Table 3.

Table 3: Clinical stratification of BC based on histological features (Nolan et al., 2023)

Subtype	Characteristics	Prognosis
Luminal A	Estrogen receptor (ER) positive Progesterone receptor (PR) positive Low Ki-67 index HER2-negative	Has the best prognosis when treated with hormone therapy
Luminal B	ER-positive PR-positive or PR negative HER2 negative or positive	More aggressive compared to Luminal A May require additional treatments such as chemotherapy
HER2-positive	PR-negative ER-negative HER2-positive	More aggressive Treated with targeted therapies, e.g., Herceptin
Triple-Negative Breast Cancer (TNBC)	HER2-negative PR-negative ER-negative	Most aggressive Treated with immunotherapy It occurs in younger women
Basal-like	Overlaps with TNBC but has high basal cytokeratin expression	Most Aggressive Has fewer targeted treatment options

Despite the recent advances in BC diagnosis and treatment, therapeutic resistance remains a major scientific challenge in achieving desirable clinical outcomes. For instance, Luminal A and B subtypes are managed with endocrine therapies that target estrogen signalling (Zhang & Peng, 2025). However, mutations in the ESR1 gene increase the propensity for hormone therapy resistance. Mutations lead to constitutive receptor activation, making these therapies ineffective and potentially leading to cancer progression and the continued survival of the PI3K/AKT/mTOR axis. While HER2-enriched BC have tremendously benefited from targeted therapies such as pertuzumab and trastuzumab, resistance can emerge through various pathways (Lopez-Gonzalez et al., 2024). For instance, the truncated forms of the HER2 receptor, including p95HER2, render the drug ineffective. There are also compensatory activation pathways, such as Mesenchymal-Epithelial Transition (MET) and insulin-like growth factor receptor (IGF-1R), which can promote cancer survival and restore tumour growth (Zhang & Peng, 2025). The treatment of triple-negative BC has primarily relied on cytotoxic chemotherapy. However, this subtype exhibits higher rates of recurrence and chemoresistance due to overexpression of ATP-binding site transporters that facilitate drug efflux. Additionally, the presence of cellular epithelial-mesenchymal transition (EMT) enhances drug resistance, invasiveness, and cellular plasticity.

2.2.3 Risk Factors of Breast Cancer

For many years, BC has had the most significant prevalence and the second biggest cause of cancer-related deaths among women in the world (Johnson et al., 2021). There is evidence of the prevalence of this malignancy in 154 of 185 countries, with Western countries having a higher prevalence than Eastern countries (Huang et al., 2021; Özmen et al., 2019). The prevalence of BC is quickly rising in low- and middle-income countries due to the adoption of Westernized dietary practices and lifestyle changes (Newman, 2022). The lifestyle-related factors, including tobacco use, alcohol activity, alcohol

use, and other factors, including socio-economic status, race, age, and hormonal factors, are all associated with the increased prevalence of BC (Roheel et al., 2023). The aggression of BC is related to high mortality rates, relapse, and metastasis, and the aggression varies widely depending on the cancer stage and other related factors, including hormone receptors, gene signature expression, and glucose metabolism (Afifi & Barrero, 2023). The androgen and estrogen levels and genetic mutations of BR1P1, BRCA1, CDH1, BRCA2, STK11, TP53, ATM, CHEK2, and PALB2 correlate with the increased risk of developing BC (Nolan et al., 2023).

2.2.4 Current Therapies Deployed in Localized and Systemic BC

The available systemic and local treatment options for BC include immunotherapy, hormone therapy, radiotherapy, HER2 targeted therapy, surgery, endocrine therapy, and chemotherapy (Mir & Mir, 2023; Wang & Wu, 2023). The treatment option depends on the patient's age, medical condition, and physical condition. The treatment for the localized BC is delivered to prevent metastatic disease recurrence and eliminate the tumour (Gote et al., 2021). However, for metastatic BC, the goal of the treatment option is to prolong the patient's life and reduce the severity of the symptoms (Yu et al., 2022). It is well-established in the literature that treating BC becomes more difficult after recurrence and metastasis (Afifi & Barrero, 2023). The disease relapse is associated with multi-drug resistance (MDR) characteristics, such as the activation of transcription factor genes and increased expression of efflux transporters, which cause gene mutations and the proliferation of cancer cells (Gote et al., 2021). Research on overcoming BC MDR is ongoing, including the use of nanomedicine chemotherapy for BC treatment (Afifi & Barrero, 2023).

Mastectomy and lumpectomy are the most extensively applied breast-conserving surgeries for the local therapy of BC (Christiansen et al., 2022). Some research groups have claimed that breast-conserving surgery followed by radiotherapy is equivalent in terms of overall survival and recurrence (Kim et al., 2021). A significant prognostic indicator of this option is the axillary lymph nodes in BC patients. Axillary lymph node dissection (ALND) is associated with a higher incidence of severe postoperative complications, including lymphedema and paresthesia, compared with sentinel lymph node biopsy (SLNB) (Pesapane et al., 2023). Therefore, ALND has emerged as a preferred method for evaluating the axilla during the early stages of cancer (Pesapane et al., 2023). Secondly, radiotherapy is also a treatment option that has been used to treat various cancers for over a century. This method involves using high-energy radiation to target and destroy cancerous cells. Two types of radiotherapy options exist: internal radioisotope therapy (RIT) and external beam radiotherapy (EBRT) (Yang et al., 2023). Generally, radiotherapy is delivered after breast-conserving surgery on the regional lymph nodes and chest wall after mastectomy to destroy cancer cells and minimize recurrence (da Luz et al., 2022).

In systemic treatment of BC, chemotherapy has been extensively used to suppress the rapid division and proliferation of cancer cells (An et al., 2021). This method targets cancer cells at different stages of the cell cycle by administering common chemotherapy agents, including platinum agents (carboplatin, cisplatin), taxanes (paclitaxel, docetaxel), and anthracyclines (doxorubicin, epirubicin)(Ferrari et al., 2022). The multi-drug combination in chemotherapy improves the anti-tumour effect compared to administering a single chemotherapy drug. There are two types of chemotherapy – neoadjuvant and adjuvant chemotherapy. Neoadjuvant chemotherapy refers to the chemotherapy administered to patients before surgery (An et al., 2021). In contrast, adjuvant chemotherapy is chemotherapy delivered after surgery for BC, particularly on cancer tumours that may recur or BC patients with lymphatic metastases (Yu et al., 2020).

Immunotherapy is also used in BC treatment, whereby the patient's immunity is strengthened to identify and destroy the tumours precisely (Anayyat et al., 2023; Dvir et al., 2024). Immunotherapeutic agents have also been shown to help minimize recurrence rates and prevent distant metastasis. Patients with TNBC benefit from this treatment option due to the presence of tumour-infiltrating lymphocytes, mutations, and increased levels of programmed death ligand 1 (Ribeiro et al., 2022). HER2 therapy is

also a treatment option recommended for patients with HER2-enriched subtypes (Shen et al., 2021). The characteristics of the HER2 subtype include more aggressive development and rapid tumor growth, which have been managed by the use of drugs such as tyrosine kinase inhibitors (lapatinib, neratinib, among others), monoclonal antibodies (pertuzumab and trastuzumab), and antibody-drug conjugates (trastuzumab emtansine) (Le Du et al., 2021; Li et al., 2023). Figure 8 presents a summary of BC cancer progression from the primary tumour to lethal cancer cells, subtypes of BC, and available pharmacological treatment for each subtype.

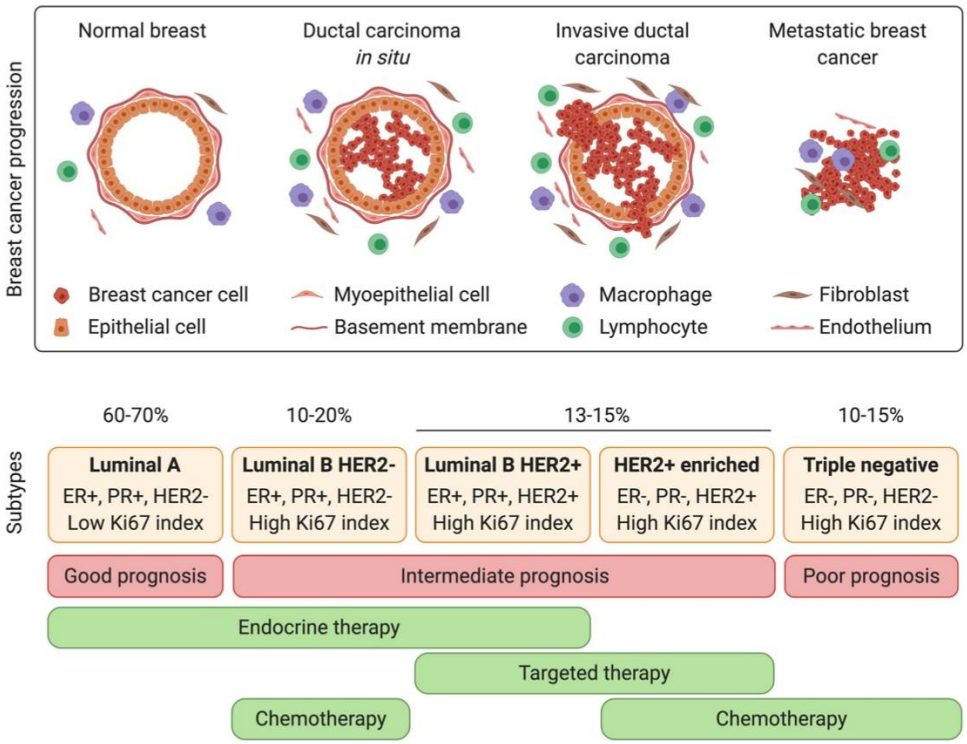

Fig 8 Breast cancer progression from the primary tumour to lethal cancer cells, subtypes of BC, and available pharmacological treatment for each subtype (Boix-Montesinos et al., 2021).

2.2.5 A comparison of treatments for BC and PCa

Remarkably, advances in targeted therapies have offered new hope for cancer patients with advanced or metastatic disease. Cancer patients with HER2-negative and ER-positive tumors have benefited from CDK4/6 inhibitors such as abemaciclib, ribociclib, and palbociclib (Wu et al., 2025). These agents are known to arrest cell cycle progression at the G1 phase. Also, the use of endocrine therapy in conjunction with P13K inhibitors such as alpelisib has been successfully administered to patients with receptor-positive BC (Hao et al., 2025). Clinical benefits have also been reported among triple-negative BC and HER2-negative patients when PARP inhibitors such as talazoparib and olaparib are used. It is worthwhile to underscore the clinical benefits realized from the use of antibody-drug conjugates (ADCs) to treat both HER2-positive and HER2-low BCs (Hao et al., 2025).

Therapeutic paradigms currently deployed in managing BC and PCa reflect divergent clinical philosophies and differences in tumour biology, which were shaped by many years of clinical practice and research undertakings. For instance, BC is characterized by profound heterogeneity that demands precise medical approaches that integrate emerging immunotherapies and hormone-targeted therapies (Wu et al., 2025). In PCa, androgen deprivation therapy (ADT) and active surveillance form the backbone for treating cancer patients. Targeted interventions and molecular profiling have continued to reshape PCa, narrowing the gaps between BC and PCa (Kwon & Joung, 2025). This review article has

disclosed that oncological decision-making is influenced by innovation, therapeutic resistance, and biological complexity. Table 4 summarizes a comparative critique of the PCa and BC treatment strategies currently deployed in clinical settings.

Table 4: A comparison of PCa and BC treatment strategies

Feature	PCa	BC
Surveillance	Common in low-risk cases	Not commonly used, except in ductal carcinoma in situ (DCIS)
Targeted therapy	Rare, except for PARP and BRCA-mutated cases	Broad spectrum (HER2, CDK4/6, PARP, PI3K)
Hormone therapy	Androgen deprivation therapy (ADT)	Estrogen blockade, such as aromatase inhibitors and tamoxifen
Immunotherapy	Emerging role in metastatic castration-resistant PCa	Limited success, mainly in TNBC
Resistance	More predictable (often slower)	Rapid emergence, especially in TNBC

2.3 Limitations of the Current Treatment Options for BC and PCa

Chemotherapy is a conventional treatment option for BC but has been associated with suppression of normal cells due to its non-specific tumour targeting (Brianna & Lee, 2023). Therefore, the chemotherapeutic agents may lead to inevitable adverse effects such as mouth ulcers, increased susceptibility to infections, diarrhea, vomiting, nausea, anemia, leucopenia, myelosuppression, and so on (Poulopoulos et al., 2017). There are also side effects related to drugs, such as cisplatin-induced ototoxicity, nephrotoxicity, and anthracycline-induced cardiotoxicity (Yang et al., 2023). Another scientific challenge is the drug resistance of the commonly used chemotherapeutic agents, which reduces their efficacy in treatment (Yang et al., 2023). Drug resistance is also a significant setback in immunotherapy and hormone therapies (Magee et al., 2015). The widely cited adverse effects of endocrine treatment include a high risk of bone-related adverse events, thromboembolic events, vaginal dryness, night sweats, and hot flashes (Dent et al., 2011; Jackson et al., 2021). Furthermore, radiation therapy has been linked to radiation-induced malignancy, radiation pneumonia, lymphedema, fatigue, swelling, myelosuppression, cardiac and pulmonary injury, and radiation dermatitis (Sung et al., 2024).

The available chemotherapeutic drugs deployed in PCa include cyclophosphamide, Cabazitaxel, docetaxel, and paclitaxel (Carpenter et al., 2020; Jiang et al., 2024). Unfortunately, these drugs have clinical challenges linked to high drug resistance, short-circulation time, therapy side effects (renal, hepatic, bone marrow, and cardiac toxicity), and impact on the normal cells, affecting the quality of life of patients (Liu et al., 2023; Zhao et al., 2022). Furthermore, immunotherapy agents such as programmed cell death protein 1 (PD-1) and its ligand (PD-L1) can slow PCa progression or manage its symptoms; however, there are no treatments that can be deployed to prolong the survival of patients (Kgatle et al., 2021).

3. Synergistic Potential of Nanomedicine in Prostate Cancer and Breast Cancer Treatment

Nanomedicine has bypassed conventional treatment protocols for lethal cancers and other intracellular diseases (Heydari et al., 2024; Wang et al., 2024). Accordingly, nanomedicine is a thriving research area that can solve therapeutic challenges associated with chemotherapy. Nanomedicine has exhibited great potential in advancing the prevention, treatment, monitoring, and management of biological diseases (Heydari et al., 2024). According to Yang et al. (2023), nanotechnology-based therapies are beneficial in overcoming drug resistance mechanisms and reducing antineoplastic-related toxicity. They have also helped prolong the circulation time of drugs in the blood, enhancing the solubility and chemical stability of drugs, and delivering drugs to tumour sites. The rapid growth of nanotechnology

and its increasing application in clinical studies hold immense potential in addressing scientific challenges in BC therapy related to chemotherapy failure, heterogeneity of cancer cells, high frequency of drug resistance, and recurrence (Gao et al., 2024). There are chemotherapeutic-bearing nanomedicines such as polymeric nanoparticles, protein nanoparticles, gold nanoparticles, micelles, solid-lipid nanoparticles, immunoconjugates, and liposomes that the US Food and Drug Administration (FDA) has approved for BC management (Chehelgerdi et al., 2023; Edis et al., 2021; Reddy et al., 2005; Tiwari et al., 2023; Yang et al., 2023). Clinical improvements in tumour targeting, drug resistance, and solubility have demonstrated efficacy in BC treatment compared to the parent drugs (Yang et al., 2023).

3.1 Clinical Applications and FDA-nanodrugs

Remarkably, nanotechnology has refined conventional chemotherapeutics, primarily due to the rapid emergence of polymeric micelles, liposomes, and albumin-bound nanoparticles (Arafat et al., 2024). Cancer patients have benefited from the FDA-approved use of nanoscale materials, which improve bioavailability, facilitate targeted drug delivery, and reduce systemic toxicity. Clinically approved nanoagents, such as Doxil, are currently deployed in the management of ovarian cancer and various myelomas (Bhowmik et al., 2018). Doxil® contains PEGylated liposomal doxorubicin (tiny spherical vesicles) that reduces the effects of the doxorubicin compound on healthy tissues, although it may also cause cardiomyopathy (Fojtu et al., 2017). Doxil® has benefits, including improved tolerability, enhanced drug delivery to the tumour site, and reduced cardiotoxicity (Rivankar, 2014; Vyas et al., 2020). Abraxane® is also another nanotherapeutic drug that the US FDA has approved to manage BC, non-small-cell lung cancer, and pancreatic cancer (Chowdhury, 2020; Wei et al., 2020). The albumin-bound formulations deliver paclitaxel efficiently to tumour sites, reducing the need for solvents to dissolve paclitaxel (Yibin et al., 2023). The advantage of this drug in cancer treatment is that it is versatile (it can be used to manage pancreatic, BC, and lung cancer (Olajubutu et al., 2023).

Additionally, albumin-bound drugs enhance the solubility of the drug and increase its circulation in the bloodstream. Myocet is similar to Doxil, both of which contain liposomal doxorubicin, which helps deliver nanodrugs efficiently to tumors (Luo et al., 2017). Myocet® is used in managing metastatic BC and is usually administered intravenously (Kitsios et al., 2023; Sawpari et al., 2023). In some cases, Myocet® can cause hair loss, neutropenia, and thrombocytopenia (Sawpari et al., 2023). Lipusu is another nanodrug used in managing PCa, including castration-resistant tumors (Huang et al., 2024). This drug is known to increase drug bioavailability and reduce multidrug resistance (Meng et al., 2024). Furthermore, Nanoxel® is a nanodrug with a paclitaxel formulation. The paclitaxel inhibits cell growth. The drug is administered intravenously every 21 days (Chaudhari et al., 2023). Another formulation of paclitaxel is Genexol-PM®, which uses polymeric micelles to deliver the drug to metastatic BC sites effectively (Ejeta et al., 2024; Shaikh & Bhattacharya, 2024). Another US FDA-approved nanodrug is Lipodox®, which works similarly to Doxil®. It utilizes PEGylated liposomes to deliver doxorubicin effectively into cancer cells (Pan et al., 2023). It is also administered every three weeks to treat lung, stomach, prostate, and breast cancers (Serras et al., 2024). Lastly, Kadcyla® is another approved drug by the FDA that effectively treats HER2+ metastatic BC. The nano drugs that the US FDA has approved for cancer treatment are summarized in Table 5

Table 5: Nanomedicine used in cancer treatment (Boix-Montesinos et al., 2021)

Name/Manufacturer	Nanocarrier	Drug/compound	Approval year	Indication	Ref
Doxil® (Janssen Pharmaceutica)	PEGylated Liposome	Doxorubicin	1995	Metastatic	(Barenholz, 2012; O'Brien et al., 2004)
Myocet® (Sopherion Therapeutics)	Non-PEGylated Liposome	Doxorubicin	2000	Metastatic	(Lao et al., 2013; Waterhouse et al., 2001)
Abraxane® (Celgene)	Albumin	Paclitaxel	2005	Metastatic	(Desai et al., 2006; Li et al., 2015; Nahleh et al., 2016)
Lipusu® (Sike Pharmaceutical Co. Ltd)	Liposome	Paclitaxel	2006	Non-metastatic	(Koudelka & Turánek, 2012; Ranade et al., 2013; Wang et al., 2017; Zhang et al., 2009)
Nanoxel® (Fresenius Kabi India Pvt Ltd)	NIPAM-VP	Paclitaxel	2006	Metastatic	(Brahmachari et al., 2011; Ranade et al., 2013)
Genexol-PM® (Samyang Biopharm)	mPEG-PDDLA	Paclitaxel	2007	Non-metastatic	(Lee et al., 2008; Lim et al., 2010)
Lipodox® (Sun Pharma Global FZE)	PEGylated Liposome	Doxorubicin	2013	Metastatic	(Aulic et al., 2020; Ventola, 2017)
Kadcyla® (Hoffmann-La Roche	Antibody	Trastuzumab/DM1	2013 2019	Metastatic HER2+, Residual disease	(Diéras et al., 2017; Verma et al., 2012; Von Minckwitz et al., 2019)

Nanoparticles, such as gold nanoparticles (AuNPs) and quantum dots, have been utilized to enhance imaging techniques and detect small lesions that are not detectable with conventional methods (Luo et al., 2021; Zhou et al., 2022). Nanotechnologies such as nanotheranostics have offered combined diagnosis and treatment approaches (Paliwal et al., 2020; Siafaka et al., 2021). This integrated technique has been conveniently used to detect and treat BC (Patel et al., 2023). Also, specific receptors and ligands have been conjugated with nanoparticles (NPs) to target BC, thereby minimizing the effect on healthy tissues. Nanotechnology-based biosensors have been used in nanomedicine to detect PCa biomarkers such as PSA among the biomarkers with higher sensitivity than any conventional method (Laraib et al., 2022). Nanoparticles have also been integrated with imaging models, such as CT or MRI, to accurately view tumors (Molkenova et al., 2022). They can also deliver drugs to the PCa cells (target therapy), thus overcoming tumour resistance (Tiburcius et al., 2021). Nanotechnologies can also be integrated with conventional treatment methods such as immunotherapy and chemotherapy. In particular, combining nanotechnology with radiation therapy increases the radiation dose delivered to the tumour with minimal side effects on the adjacent normal cells (Kareliotis et al., 2020; Khan et al., 2022). Additionally, photodynamic therapy has been combined with hyperthermia to destroy tumor cells (Bienia et al., 2021).

3.2 Nano-oncology

Nano-oncology, also called nanotechnology in oncology, has emerged as a cutting-edge approach in cancer detection, treatment, and prevention. The current nanotechnologies have necessitated the combination of medicinal agents in cancer management with nanoscale technology. The therapeutic

outcomes have significantly improved by maintaining targeted treatment dosages due to advancements in nanobiosensors, biological machinery, and medical equipment (Samathoti et al., 2025). With the emergence of AI, AI-optimized drug nanomedicine combinations have surpassed those chosen randomly. For instance, patients with metastatic castration-resistant PCa have benefited from an AI-driven platform (CURATE AI) that has refined the treatment regimen for this malignancy, supporting the evidence of CURATE AI in addressing significant data challenges in personalized treatment and providing information on the safety and efficacy of lead candidates in oncology trials (Samathoti et al., 2025). The integration of AI platforms in nanomedicine has contributed to the optimization of drug delivery by enabling the accurate prediction of nanoparticle functionalization, surface charge, shape, and optimal size. This has paved the way for optimizing drug-loading capabilities, delivering regimens specifically tailored to tumor microenvironments (Zheng et al., 2023). AI synergy with nanomedicine is instrumental in forecasting tumor accumulation, potential side effects, and biodistribution of nanoparticles within the body. Nanomedicine-based therapies have also benefited from the implementation of AI through the development of personalized treatment plans, which identify optimal drug combinations and nanoparticle formulations. Integrating AI in the development of nanomedicines has enabled the easier analysis of chemical libraries and the prediction of the nature of biological systems in drug-nanocarrier combinations. Nanomedicine has also benefited from AI through the delivery of drugs to specific tumours, in theranostic platforms (accurate combination of diagnosis and treatment), the use of AI-driven nano-robotics in drug delivery, and rapid simulation of biological environments (Zheng et al., 2023). As such, the synergistic potential of AI and nanomedicine is envisaged to revolutionize the full potential of AI and nanomedicine in diagnosis, detection, and treatment of PCa and BC.

4. Clinical application of artificial intelligence in breast cancer and prostate cancer management

Artificial intelligence (AI) is broadly classified into deep learning (DL) and traditional machine learning (ML) (Sarker, 2021). The former relies on automatically extracted features by convolutional neural networks (CNN), enabling the detection of complex information that is difficult for the human brain to process. The latter utilizes hand-crafted features, such as texture and color (Sarker, 2021). Recent advances in AI-assisted imaging have shown huge potential in automatically diagnosing, recognizing, and segmenting suspicious tumour lesions (Ouma et al., 2024; Zhang et al., 2023). AI has immense potential in biomarker evaluation, staging, and prognostication (Zheng et al., 2023). AI can also be used to measure cell volume and length, quantify cribriform patterns, quantify immunohistochemistry, and recognize and quantify perineural invasion (Zheng et al., 2023). BC patients have benefited from AI-assisted imaging diagnosis in various ways: early detection of tumours through precise analysis of the mammograms, minimizing unnecessary biopsies (often associated with false positives), helping in the analysis of patients' genetic information, which guides the development of personalized treatment plans, and AI-powered software is highly efficient in the interpretation of breast imaging (Zheng et al., 2023). AI-assisted imaging is also used to obtain information about tumour heterogeneity, identify tumour progression or treatment response, and differentiate molecular biological features of localized/metastatic BC (Yue et al., 2021). In PCa contexts, AI has been used to distinguish between malignant and benign tumors, identify molecular subtypes, grade Gleason scores, and predict clinical prognosis (Khalid et al., 2024). Accordingly, AI models have helped urologists make clinical decisions and stratify patient risks. Figure 9 shows the clinical application of BC diagnosis and treatment.

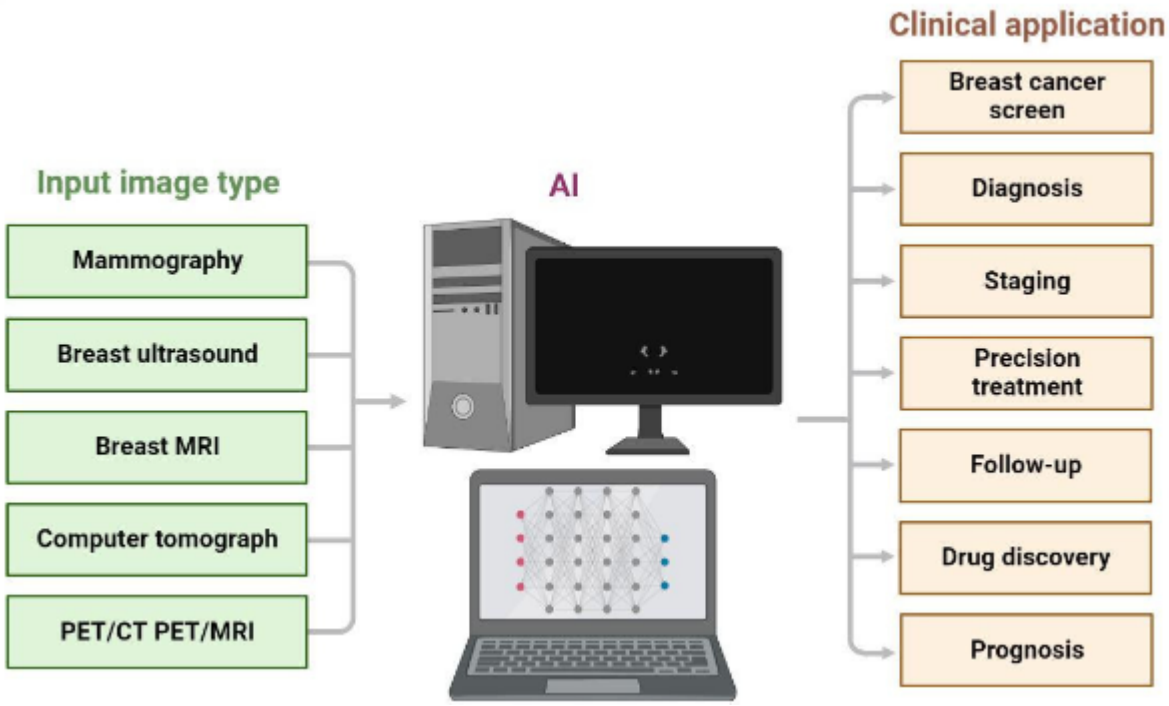

Fig. 9 Clinical Application of artificial intelligence in breast cancer diagnosis (Zhang et al., 2023)

4.1 AI Application in Practice

Accumulating scientific evidence suggests that AI in imaging and radiomics analysis has enabled the extraction of high-dimensional data from MRI, PET, and CT scans during tumor detection and the prediction of treatment responses (Panchpuri et al., 2025). AI has also enhanced the analysis of histopathological slides and genomic data to identify mutations and molecular subtypes of BC. Oncologists have also benefited from AI in selecting optimal therapies based on patient-specific data, thereby reducing variability and improving patient clinical outcomes. Research in BC and PCa will transition towards an AI-guided nanomedicine. As such, AI can predict patient-specific responses to specific nanoformulations, enhance the design of smart nanocarriers with stimuli-responsive features, and simulate drug release, intracellular trafficking, and kinetics (Panchpuri et al., 2025). However, the innovative intersection of cancer care and AI is not without challenges. AI systems require clinical validation to be effective in clinical settings (Tsopra et al., 2021). A scientific challenge is also associated with generalizing the AI models across different settings and demographic groups. AI models, such as deep algorithms, operate as “black boxes”, impeding accurate explanations of the findings (Marey et al., 2024). Therefore, AI models should undergo rigorous clinical validations to navigate the “black box” conundrum and model generalizability (Ratti & Graves, 2022). In addition, the widespread adoption of AI faces challenges related to its successful implementation. These include costly AI systems and the process of designing, developing, and manufacturing nanodrugs. There are also regulatory challenges related to the AI standard developed by policy-makers for reproducibility, transparency, and clinical validation. The accessibility and equity of AI models are also glaring barriers, particularly in middle- and low-income populations. Lastly, successful integration in clinical systems will require collaboration across data science, regulatory science, and oncology, which may become a significant barrier to overcome.

5. Future Outlook

Eventually, the current research undertakings on cancer treatment will transition toward a convergence of AI and nanomedicine. These innovative approaches have not yet realized their full potential in improving treatment efficacy. On this roadmap, the industry stakeholders, clinicians, regulatory

agencies, and teachers must engage in collaborative partnerships. There is a need to develop standardized frameworks for AI and nanomedicine to ensure a smoother regulatory approval process. To expedite the clinical translation of AI and nanomedicine, adaptive regulatory pathways should be established that enable iterative improvements based on in vivo and in vitro analyses. This will bridge the gap between the identification of novel lead candidates and implementation. To revolutionize BC and PCa healthcare, pathologists should not rely solely on AI predictions but also on their own diagnostic skills. The collaboration between AI experts, regulatory bodies, and pathologists can be helpful in successfully integrating AI and nanomedicine into clinical systems. Future research should prioritize the development of robust AI systems and the integration of emerging generative AI tools, such as ChatGPT, for specific tasks in cancer diagnosis and treatment.

6. Conclusions

The evolution of molecular biology, combined with the application of combinatorial chemistry, structural biology, and computer-aided drug design, has significantly benefited the development of anti-cancer drugs. Drug resistance has emerged as a considerable obstacle to delivering optimized treatments for BC and PCa. Drug resistance is attributed to enhanced DNA repair of tumour cells, defects in cancer cell apoptosis, changes in the target, and enhanced efflux mechanisms. Despite the noteworthy advances in cancer treatment, further research and development are still necessary to overcome the aforementioned scientific challenges. Next-generation technologies should enhance diagnostic pathways, reduce cancer recurrence, and optimize treatment delivery. Further therapeutic studies should focus more on tumour biology and early detection of biomarkers to develop individualized treatment plans for BC and PCa patients.

Advances in computational chemistry have played a crucial role in polypharmacology, leading to the development of pharmaceutical agents that act on multiple drug pathways or targets. Nanotechnologies have been designed to deliver chemotherapy drugs, radionuclides, and hormones to tumour sites. This technology has also been combined with conventional treatments such as hormone and radiation therapy and surgery to deliver drugs more precisely and spare the surrounding healthy cells. Ultimately, the future of BC and PCa treatment is poised to undergo a significant transformation, enhancing the specificity and sensitivity of diagnostic tools. For instance, the nanoparticles have been used to detect PSA and other biomarkers. Nanotechnology will also guide the development of precision medicine designed to target particular molecular markers or gene mutations in BC, ensuring that the treatment is less toxic and more effective, and reduces drug resistance. Nanotechnology offers promising opportunities, such as nanotheranostics, to revolutionize PCa and BC treatment by enhancing diagnostic accuracy, minimizing side effects, and enabling targeted drug delivery for more effective and personalized therapies. Integrating AI in cancer diagnosis has enhanced the efficacy and efficiency of early cancer detection. Furthermore, AI has been utilized to monitor treatment responses and predict potential cancer recurrences.

7. Recommendations for Future Research

Undoubtedly, the PCa and BC landscape will continually evolve in both practice and research. In light of this, this review offers specific recommendations for both short- and long-term studies that warrant further investigation. The short-term recommendations include: (1) prioritizing research into DNA repair, apoptosis, efflux pathways, and drug resistance, (2) advancing biomarker identification and tumor biology to design individualized treatment plans, (3) the need for integration of AI in diagnosis and in monitoring treatment responses, and (4) leveraging nanotechnology to reduce toxicity and protect healthy tissues. The long-term recommendations include (1) the need to expand the scope of nanotheranostics to improve personalized cancer care, (2) the need to invest in next-generation technologies that will promote optimized treatment deliveries, (3) precision medicine approaches that target specific gene mutations and biomolecular markers must be developed, and (4) scientists should

leverage computation chemistry and structural biology to address the scientific challenges associated with cancer management.

Declaration and Statements

Consent for Publication

This article has the consent of all the authors.

Availability of data and materials

The data associated with the findings of this study are available from the corresponding author upon reasonable request.

Competing interests

The authors have no competing interests

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Authors' contributions

RBOO: Method development, writing & editing, **JKK**: Conceptualization, Editing & Supervision, **SMN**:

Visualization, Editing, & amp; supervision. All authors have read and approved the manuscript.

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