Research Article

Molecular Composition of Genomic TMPRSS2-ERG Rearrangements in Prostate Cancer

Manuela Krumbholz, Abbas Agaimy, Robert Stoehr, Maximilian Burger, Sven Wach, Helge Taubert, Bernd Wullich, Arndt Hartmann, and Markus Metzler

1Department of Pediatrics, University Hospital Erlangen, 91054 Erlangen, Germany
2Department of Pathology, University Hospital Erlangen, 91054 Erlangen, Germany
3Department of Urology, University of Regensburg, Caritas St. Josef Medical Center, 93053 Regensburg, Germany
4Department of Urology and Pediatric Urology, University Hospital Erlangen, 91054 Erlangen, Germany

Correspondence should be addressed to Manuela Krumbholz; manuela.krumbholz@uk-erlangen.de

Received 30 August 2019; Accepted 23 November 2019; Published 12 December 2019

Academic Editor: Jacopo Gervasoni

Copyright © 2019 Manuela Krumbholz et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

There is increasing interest in the use of cell-free circulating tumor DNA (ctDNA) as a serum marker for therapy assessment in prostate cancer patients. Prostate cancer is characterized by relatively low numbers of mutations, and, in contrast to many other common epithelial cancers, commercially available single nucleotide mutation assays for quantification of ctDNA are insufficient for therapy assessment in this disease. However, prostate cancer shares some similarity with translocation-affected mesenchymal tumors (e.g., leukemia and Ewing sarcoma), which are common in pediatric oncology, where chromosomal translocations are used as biomarkers for quantification of the tumor burden. Approximately 50% of prostate cancers carry a chromosomal translocation resulting in generation of the TMPRSS2-ERG fusion gene, which is unique to the tumor cells of each individual patient because of variability in the fusion breakpoint sites. In the present study, we examined the structural preconditions for TMPRSS2-ERG fusion sites in comparison with mesenchymal tumors in pediatric patients to determine whether the sequence composition is suitable for the establishment of tumor-specific quantification assays in prostate cancer patients. Genomic repeat elements represent potential obstacles to establishment of quantification assays, and we found similar proportions of repeat elements at fusion sites in prostate cancer to those reported for mesenchymal tumors, where genomic fusion sequences are established as biomarkers. Our data support the development of the TMPRSS2-ERG fusion gene as a noninvasive tumor marker for therapy assessment, risk stratification, and relapse detection to improve personalized therapy strategies for patients with prostate cancer.

1. Introduction

Prostate cancer is a common tumor in men and a highly heterogeneous disease that can vary from low-risk lesions to highly aggressive tumors [1–3]. Prostate cancer also exhibits substantial heterogeneity at the genetic level, which is reflected in chromosomal rearrangements, copy number gains or losses, and somatic mutations. Somatic mutations are preferentially detected in advanced or metastatic tumors; hence, they are unsuitable for monitoring primary, nonmetastatic disease [4, 5], whereas chromosomal rearrangements represent an early event in pathogenesis [6–8]. The most common chromosomal rearrangement in prostate cancer results in the fusion of the androgen-regulated gene, TMPRSS2 (chr21q22.2), with ETS-related gene, ERG (chr21q22.3), which is present in approximately 50% of patients [9]; due to the high incidence of prostate cancer, this is the most prevalent fusion gene in human cancer [10].

Therapy monitoring and tumor surveillance control in prostate cancer are mainly based on quantification of serum levels of prostate-specific antigen (PSA); however, due to a high rate of false positive results, the benefits of the PSA as
a serum marker are the subject of controversial discussion [11]. Overtreatment is a clinical challenge in local prostate cancer and exposes patients to unnecessary morbidity.

A number of novel noninvasive biomarkers, isolated from blood or urine samples, are currently under investigation for use in personalized risk stratification of patients with prostate cancer. Such markers include adipokines like omentin [12], fatty acid binding protein 5 (FABP5), and granulin [13]; miRNAs [14]; circulating tumor cells (CTCs) [15–17]; and plasma or urine-derived cell-free RNA and DNA. Although total nucleic acid concentrations in plasma and urine samples are not reliable biomarkers for assessment of tumor burden [18, 19], the quantification of tumor-specific mutations or copy number variations appears to be more promising [20–24].

The establishment of fusion gene assays for therapy assessment in cancer patients is more complex compared with the development of single nucleotide mutation detection assays, which are commercially available for a large number of recurrent mutations. However, fusion genes may be an advantageous target for those tests due to the high clonal stability of genomic fusion sequences. The quantification of fusion genes at the level of circulating tumor DNA (ctDNA) is superior to RNA-based assays because of the higher stability of cell-free DNA in blood plasma and urine samples. We previously demonstrated the benefit of DNA-based therapy assessment using patient-specific genomic fusion sequences for mesenchymal tumors including leukemia, lymphoma, and Ewing sarcoma (EWS) [25–28].

Here, we evaluate the TMPRSS2-ERG fusion gene in prostate cancer tissue, as representative of a translocation-positive epithelial tumor, for a putative application as a noninvasive ctDNA biomarker. To this end, we studied the structure and distribution of genomic TMPRSS2-ERG breakpoints and compared the results with data derived from mesenchymal malignancies.

2. Materials and Methods

2.1. Patients and Material. The tumor material included in our study was derived from 24 patients with ERG rearrangement-positive prostate cancer. These patients were identified using immunohistochemistry for detection of nuclear ERG overexpression. The median age at diagnosis was 67.5 years (range, 56–74 years). Written informed consent was obtained from all patients, in accordance with the Declaration of Helsinki. The study is based on the approvals of the Ethics Committees of the University Hospital Regensburg (No. 05/16) and the University Hospital Erlangen (No. 3755, dated Feb. 2008).

DNA was extracted from fresh frozen tumor tissue using the QIAamp DNA Blood Mini Kit (Qiagen), according to the protocol for DNA purification from tissue samples. To demonstrate sufficient DNA quality for long-range PCR, tumor DNA was tested by amplification of an 11.4 kb region of the single copy gene, BCR, on chromosome 22.

2.2. Identification of Patient-Specific Genomic TMPRSS2-ERG Fusion Sequences. Genomic TMPRSS2-ERG fusion sequences were amplified using two rounds of multiplex long-range PCR (MLR-PCR), with nine forward nested primer pairs covering the breakpoint cluster region of the TMPRSS2 gene (18.5 kb), and 24 reverse nested primer pairs covering the breakpoint cluster region of the ERG gene (161.5 kb) (Figure 1). Primer sequences are shown in Supplemental Table 1.

To minimize nonspecific amplification products, both TMPRSS2 and ERG primers were separated into two sets each. Accordingly, we started with four different first round MLR-PCR reactions: TMPRSS2 primer sets 1 and 2 were each combined with ERG primer set 1 or 2. For first round PCR reactions, external primers were used. PCR conditions were optimized using DNA from the TMPRSS2-ERG-positive prostate cancer cell line, VCaP. All MLR-PCR assays were performed using the AccuPrime™ Taq DNA Polymerase System (Thermo Fisher Scientific), according to the manufacturer's instructions, with 100 ng template DNA. If no specific amplification was visible after the first round of PCR, 1 μl of each reaction product was transferred as template to a second round MLR-PCR, with the corresponding nested (internal) primers.

MLR-PCR sets that generated specific amplification products were examined in more detail. To identify the ERG primer positioned next to the fusion site, and therefore responsible for the amplification product, a series of single PCRs with separate ERG primers were prepared. Aliquots (1 μl) of reaction products from the first round PCR were combined with all internal nested TMPRSS2 primers from the MLR-PCR primer set, and one of each corresponding internal ERG primers. The ERG primer that generated a specific amplification product was used in a further series of single PCRs, in combination with each of the TMPRSS2 internal primers, to identify the TMPRSS2 primer located closest to the fusion site. Amplified products were confirmed by an independent PCR using the identified specific primer sets adjacent to the patient's fusion site and 50 ng tumor DNA. Subsequently, PCR products were purified using the QIAquick PCR Purification Kit (Qiagen) and sequenced (Eurofins Genomics).

2.3. Analysis of Breakpoint Distribution and Breakpoint Characteristics. Genomic TMPRSS2-ERG fusion sequences were aligned to the human genome (GRCgh37/hg19) using the nucleotide BLAST tool (https://blast.ncbi.nlm.nih.gov/Blast.cgi) to determine patient-specific DNA breakpoints (Table 1). For comparison and detailed characterization of genomic TMPRSS2-ERG fusion sites, we analyzed fusion genes in our cohort, and compared and combined the data with that from previously published fusion sequences (Weier et al., n = 26; Haffner et al., n = 3; Demichelis et al., n = 1; and Liu et al., n = 4) [29–32]. Kernel density analysis was performed using components of the free software environment R (https://www.r-project.org) to determine genomic breakpoint distribution, as described previously [33]. Repeat elements were identified using the RepeatMasker tool (http://www.repeatmasker.org). More than 20 genomic sequence motifs described as showing low DNA stability, or that were associated with DNA cleavage or rearrangement, were identified using VectorNTI software (Supplemental Table 2). Palindromic regions were detected using the EMBOSS...
explorer tool (http://emboss.bioinformatics.nl). Fisher’s exact test was used to determine whether there was significant colocalization of patient-specific fusion sites and repeat elements, or recombination-related DNA sequence motifs.

3. Results

3.1. Distribution of Genomic TMPRSS2 and ERG Breakpoints

Genomic TMPRSS2-ERG breakpoints in the prostate cancer cell line, VCap, and 24 prostate cancer patients are listed in Table 1. Kernel density analyses of a total of 58 genomic TMPRSS2-ERG fusion sites, including data generated in this study and previously published results [29–32], revealed a uniform distribution of genomic breakpoints within the TMPRSS2 breakpoint cluster region (18.5 kb) with a significant accumulation of breakpoints within a 4.4 kb region (chr21:42,873,136–42,868,746) flanking exon 2 (Figure 1(a)). Breakpoints in the large ERG
breakpoint cluster region (161.5 kb) showed significant clustering within a 21.5 kb region (chr21:39,883,170–39,861,720) in intron 3 (Figure 1(a)) and enrichment in a second 5 kb region at the end of intron 3 (chr21:39,831,825–39,826,714). Our data from increased sample numbers confirm the results reported by Weier et al. [29]. No correlation was observed between breakpoint positions and age at diagnosis or patient Gleason scores (Figures 1(b) and 1(c)).

### 3.2. Characterization of TMPRSS2-ERG Fusion Sites

Detailed characterization of the breakpoint fusion sites revealed accurate transitions (36%), small microhomologies (46%), or small fillers (18%) (Figure 2), consistent with the inaccurate nonhomologous end joining repair mechanism that generates chromosomal rearrangements in prostate cancer [29]. Interestingly, the microstructure of genomic fusion sites from epithelial prostate cancer cells was not significantly different from those derived from mesenchymal tumor cells from patients with chronic myeloid leukemia, acute lymphoid leukemia (ALL), anaplastic large-cell lymphoma, and EWS [26, 27, 33, 34] (Figure 2).

### 3.3. Colocalization of TMPRSS2 and ERG Breakpoints within Repeat Elements or DNA-Destabilizing Sequence Motifs

We further examined the localization of genomic TMPRSS2-ERG fusion sequences with regard to repeat elements and other genomic DNA sequence motifs associated with chromosomal rearrangements (Supplemental Table 2). No correlation was identified between any specific DNA motif and the localization of genomic fusion breakpoints, including those within the ERG breakpoint cluster region (Supplemental Figure 1). Comparison of the expected numbers of breakpoints within a particular DNA sequence motif or repeat element (calculated as the number of bp comprising the DNA motifs within the whole breakpoint cluster region) and the observed numbers of breakpoints within these sequence motifs revealed no significant discrepancy (Figure 3).

Repeat elements at the fusion site impede the design of specific primers for sensitive quantification of tumor-specific circulating DNA copy number. Therefore, we evaluated the distribution of repeat elements within the TMPRSS2 and ERG breakpoint cluster regions to assess the potential limitations of personalized therapy monitoring attributable

### Table 1: Patient characteristics and genomic breakpoint positions.

| Patient ID | Age at diagnosis (y) | Gleason score | Break position (GRCh37/hg19) | Filler (bp) | Microhomology (bp) |
|------------|----------------------|---------------|-----------------------------|-------------|-------------------|
| UPN01      | 56                   | 6             | chr21:42,869,431 chr21:39,882,942 | 0           | 1                 |
| UPN02      | 59                   | 7             | chr21:42,873,985 chr21:39,853,572 | 0           | 1                 |
| UPN03      | 59                   | 7             | chr21:42,869,696 chr21:39,829,922 (inversion 43 bp) | 0           | 5                 |
| UPN04      | 60                   | 5             | chr21:42,873,983 chr21:39,893,342 | 0           | 1                 |
| UPN05      | 61                   | 7             | chr21:42,871,961 chr21:39,878,090 | 0           | 1                 |
| UPN06      | 62                   | 7             | chr21:42,871,305 chr21:39,864,401 | 3           | 0                 |
| UPN07      | 63                   | 6             | chr21:42,868,091 chr21:39,866,577 | 0           | 0                 |
| UPN08      | 64                   | 6             | chr21:42,872,946 chr21:39,870,469 | 4           | 0                 |
| UPN09      | 65                   | 7             | chr21:42,868,907 chr21:39,829,216 | 2           | 0                 |
| UPN10      | 66                   | 7             | chr21:42,874,680 chr21:39,864,869 | 0           | 0                 |
| UPN11      | 66                   | 9             | chr21:42,872,341 chr21:39,877,041 | 0           | 1                 |
| UPN12      | 67                   | 9             | chr21:42,876,941 chr21:39,878,531 | 0           | 0                 |
| UPN13      | 68                   | 5             | chr21:42,869,152 chr21:39,859,803 | 0           | 2                 |
| UPN14      | 68                   | 6             | chr21:42,874,909 chr21:39,875,817 | 0           | 1                 |
| UPN15      | 68                   | 7             | chr21:42,870,630 chr21:39,869,687 | 0           | 0                 |
| UPN16      | 69                   | 7             | chr21:42,873,489 chr21:39,860,650 | 0           | 3                 |
| UPN17      | 69                   | 8             | chr21:42,865,245 chr21:39,835,822 | 0           | 0                 |
| UPN18      | 69                   | 8             | chr21:42,868,095 chr21:39,950,289 | 0           | 0                 |
| UPN19      | 70                   | 8             | chr21:42,868,866 chr21:39,878,045 | 1           | 0                 |
| UPN20      | 70                   | 9             | chr21:42,870,028 chr21:39,885,074 | 0           | 7                 |
| UPN21      | 72                   | 7             | chr21:42,868,434 chr21:39,867,273 | 0           | 1                 |
| UPN22      | 72                   | 9             | chr21:42,872,857 chr21:39,862,072 | 0           | 0                 |
| UPN23      | 73                   | 7             | chr21:42,867,920 chr21:39,868,183 | 0           | 1                 |
| UPN24      | 74                   | 7             | chr21:42,869,364 chr21:39,930,902 | 0           | 1                 |
| VCap cell line | n.a.            | n.a.          | chr21:42,871,953 chr21:39,876,353 (inversion 81 bp) | 4           | 0                 |

n.a.: not available.
to sequence composition. The proportion of repeat regions within the breakpoint cluster regions was 25% for \textit{TMPRSS2} and 34% for \textit{ERG}, which is comparable to other mesenchymal tumors for which DNA-level genomic fusion sequences have been successfully established as patient-specific biomarkers (Supplemental Figure 2).

4. Discussion

Today, PSA is the most widely used noninvasive tumor marker for evaluation of prostate cancer; however, PSA is not exclusively expressed in malignant tissue. Inflammation, benign prostate hyperplasia, and trauma can also result in increased PSA levels and lead to false positive results [35]. In Germany, approximately 70,000 men are diagnosed with prostate cancer annually, and statistical models predict that prostate cancer will be the most common malignancy by 2030, affecting around 120,000 men per year [36], illustrating the need to improve therapy assessment for this patient cohort. In the present study, we investigated whether genomic \textit{TMPRSS2-ERG} fusion sequences fulfill the molecular criteria for use as patient individual noninvasive tumor markers.

Quantifications of CTCs and cell-free circulating tumor nucleotides in blood or urine samples have been proposed as new molecular strategies for noninvasive tumor monitoring in prostate cancer. The detection of tumor-specific genetic variations enables the establishment of highly specific biomarkers. CTCs are mainly detectable in blood samples from patients with advanced prostate cancer, which carry the complete mutation spectrum from primary tumors and metastases, and therefore represent appropriate biomarkers for advanced-stage disease [15, 16, 37–39]. Cell-free DNA may be more suitable for assessment of therapy effects in patients with early-stage disease [21].

CtDNA has been presented as a valuable biomarker in several other epithelial tumors, including colorectal, breast, lung cancer, and melanoma [40–43], where recurrent point mutations in tumor-suppressor genes or oncogenes were used as molecular markers. Relatively few recurrent point mutations are identified in primary prostate tumors [44]; however, approximately 50% of prostate tumors carry a
TMPRSS2-ERG translocation [9], which could be considered a highly tumor-specific molecular biomarker for ctDNA quantification in blood or urine samples. The short half-life of ctDNA in blood (less than 2 h [41]) is comparable with that of serum-free PSA [45] and enables real-time therapy assessment.

To use genomic fusion sequences as molecular biomarkers, individual quantification assays are required for each patient because the genomic breakpoints are specific to every individual. Here, we applied nested long-range multiplex PCR to identify patient-specific genomic TMPRSS2-ERG fusion sequences. In principle, genomic fusion sequences can also be identified using next-generation sequencing techniques that allow parallel sequencing of several patients in an automated pipeline. Based on the organization of genomic breakpoints in ERG, which were preferentially detected within a subcluster region of approximately 25 kb in intron 3, our results provide the basis for the establishment of targeted enrichment assays, including genomic fusion sequences.

In the present study, we analyzed the molecular composition and distribution of genomic TMPRSS2-ERG fusion sites from 24 newly sequenced cases together with 34 previously reported patients with prostate cancer to evaluate the suitability of this genomic fusion sequence as a noninvasive tumor marker for patients with prostate cancer. We observed high similarity of the microstructure of genomic fusion sites of epithelial prostate cancer cells compared to mesenchymal tumor cells.

Genomic fusion sequences are considered highly specific tumor markers in leukemic diseases and EWS patients; however, several fusion genes (e.g., CIC-DUX in Ewing-like sarcoma and BCR-ABL1 in Ph+ALL patients) have unfavorable genetic structures for the establishment of high-sensitivity quantification assays. Numerous repeated segments in the DUX gene have made the design of tumor-specific primers for therapy assessment in patients with Ewing-like sarcoma impossible. In Ph+ALL patients, the very large breakpoint cluster regions in the fusion genes (55.7 kb in BCR and 141 kb in ABL1), in combination with the high proportion of repeat elements (50%), complicate the establishment of high-sensitivity quantification assays for therapy assessment. Hence, the localization of genomic breakpoints at repeat elements is crucial for successful application of fusion genes as reliable noninvasive biomarkers, which is especially interesting in the context of ctDNA quantification in patients with solid cancers. Due to the high levels of fragmentation of cell-free DNA in blood plasma or urine samples, to establish highly sensitive assays for therapy assessment primers and probes needs to be positioned close to the fusion site. To ensure that an assay is highly tumor-specific, there should be as few repeat elements as possible associated with the genomic breakpoints.

The present data demonstrate that the proportion of repeat elements in the epithelial tumor, prostate cancer, is comparable to that observed in mesenchymal tumors, where genomic fusion sequences are established as biomarkers (Supplemental Figure 2). Hence, the TMPRSS2-ERG fusion gene in prostate cancer could be considered for use as a noninvasive tumor marker for therapy assessment, risk stratification, and relapse detection to improve personalized therapy strategies.

5. Conclusions

Large, repeat-rich intronic regions impede the sequencing of genomic TMPRSS2-ERG fusion sites. MLR-PCR and next-generation sequencing technologies enable a routine
identification of patients’ individual fusion sequences. Hence, TMPRSS2-ERG fusion sequences are available for the establishment of quantification assays for therapy assessment. The observed comparable proportion of genomic repeat regions within the TMPRSS2 and ERG breakpoint cluster region to other mesenchymal tumors is an important prerequisite for the design of tumor-specific primers and probes for a highly sensitive therapy monitoring in prostate cancer patients.

**Data Availability**

The data used to support the findings of this study are available from the corresponding author upon request.

**Conflicts of Interest**

The authors confirm that there are no conflicts of interest.

**Acknowledgments**

The authors thank Ursula Jacobs and Sabine Semper for excellent technical assistance. This work was supported by a grant from the Schornsteinfeiger helfen krebskranke Foundation, Germany (to MK and MM).

**Supplementary Materials**

Supplemental Figure 1: genomic breakpoint cluster regions for TMPRSS2 and ERG. Black vertical bars above the breakpoint cluster region represent individual genomic breakpoints in patients with prostate cancer identified in the present study. Orange vertical bars represent individual genomic breakpoints in patients with prostate cancer published in the literature. Localization of repeat elements and different DNA sequence motifs within the breakpoint cluster region are indicated below. Supplemental Figure 2: proportion of repeat regions within the breakpoint cluster regions of fusion genes in prostate cancer (PC), Ewing sarcoma (EWS), anaplastic large-cell lymphoma (ALCL), acute lymphoid leukemia (ALL), and chronic myeloid leukemia (CML). Supplemental Table 1: sequences of primers used in nested multiplex PCR assay. Supplemental Table 2. (Supplementary Materials)

**References**

[1] J. Haberland, J. Bertz, U. Wolf, T. Ziese, and B. M. Kurth, “German cancer statistics 2004,” BMC Cancer, vol. 10, no. 1, p. 52, 2010.

[2] J. Ferlay, E. Stelianova-Foucher, J. Lortet-Tieulent et al., “Cancer incidence and mortality patterns in Europe: estimates for 40 countries in 2012,” European Journal of Cancer, vol. 49, no. 6, pp. 1374–1403, 2013.

[3] H. Goldberg, J. Baniel, and O. Yossepowitch, “Defining high-risk prostate cancer,” Current Opinion in Urology, vol. 23, no. 4, pp. 337–341, 2013.

[4] S. C. Baca and L. A. Garraway, “The genomic landscape of prostate cancer,” Frontiers in Endocrinology, vol. 3, p. 69, 2012.

[5] C. S. Grasso, Y. M. Wu, D. R. Robinson et al., “The mutational landscape of lethal castration-resistant prostate cancer,” Nature, vol. 487, no. 7406, pp. 239–243, 2012.

[6] R. Mehra, S. A. Tomlins, J. Yu et al., “Characterization of TMPRSS2-ETS gene aberrations in androgen-independent metastatic prostate cancer,” Cancer Research, vol. 68, no. 10, pp. 3584–3590, 2008.

[7] C. C. Guo, Y. Wang, L. Xiao, P. Troncoso, and B. A. Czerniak, “The relationship of TMPRSS2-ERG gene fusion between primary and metastatic prostate cancers,” Human Pathology, vol. 43, no. 5, pp. 644–649, 2012.

[8] A. G. Sowalsky, H. Ye, G. J. Bubley, and S. P. Balk, “Clonal progression of prostate cancers from Gleason grade 3 to grade 4,” Cancer Research, vol. 73, no. 3, pp. 1050–1055, 2013.

[9] S. A. Tomlins, A. Bjartell, A. M. Chinnaiyan et al., “ETS gene fusions in prostate cancer: from discovery to daily clinical practice,” European Urology, vol. 56, no. 2, pp. 275–286, 2009.

[10] S. Perner, J. M. Mosquera, F. Demichelis et al., “TMPRSS2-ERG fusion prostate cancer: an early molecular event associated with invasion,” The American Journal of Surgical Pathology, vol. 31, no. 6, pp. 882–888, 2007.

[11] F. H. Schröder, “Landmarks in prostate cancer screening,” BJU International, vol. 110, pp. 3–7, 2012.

[12] M. Fryczkowski, R. J. Buldak, T. Hejmo, M. Kukla, and K. Zwirska-Korczala, “Circulating levels of omentin, leptin, VEGF, and HGF and their clinical relevance with PSA marker in prostate cancer,” Disease Markers, vol. 2018, Article ID 3852401, 9 pages, 2018.

[13] K. Fujita, H. Kume, K. Matsuoka et al., “Proteomic analysis of urinary extracellular vesicles from high Gleason score prostate cancer,” Scientific Reports, vol. 7, no. 1, article 42961, 2017.

[14] A. H. Zedan, T. F. Hansen, J. Assenholt, J. S. Madsen, and P. J. S. Østher, “Circulating miRNAs in localized/locally advanced prostate cancer patients after radical prostatectomy and radiotherapy,” Prostate, vol. 79, no. 4, pp. 425–432, 2019.

[15] G. Galletti, D. Worroll, D. M. Nanus, and P. Giannakakou, “Characterization of tumor cells in the era of precision medicine,” Disease Markers, vol. 2015, Article ID 574120, 6 pages, 2015.

[16] K. Pantel, C. Hille, and H. I. Scher, “Circulating tumor cells in prostate cancer: from discovery to clinical utility,” Clinical Chemistry, vol. 65, no. 1, pp. 87–99, 2019.

[17] Y. S. Suh, J. Y. Joung, S. H. Kim, H. K. Seo, J. Chung, and K. H. Lee, “Establishment and application of prostate cancer circulating tumor cells in the era of precision medicine,” BioMed Research International, vol. 2017, Article ID 7206307, 9 pages, 2017.

[18] A. D. Choudhury, L. Werner, E. Francini et al., “Tumor fraction in cell-free DNA as a biomarker in prostate cancer,” JCI Insight, vol. 3, no. 21, 2018.

[19] S. Salvi, G. Gurioli, F. Martignano et al., “Urinary cell-free DNA integrity analysis for early detection of prostate cancer patients,” Disease Markers, vol. 2015, Article ID 574120, 6 pages, 2015.

[20] M. Annala, G. Vankerskophove, D. Khalaf et al., “Circulating tumor DNA genomics correlate with resistance to abiraterone and enzalutamide in prostate cancer,” Cancer Discovery, vol. 8, no. 4, pp. 444–457, 2018.

[21] A. Wu and G. Attard, “Plasma DNA analysis in prostate cancer: opportunities for improving clinical management,” Clinical Chemistry, vol. 65, no. 1, pp. 100–107, 2019.
[22] A. W. Wyatt, M. Annala, R. Aggarwal et al., "Concordance of circulating tumor DNA and matched metastatic tissue biopsy in prostate cancer," *Journal of the National Cancer Institute*, vol. 109, no. 12, 2017.

[23] Y. Xia, C. C. Huang, R. Dittmar et al., "Copy number variations in urine cell free DNA as biomarkers in advanced prostate cancer," *Oncotarget*, vol. 7, no. 24, pp. 35818–35831, 2016.

[24] H. K. Woo, J. Park, J. Y. Ku et al., "Urine-based liquid biopsy: non-invasive and sensitive AR-V7 detection in urinary EVs from patients with prostate cancer," *Lab on a Chip*, vol. 19, no. 1, pp. 87–97, 2018.

[25] M. Krumbholz, J. Hellberg, B. Steif et al., *Clinical Cancer Research*, vol. 22, no. 17, pp. 4356–4365, 2016.

[26] M. Krumbholz, M. Karl, J. T. Tauer et al., "Genomic BCR-ABL1 breakpoints in pediatric chronic myeloid leukemia," *Genes, Chromosomes & Cancer*, vol. 51, no. 11, pp. 1045–1053, 2012.

[27] M. Krumbholz, W. Woessmann, J. Zierk et al., "Response monitoring of infant acute myeloid leukemia treatment by quantification of the tumor specific MLL–FNBP1 fusion gene," *Leukemia & Lymphoma*, vol. 56, no. 3, pp. 793–796, 2015.

[28] C. Weier, M. C. Haaffner, T. Mosbruger et al., "Nucleotide resolution analysis of TMPRSS2 and ERG rearrangements in prostate cancer," *The Journal of Pathology*, vol. 230, no. 2, pp. 174–183, 2013.

[29] M. C. Haaffner, M. J. Aryee, A. Toubaji et al., "Androgen-induced TOP2B-mediated double-strand breaks and prostate cancer gene rearrangements," *Nature Genetics*, vol. 42, no. 8, pp. 668–675, 2010.

[30] F. Demichelis, S. R. Setlur, R. Beroukhim et al., "Distinct genomic aberrations associated with ERG rearranged prostate cancer," *Genes, Chromosomes and Cancer*, vol. 48, no. 4, pp. 366–380, 2009.

[31] W. Liu, S. Laitinen, S. Khan et al., "Copy number analysis indicates monoclonal origin of lethal metastatic prostate cancer," *Nature Medicine*, vol. 15, no. 5, pp. 559–565, 2009.

[32] M. Berger, U. Dirksen, A. Braeuninger et al., "Genomic EWS-FLI1 fusion sequences in Ewing sarcoma resemble breakpoint characteristics of immature lymphoid malignancies," *PLoS One*, vol. 8, no. 2, article e56408, 2013.

[33] H. von Goessel, U. Jacobs, S. Semper et al., "Cluster analysis of genomic ETV6 - RUNX1 (TEL - AML1) fusion sites in childhood acute lymphoblastic leukemia," *Leukemia Research*, vol. 33, no. 8, pp. 1082–1088, 2009.

[34] Z. Kornberg, M. R. Cooperberg, D. E. Spratt, and F. Y. Feng, "Genomic biomarkers in prostate cancer," *Translational Andrology and Urology*, vol. 7, no. 3, pp. 459–471, 2018.

[35] A. S. Quante, C. Ming, M. Rottmann et al., "Projections of cancer incidence and cancer-related deaths in Germany by 2020 and 2030," *Cancer Medicine*, vol. 5, no. 9, pp. 2649–2656, 2016.

[36] H. Schwarzenbach, C. Alix-Panabieres, I. Muller et al., "Cell-free tumor DNA in blood plasma as a marker for circulating tumor cells in prostate cancer," *Clinical Cancer Research*, vol. 15, no. 3, pp. 1032–1038, 2009.

[37] O. Reig, M. Marin-Aguilera, G. Carrera et al., "TMPRSS2-ERG in Blood and Docetaxel Resistance in Metastatic Castration-resistant Prostate Cancer," *European Urology*, vol. 70, no. 5, pp. 709–713, 2016.

[38] M. Hegemann, A. Stenzl, J. Bedke, K. N. Chi, P. C. Black, and T. Todenhöfer, "Liquid biopsy: ready to guide therapy in advanced prostate cancer?" *BJU International*, vol. 118, no. 6, pp. 855–863, 2016.

[39] S. J. Dawson, D. W. Tsui, M. Murtaza et al., "Analysis of circulating tumor DNA to monitor metastatic breast cancer," *The New England Journal of Medicine*, vol. 368, no. 13, pp. 1199–1209, 2013.

[40] F. Diehl, K. Schmidt, M. A. Choti et al., "Circulating mutant DNA to assess tumor dynamics," *Nature Medicine*, vol. 14, no. 9, pp. 985–990, 2008.

[41] G. R. Oxnard, C. P. Paveletz, Y. Kuang et al., "Noninvasive detection of response and resistance in EGFR-mutant lung cancer using quantitative next-generation genotyping of cell-free plasma DNA," *Clinical Cancer Research*, vol. 20, no. 6, pp. 1698–1705, 2014.

[42] E. Alegre, J. P. Fusco, P. Restituto et al., "Total and mutated EGFR quantification in cell-free DNA from non-small cell lung cancer patients detects tumor heterogeneity and presents prognostic value," *Tumour Biology*, vol. 37, no. 10, pp. 13687–13694, 2016.

[43] B. Liu, F. F. Hu, Q. Zhang et al., "Genomic landscape and mutational impacts of recurrently mutated genes in cancers," *Molecular Genetics & Genomic Medicine*, vol. 6, no. 6, pp. 910–923, 2018.

[44] T. D. Richardson, K. J. Wijno, L. W. Liang et al., "Half-life determination of serum free prostate-specific antigen following radical retropubic prostatectomy," *Urology*, vol. 48, no. 6, pp. 40–44, 1996.