FGFR3 and TP53 Gene Mutations Define Two Distinct Pathways in Urothelial Cell Carcinoma of the Bladder

Ashraf A. Bakkar, Herve Wallerand, François Radvanyi, Jean-Baptiste Lahaye, Serge Pissard, Laure Lecerf, Jean-Claude Kouyoumdjian, Claude C. Abbou, Jean-Claude Pairon, Marie-Claude Jaurand, Jean-Paul Thiery, Dominique K. Chopin, and Sixtina Gil Diez de Medina

Abstract

FGFR3 and TP53 mutations are frequent in superficial papillary and invasive disease, respectively. We used denaturing high-performance liquid chromatography and sequencing to screen for FGFR3 and TP53 mutations in 81 newly diagnosed urothelial cell carcinomas. Tumors were classified as follows: 31 pTa, 1 carcinoma in situ, 30 pT1, and 19 pT2-T4. Tumor grades were as follows: 10 G1, 29 G2, and 42 G3. FGFR3 mutations were associated with low-stage (P < 0.0001), low-grade (P < 0.008) tumors, whereas TP53 mutations were associated with high-stage (P < 0.003), high-grade (P < 0.02) tumors. Mutations in these two genes were almost mutually exclusive. Our results suggest that FGFR3 and TP53 mutations define separate pathways at initial diagnosis of urothelial cell carcinoma.

Introduction

UCC of the bladder is a spectrum disease characterized by unpredictability in its biological behavior and response to treatment. UCCs are classified into two broad types: superficial and invasive tumors. Most UCCs present as superficial bladder cancer, confined in 75% of cases to the epithelium (CIS, pTa) or lamina propria (pT1). The remaining (25%) tumors present as muscle invasive disease (≥pT2), with no history of superficial disease. However, superficial bladder cancer covers many lesions with different biological potentials, and morphologically similar tumors of the same stage may display completely different patterns of behavior (1). It has been suggested that different genetic changes account for these different forms of UCC and for the observed differences in biological behavior (2). Losses of chromosome 9 have been described as the most common finding in superficial papillary tumors, but such losses are in fact observed at all stages and grades. Alterations of chromosome 9q occur very early in the disease and seem to be involved in the development of bladder cancer. Regions of interest (at 9p21, 9q12–31, 9q32–33, and 9q34) harboring candidate tumor suppressor genes have been identified on both arms of chromosome 9 (reviewed in Ref. 2). However, the prognostic significance of these findings remains unclear. TP53 mutations are frequent in bladder tumors of high stage and grade, and have been associated with invasiveness (3). It has also been shown that loss of heterozygosity on chromosome 17p, to which TP53 maps, is more frequent in high-grade than in low-grade tumors. The p53 protein functions as a transcription factor, regulating the expression of several downstream genes. Two major functions of p53 are cell cycle arrest and apoptosis (reviewed in Ref. 4).

Spruck et al. (5) suggested that UCCs progress via two molecular pathways, with TP53 mutations and loss of heterozygosity on chromosome 17 more frequent in CIS and invasive tumors. In contrast, selective deletions of chromosome 9 are more common in superficial papillary tumors. It was suggested that CIS is the most likely precursor of invasive tumors (5). However, the role and the position of FGFR3 mutations in current models of bladder carcinogenesis still need to be clarified. FGFR3 receptors belong to a family of highly conserved, structurally related genes, which is classified into four subtypes (FGFR1, 2, 3, and 4) that bind fibroblast growth factors with different affinity (6). These tyrosine kinase receptors regulate several cellular processes including cell growth, differentiation, migration, wound healing, and angiogenesis, and this depends on the target cell type and the developmental stage (7, 8). FGFR3 is located at 4p16.3 and comprises 19 exons spanning 16.5 Kb (9). FGFR3 activating mutations identified in thanatophoric dysplasia were also found in cervix and bladder cancer (10). Currently, it is believed that these mutations result in constitutive activation of the receptor (11). An oncogenic role has been attributed to these mutations in bladder neoplasms, whereas they have an inhibitory role in skeletal diseases (10, 12). The coding sequence of FGFR3 spanning exons 2–19 was investigated previously, and somatic mutations in bladder tumors were localized in exons 7, 10, and 15 (10, 13). FGFR3 somatic mutations were shown to be the most frequent gene mutation in low-stage bladder tumors, which underlie their importance in bladder cancer (10, 13). The high frequency of FGFR3 and TP53 mutations in superficial papillary and invasive bladder cancers, respectively, led us to compare these two genetic alteration in 81 bladder cancer tumors of all stages and grades at initial diagnosis, to determine whether they correspond to different disease pathways and could be used for molecular classification of these tumors. In this study, we screened for FGFR3 (exons 7, 10, and 15) and TP53 (exons 2–11) mutations by DHPLC analysis and sequencing in consecutive primary tumors. We found that mutations in FGFR3 and TP53 were almost mutually exclusive, and defined several groups of tumors consistent with the TNM classification in terms of tumor aggressiveness: (a) superficial papillary UCCs with FGFR3 mutations and no TP53 mutations; (b) superficial papillary UCCs with no mutation in either gene; (c) superficial papillary UCCs with TP53 mutations but no FGFR3 mutations; and (d) invasive UCCs with and without TP53 mutations. This observation provides a framework for the molecular classification of bladder cancer.
Materials and Methods

Characteristics of the Patients and Tissue Samples. All 81 patients of the cohort studied here had newly diagnosed bladder tumors and were admitted for transurethral resection or radical cystectomy. None of the patients had received treatment before the analysis. Median age at time of diagnosis was 64 years (range, 38–86).

We collected matched tumors and blood samples after the patients had given written informed consent. Tumors were graded according to the WHO classification (14) and staged according to the 1997 TNM classification guidelines (15) with each annealing step lasting 1 min. For the remaining of the 35 cycles, annealing temperatures were maintained at 62°C, 62°C, and 61°C for exons 7, 10, and 15, respectively, with each annealing step lasting 1 min. In each cycle, the denaturation step consisted of heating at 94°C for 1 min and the extension step of heating at 72°C for 1.20 min. At the end of the last cycle, samples were incubated for an additional 15 min at 72°C. The primers used for FGFR3 amplification are shown in Table 1.

DHPLC. We carried out DHPLC analysis with the Varian (Prostar) Helix system, using the helix analysis column (the helix DNA column). The formation of heteroduplexes and homoduplexes was encouraged by first denaturing PCR products by heating at 95°C for 10 min and then allowing them to reanneal at 62°C (FGFR3) and 58°C (TP53) for 1 h. We applied a 5-μL DNA sample to the column and eluted within a linear acetonitrile gradient as the eluent. The acetonitrile gradient was created by mixing buffer A [100 mM triethylammonium acetate (pH 7.0) and 0.1 mM EDTA] and buffer B [100 mM triethylammonium acetate (pH 7.0), 0.1 mM EDTA, and 25% (v/v) acetonitrile]. The flow rate was 0.45 μl/min, and we increased the proportion of buffer B by 3.3% per min for 4.5–5.5 min. The optimal melting temperature for each amplicon was first roughly determined by the analysis of wild-type sequence using an annealing algorithm at the Stanford DHPLC website (17). The melting behavior of the specific DNA was established by repeatedly injecting the sample at temperature steps beginning at 50°C until complete denaturation is reached. A melting curve, retention time versus temperature, is made, and the temperature at which 25–50% denaturation was observed was selected (retention time is 0.75–1 min shorter than that under non-denaturing conditions), using the universal gradient (Varian). The acetonitrile gradient was then adjusted such that the peaks were eluted between 3 and 6.30 min. Whenever possible, mutation detection was checked by analyzing a sample known to harbor a specific sequence variation. DNA fragments were monitored by UV absorbency at 260 nm. Specific values for the gradient ranges and mobile-phase temperatures used are shown in Table 1.

DNA Sequencing. PCR products with elution profiles different from that of the corresponding wild-type DNA were sequenced. Sequencing was performed with the Big Dye Terminator kit, following the Applied Biosystems protocol. Samples were sequenced in an ABIPRISM 377 sequencer (Perkin-Elmer Applied Biosystems). If a mutation was identified, matched constitu-
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Table 2. FGFR3 mutations in newly diagnosed bladder tumors

| Exon | Codon | Nucleotide position and base change | Amino acid change | Number of tumors | %  
|------|-------|-----------------------------------|------------------|------------------|---
| 59   | 7     | 742C>T                            | Arg/Cys (R248C)  | 3                | 9%  
| 7    | 248   | 746G>G                            | Ser/Cys (S249C)  | 19               | 60% 
| 10   | 372   | 1114G>T                           | Gly/Cys (G372C)  | 1                | 3%  
| 10   | 375   | 1124A>G                           | Tyr/Cys (Y375C)  | 6                | 19% 
| 15   | 652   | 1954A>G                           | Lys/Gln (K652E)  | 2                | 6%  
| 15   | 652   | 1955A>T                           | Lys/Met (K652M)  | 1                | 3%  

*% calculated as a percentage of the total number of FGFR3 mutations found in this study.

Table 3. TP53 mutations and tumor characteristics in newly diagnosed bladder tumors

| Tumor number | Stage | Grade | Exon | Codon | Nucleotide position and base change | Type of mutation | Amino acid change  
|--------------|-------|-------|------|-------|-----------------------------------|------------------|------------------|---
| 27           | pTa   | G2    | 7    | 244   | 14058G>T                          | transversion     | Gly244Val+      
| 80           | pT1   | G3    | 5    | 136   | 13068A>C                          | transversion     | Glu368Pro       
| 58           | pT1   | G3    | 5    | 152   | 13134C>T                          | transversion     | Pro152Leu       
| 70           | pT1   | G3    | 6    | 220   | 13419A>G                          | transversion     | Tyr220Cys       
| 30           | pT1   | G2    | Intron 6 | 249 | 14072A>G                          | transversion     | Arg249Gly       
| 41           | pT1   | G3    | 7    | 249   | 14072A>G                          | transversion     | Arg249Gly       
| 9            | pT1   | G3    | 9    | 331   | 14755G>A                          | transversion     | Glu311Gln       
| 16           | pT2   | G2    | 4    | 110   | 12253G>T                          | transversion     | Arg110Leu       
| 19           | pT2   | G3    | 5    | 181   | 13221delG                          | frameshift       | Arg213Leu       
| 4            | pT2   | G3    | 6    | 213   | 13398G>T                          | transversion     | Tyr220Cys       
| 59           | pT2   | G3    | 6    | 220   | 13419A>G                          | transversion     | Tyr220Cys       
| 63           | pT2   | G3    | 7    | 241   | 14049C>A                          | transversion     | Ser241Tyr       
| 46           | pT2   | G3    | 7    | 248   | 14070G>A                          | transversion     | Arg248Gln       
| 35           | pT3   | G3    | 8    | 294   | 14549G>T                          | transversion     | Gin294V*        
| 20           | pT3   | G3    | 5    | 136   | 13085delC*                        | frameshift       | Arg248Gln       
| 65           | pT3   | G3    | 7    | 248   | 14070G>A                          | transversion     | Arg248Gln       

Table 3 TP53 mutations and tumor characteristics in newly diagnosed bladder tumors

Accession number for the genomic reference sequence: U94788.1.

The various FGFR3 mutations identified are listed in Table 2. Overall, these mutations were found in 40% (32 of 81) of the tumors. Six different mutations were detected, five of which (R248C, S249C, G372C, Y375C, and K652E) are identical to those found in thomatomorphic dysplasia. The sixth mutation, K652M, has been reported in cases of severe achondroplasia with developmental delay and achondroplasia nigricans. The various TP53 mutations identified are listed in Table 3. We identified 19 mutations in 17 of the 81 patients studied (23%; 2 patients had a double mutation). Mutations were found in all of the exons from 4 to 9, but no mutations were found in exons 2, 3, 10, or 11. Nine mutations were transitions (4 G>A, 3 A>G, and 2 C>T), and 8 were transversions (5 G>T, 1 A>C, 1 C>A, and 1 C>G). The C>G transversion was found in intron 6, at a splice acceptor site (patient 30). Two deletions were also found in exon 5 (patients 19 and 20). Two patients had a double mutation. Patient 27 had a double mutation in exon 7, with the first mutation at codon 244 and the second at codon 245. The other patient (number 41) had one mutation in exon 5, codon 175, and the second at exon 8, codon 306.

Sixty-one of the 81 bladder tumors studied (76%) were superficial papillary tumors; these tumors included 31 pTa, 30 pT1, and 1 (1%) flat CIS. Nineteen tumors (24%) were muscle invasive tumors (pT2-pT4), comprised of 16 pT2, 2 pT3, and 1 pT4. The frequency of superficial and muscle invasive tumors in this study was consistent with previous epidemiological studies on the stage at initial diagnosis, demonstrating the validity of our cohort of patients.

FGFR3 and TP53 mutations identified as a function of stage and grade are shown in Fig. 1, A and B, respectively. These data clearly show opposite patterns for FGFR3 and TP53 mutations, in terms of distribution according to stage and grade, and a significant linear trend was observed for the distribution of mutations according to stage and grade for both genes (Fig. 1, A and B).

We found that FGFR3 and TP53 mutations were almost mutually exclusive (Fig. 1C). The frequency of the tumor group containing both mutations (FGFR3 mut/TP53 wt) at various stages was not significant (P < 0.9).

In pTa tumors, FGFR3 mut/TP53 wt was the most prevalent genotype, accounting for 68% of tumors (21 of 31). The next most prevalent genotype was FGFR3 wt/TP53 wt, found in 31 of 31 tumors (99%). No FGFR3 wt/TP53 wt genotype was found. The FGFR3 mut/TP53 mut genotype was found in only 1 of 31 tumors (3%), a pTa2 tumor (Fig. 1C).

In pT1 tumors, FGFR3 wt/TP53 wt was the most frequent genotype, found in 15 of 30 tumors (50%), followed by FGFR3 mut/TP53 wt, which was found in 8 of 30 tumors (27%), and FGFR3 wt/TP53 mut,
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FGFR3 and TP53 mutations provide additional evidence that clinical behavior and prognosis of superficial papillary noninvasive tumors were more frequent in CIS and invasive tumors. It was suggested that mutations in both FGFR3 and TP53 are associated with high grade (TP53 mut/TP53 wt) at various stages. The FGFR3 mut tumor (pT3G3; 5%) was identified (Fig. 1C). Therefore, genomic stability may have been maintained, because it has been suggested that TP53 mutations destabilize the genome.

Our results on TP53 mutations, which were most frequent in high-stage, high-grade tumors, are consistent with those of previous investigators.

We analyzed the mutations in the two genes in individual tumors and found that FGFR3mut/TP53wt was the most prevalent genotype in pTa (68%) tumors. Thus, FGFR3 mutations are probably key genetic alterations in these lesions and may occur early in their development. FGFR3 mutations occur with high frequency (75%) in urothelial papilloma (22), and it is still to be determined whether some pTa tumors might have been evolved from these lesions. In pT1 tumors, this genotype accounts for 27% of cases and was not observed in muscle invasive cancer. The presence of this genotype in both pTa and pT1 tumors indicates that a subgroup of pT1 is, from a molecular point of view, related to pTa. However, the clearly higher frequency of this genotype in pTa than in pT1 tumors may be associated with a different genetic changes (23) and that their grouping together as superficial bladder cancer is imprecise and misleading.

The FGFR3wt/TP53wt genotype accounted for a considerable proportion of tumors, and was found in 29% of pTa, 50% of pT1, and 53% of pT2 tumors. The search for key genetic and/or epigenetic alterations that may occur in these lesions, as other pathways may also be at work. Other alterations described in bladder cancer should perhaps also be studied in light of FGFR3 and TP53 mutations.

The FGFR3mut/TP53mut genotype was not observed in pTa tumors, but was found in 20% of pT1 and 42% of pT2 tumors. The increasing frequency of this genotype from pTa to pT2-pT4 suggests that this genotype may be associated with more chromosomal alterations. This possibility is consistent with data showing a higher level of allelic imbalances in pT2-pT4 than in pT1 tumors and that tumors in which both TP53 alleles are inactivated have many imbalances (24). Because TP53 is involved in checkpoint control after DNA damage, changes in this gatekeeper gene may lead to the accumulation of additional genetic changes.

Our data suggest that pT1 tumors may be seen as an intermediate group, resembling both pTa and pT2-pT4 tumors, as they included the three main genotypes: FGFR3mut/TP53wt (27%), FGFR3wt/TP53wt (50%), and FGFR3wt/TP53mut (20%). These findings reaffirm the heterogeneity of this group of tumors. Given the clear variability in the biological potential of these lesions, grouping them according to common molecular changes may improve predictions of prognosis. Tumors with TP53 mutations may not be grouped with those harboring FGFR3 mutations.

The FGFR3mut/Tp53mut genotype was found in only a few tumors: a pTaG2 (3%), a pT1G3 (3%), and a pT2G3 (5%) tumor. Mutations in both genes may result from different oncogenic mechanisms occurring in the same tumor, which is not the general rule, at

Fig. 1. A, FGFR3 and TP53 mutations according to stage. The P was calculated by a χ² test. P < 0.05 was considered significant. FGFR3 mutations were detected in 71% pTa, in 30% pT1, and 44% pT2-pT4 tumors. FGFR3 mutations are associated with low stage (P < 0.0001). TP53 mutations were identified in 6% pTa, in 27% pT1, and in 47% pT2-pT4 tumors. TP53 mutations were associated with high stage (P < 0.0003). No mutations in TP53 or FGFR3 were found in the CIS studied here. B, FGFR3 and TP53 mutations according to grade. The P was calculated by χ² test. P < 0.05 was considered significant. FGFR3 mutations were found in 70% G1, 52% G2, and 24% G3 tumors. FGFR3 mutations are associated with low grade (P < 0.008). TP53 mutations were not found in the G1 tumors, and were identified in 14% G2 tumors and in 36% G3 tumors. TP53 mutations are associated with high grade (P < 0.02). C, tumor genotypes according to mutations in both FGFR3 and TP53 at various stages. P was calculated using a two-sided Fisher’s exact test. The frequency of the tumor group containing both mutations (FGFR3mut/TP53mut) at various stages was not significant (P < 0.09).

which was found in 6 of 30 tumors (20%). The FGFR3mut/TP53mut genotype was found in only 1 tumor (3%), a (pT1G3; Fig. 1C).

In pT2-pT4 tumors, the FGFR3wt/TP53wt genotype accounted for 10 of 19 (53%) cases. The next most frequent genotype was FGFR3wt/TP53mut, which was observed in 8 of 19 (42%) tumors. The FGFR3mut/TP53wt genotype was not found. A single FGFR3wt/TP53mut tumor (pT3G3; 5%) was identified (Fig. 1C).

Discussion

Elucidation of the molecular pathways involved in UCC is essential for our understanding of the etiopathogenesis of the disease, and, hence, for more precise diagnosis, accurate prognosis and better management of patients. To our knowledge, this is the first study investigating mutations in both FGFR3 and TP53 in bladder cancer. This analysis of genotypes in newly diagnosed bladder cancer patients, who had not received treatment previously, provides insight into the molecular basis of bladder cancer. Our results clearly show that FGFR3 and TP53 mutations are almost mutually exclusive at initial diagnosis (Fig. 1C) and more likely define separate pathways in the development of this disease.

Spruck et al. (5) observed that alterations of chromosome 9 were more frequent in superficial papillary tumors, whereas TP53 mutations were more frequent in CIS and invasive tumors. It was suggested that these genetic differences might account for the markedly different clinical behavior and prognosis of superficial papillary noninvasive tumors and CIS. Indeed, they highlighted that UCCs progress via two distinct pathways. Our data concerning the frequency of FGFR3 mutations provide additional evidence that FGFR3 mutations are associated with low-stage, low-grade superficial papillary tumors, as reported previously in retrospective studies (18). It should also be noted that, in the same study, we found no FGFR3 mutations in the 20 CIS studied (18). Studies on the prognostic value of FGFR3 mutations have generated promising results, indicating that these mutations are associated with favorable disease characteristics, lower rates of recurrence, and progression (19). These mutations may correspond to the so-called “primary abnormalities” (20) involved in the production of low-grade/well-differentiated neoplasms. Such abnormalities alter cellular proliferation, but have little effect on cellular differentiation. FGFR3 mutations might give a growth advantage for cancer cells, but, on the other hand, cell cycle and/or apoptosis mechanisms or genomic stability may still be maintained. Most of the FGFR3 mutations we identified were in tumors that did not harbor TP53 mutations (Fig. 1C). Therefore, genomic stability may have been maintained, because it has been suggested that TP53 mutations destabilize the genome.

The search for key genetic and/or epigenetic alterations should focus on these lesions, as other pathways may also be at work. Other alterations described in bladder cancer should perhaps also be studied in light of FGFR3 and TP53 mutations.

The FGFR3mut/TP53mut genotype was not observed in pTa tumors, but was found in 20% of pT1 and 42% of pT2 tumors. The increasing frequency of this genotype from pTa to pT2-pT4 suggests that this genotype may be associated with more chromosomal alterations. This possibility is consistent with data showing a higher level of allelic imbalances in pT2-pT4 than in pT1 tumors and that tumors in which both TP53 alleles are inactivated have many imbalances (24). Because TP53 is involved in checkpoint control after DNA damage, changes in this gatekeeper gene may lead to the accumulation of additional genetic changes (25).

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The FGFR3mut/Tp53mut genotype was found in only a few tumors: a pTaG2 (3%), a pT1G3 (3%), and a pT2G3 (5%) tumor. Mutations in both genes may result from different oncogenic mechanisms occurring in the same tumor, which is not the general rule, at
least with respect to these two gene mutations. It is possible that these mutations define distinctive, separate pathways that are occasionally interrelated. The identification of this genotype in pTa, pT1, and pT3 tumors suggests that there is an intricate interplay between the effects of the two mutations, according to the surrounding molecular microenvironment, which would finally determine tumor phenotype.

The data presented herein suggest that mutations in the FGFR3 and TP53 genes at initial diagnosis probably define separate molecular pathways in UCCs, possibly leading to two different major clinical phenotypes. Moreover, molecular classification according to FGFR3 and TP53 mutational status might parallel that of TNM and grading classification, constituting an initial step toward a simple practical molecular classification of tumors facilitating the identification of patients with low and high risks of progression. FGFR3 mutations might prove to be a powerful diagnostic tool and an important therapeutic target in UCC. Furthermore, tumor classification according to both gene mutations might serve as landmarks for future searches for other genetic or epigenetic alterations in bladder cancer.

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References

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