A Novel Two-Stage, Transdisciplinary Study Identifies Digoxin as a Possible Drug for Prostate Cancer Treatment
Identification of novel indications for commonly prescribed drugs could accelerate translation of therapies. We investigated whether any clinically used drugs might be useful in treating prostate cancer by coupling an efficient, high-throughput laboratory-based screen and a large prospective cohort study. In stage one, we conducted an in vitro prostate cancer cell cytotoxicity screen of 3,187 compounds. Digoxin emerged as the leading candidate, given its potency in inhibiting proliferation in vitro (the concentration of the drug at which proliferation was inhibited by 50%; mean of 163 nM) and its common use. In stage two, we evaluated the association between the leading candidate drug from stage one and prostate cancer risk in 47,884 men followed up from 1986 through 2006. Regular digoxin users (vs nonusers: relative risk (RR) = 0.76; 95% confidence interval (CI), 0.61–0.95) especially users for ≥10 years (RR = 0.54; 95% CI, 0.37–0.79; P trend < 0.001), had a lower prostate cancer risk. Digoxin was highly potent in inhibiting prostate cancer cell growth in vitro, and its use was associated with a 25% lower prostate cancer risk.

**Significance:** Our two-stage transdisciplinary approach for drug repositioning provides compelling justification for further mechanistic and possibly clinical testing of the leading nonchemotherapy candidate, digoxin, a cardiac glycoside, as a drug for prostate cancer treatment. Perhaps of equal importance, our study illustrates the power of the transdisciplinary approach in translational cancer research. By coupling laboratory and epidemiologic methods and thinking, we reduced the probability of identifying false-positive candidate drugs for the next steps in testing. Cancer Discovery; 1(1). ©2011 AACR.

**Introduction**

In the midst of public debate over how to decrease healthcare expenses, the exorbitant costs of new drug development, now estimated to exceed $1 billion for a drug receiving regulatory approval (1), have come under scrutiny (2). One approach to reducing these costs is to find drugs with established toxicologic, pharmacokinetic, and pharmacodynamic profiles that may be effective for unanticipated indications (3, 4). Rapid laboratory screening of such drugs, followed by focusing on the strengths of existing, well-characterized cohort studies could, with relatively little expense, expedite screening of a library of drugs for inhibition of prostate cancer cell growth. In stage 2, we evaluated the association between the leading nonchemotherapy drug candidate and prostate cancer risk in a large prospective cohort study with long-term follow-up. In this article, we describe our strategy of drug repositioning and present findings that provide compelling justification for further mechanistic and, possibly, clinical testing of the leading nonchemotherapy candidate, digoxin, a cardiac glycoside, as a treatment for prostate cancer.

**Results**

**Stage One**

The primary screen yielded 70 compounds that demonstrated >50% inhibition of LNCaP or PC3 human prostate cancer cell proliferation at a concentration of 5 μM. Of these, 38 compounds are FDA approved or have a history of clinical use internationally, including 20 that are known antineoplastic agents and 18 that are not typically used as such. We focused on these 38 drugs in more detail in the secondary screen (Fig. 1). Among the nonantineoplastic agents, the class of cardiac glycoside Na+/K+ ATPase inhibitors showed the most striking inhibition of prostate cancer cell growth, with 2 of these drugs—digoxin (mean across the 6 prostate cancer cell lines: IC50 = 163 nM; range, 23–255 nM) and lanatoside C (mean IC50 = 408 nM; range, 176–843 nM)—ranking in the top 5 most potent of all nonantineoplastic agents. A third compound from the class of glycoside Na+/K+ ATPases, proscillaridin A, was the most potent of all nonantineoplastic compounds from the primary screen (mean IC50 = 13 nM; range, <5–24 nM) but was not considered further because of the lack of clinical experience with this compound. The potency of this class of drug compounds was comparable with...
that of several known antineoplastic drugs (Fig. 1). Given its potency in inhibiting prostate cancer cell proliferation \textit{in vitro} and its common use, digoxin was the leading candidate to carry forward into stage 2.

**Stage Two**

At baseline in 1986, 2.0% of the men in the Health Professionals Follow-up Study, an ongoing prospective cohort study on risk factors for cancer and other chronic diseases in men aged 40 to 75 years in 1986 (5), reported regularly using digoxin. Digoxin users tended to be older, were more likely to be white, had a higher body mass index (BMI), were less likely to have a family history of prostate cancer, had less vigorous physical activity, were more likely to be diabetic, and were more likely to regularly use cholesterol-lowering drugs, aspirin, and other cardiovascular drugs (Table 1). Users did not differ notably from nonusers in terms of food and nutrient intake (Table 1). Men who used digoxin to treat arrhythmia, congestive heart failure, or both conditions differed in their age-standardized characteristics (Table 1). The age-standardized prevalence of ever having had a screening prostate-specific antigen (PSA) test by 1994 (the first year we asked the men to report on PSA screening), was 47.7% in nonusers and 56.3%, 23.3%, and 46.3% in users whose indications were arrhythmia, congestive heart failure, or both, respectively.

Compared with nonusers, men who regularly used digoxin at baseline had a 25% lower risk of prostate cancer (Table 2). Current digoxin users and men who had ever used digoxin during follow-up had a lower risk of prostate cancer than did men who were not currently using the drug or who had never used the drug (Table 2); the association was similar when restricting to follow-up time during which digoxin information was not missing \((R R = 0.73; 95\% \text{ CI}, 0.57–0.94)\). Risk decreased with increasing duration of digoxin use during the study period, compared with never use \((P_{\text{trend}} < 0.001)\); the RR for \(\geq 10\) years of use was 0.54 \([95\% \text{ confidence interval (CI)}, 0.37–0.79; Table 2]\).

Additionally adjusting for use of other medications did not appreciably change the results (Table 2). The associations for current use of other cardiovascular drugs and prostate...
The inverse associations for regular use of digoxin at baseline and current use during follow-up were present for organ-confined, advanced stage or lethal disease, and lower and higher Gleason sum disease (Table 3). Long duration of use during the study period was inversely associated with organ-confined and advanced or lethal disease (Fig. 2) as well as with lower (≥10 years of use: RR = 0.54; 95% CI, 0.30–0.97; P trend = 0.009). The associations appeared inverse but were not statistically significant for lethal, fatal, and very high-grade prostate cancer, endpoints for which sample sizes were smaller (Table 3 and data not shown). For both regular use at baseline and current use, inverse associations were stronger for cases that were organ confined but higher grade (n = 1,285; RR = 0.48; 95% CI, 0.25–0.89 and RR = 0.64; 95% CI, 0.45–0.89, respectively) than for cases that were organ confined but lower grade (n = 1,962; RR = 0.73; 95% CI, 0.48–1.09 and RR = 0.72; 95% CI, 0.55–0.94, respectively).

The inverse association between current digoxin use and prostate cancer risk was suggested for each current indication.
Table 2. Association between digoxin use and total prostate cancer

|                                      | Prostate cancer cases (n) | Person-years at risk | RR (95% CI) | Age-adjusted | Multivariable-adjusted | Additionally adjusted for use of other medications |
|--------------------------------------|---------------------------|----------------------|--------------|--------------|------------------------|--------------------------------------------------|
| Regular digoxin use at baseline      |                           |                      |              |              |                        |                                                  |
| No                                   | 4,923                     | 804,663              | 1.00 (ref)   | 1.00 (ref)   | 1.00 (ref)             |                                                  |
| Yes                                  | 79                        | 11,001               | 0.74 (0.59–0.93) | 0.76 (0.61–0.95) | 0.76 (0.60–0.95)       |                                                  |
| Current digoxin use during follow-up |                           |                      |              |              |                        |                                                  |
| No                                   | 4,827                     | 793,305              | 1.00 (ref)   | 1.00 (ref)   | 1.00 (ref)             |                                                  |
| Yes                                  | 175                       | 22,359               | 0.76 (0.65–0.88) | 0.78 (0.67–0.90) | 0.77 (0.66–0.90)       |                                                  |
| Never/ever use of digoxin during follow-up |                        |                      |              |              |                        |                                                  |
| Never                               | 4,759                     | 786,326              | 1.00 (ref)   | 1.00 (ref)   | 1.00 (ref)             |                                                  |
| Ever                                 | 243                       | 29,338               | 0.81 (0.71–0.92) | 0.83 (0.72–0.94) | 0.82 (0.72–0.94)       |                                                  |
| Duration of digoxin use (y)          |                           |                      |              |              |                        |                                                  |
| Never                                | 4,759                     | 786,326              | 1.00 (ref)   | 1.00 (ref)   | 1.00 (ref)             |                                                  |
| <5                                   | 125                       | 14,736               | 0.84 (0.71–1.01) | 0.87 (0.73–1.04) | 0.87 (0.72–1.04)       | <0.001                                           |
| 5–9.9                                | 90                        | 9,521                | 0.85 (0.69–1.05) | 0.87 (0.70–1.07) | 0.86 (0.70–1.07)       | <0.001                                           |
| ≥10                                  | 28                        | 5,082                | 0.53 (0.36–0.77) | 0.54 (0.37–0.79) | 0.54 (0.37–0.79)       | <0.001                                           |
| P trend                              |                           |                      |              |              |                        |                                                  |

NOTE: Data from 47,884 men in the Health Professionals Follow-up Study, 1986–2006.
Abbreviation: ref, reference.

* Adjusted for calendar year, age, race, current body mass index (BMI; kg/m²), body mass index at age 21, height (inches), first-degree family history of prostate cancer, pack-years smoked in the past 10 years, vigorous physical activity [metabolic equivalent (MET)–hours/week], diabetes mellitus, daily intake of energy (kcal/day), energy-adjusted α-linolenic acid (g/d), energy-adjusted calcium (mg/d), energy-adjusted magnesium (mg/d), energy-adjusted iron (mg/d), energy-adjusted zinc (mg/d), energy-adjusted vitamin E (mg/d), vitamin C (mg/d), and use of a vitamin E supplement.

** Adjusted for use of cholesterol-lowering drugs, aspirin, ibuprofen, furosemide diuretics, other diuretics, beta blockers, calcium channel blockers, other antihypertensives, and antiarrhythmics.

for use—arrhythmia (RR = 0.75; 95% CI, 0.62–0.91), congestive heart failure (RR = 0.70; 95% CI, 0.38–1.26), or both (RR = 0.86; 95% CI, 0.65–1.15)—including after adjustment for use of other medications (data not shown). Because patients with atrial fibrillation, the most common type of arrhythmia, are sometimes prescribed anticoagulants to reduce stroke risk and men taking an anticoagulant might be less likely to undergo biopsy after an elevated PSA level, we ran subanalyses beginning follow-up in 1996, the first year we asked about warfarin (e.g., Coumadin) use: RR of total prostate cancer for current digoxin use during follow-up was 0.77 (95% CI, 0.61–0.97) and was 0.70 (95% CI, 0.51–0.96) after excluding warfarin users.

To reduce the potential for bias that might result from differences between digoxin users and nonusers in intensity of health care, we ran several subanalyses. When we restricted the cohort to men (n = 9,576; 1,157 cases) who at baseline used at least 1 medication for cardiovascular indications (except aspirin), digoxin use (current use during follow-up: age-adjusted RR = 0.67; 95% CI, 0.54–0.83) was inversely associated with prostate cancer. The results were similar when restricting the cohort to men (n = 6,700; 761 cases) using blood pressure medications at baseline (RR = 0.70; 95% CI, 0.53–0.92). Beginning follow-up in 1994, the first time we asked the men to report on PSA screening, (which was concurrent with the routine use of PSA for prostate cancer screening in the United States), the RR of total prostate cancer for current digoxin use during follow-up was 0.78 (95% CI, 0.63–0.96). The results were unchanged when we restricted the analysis to men only after a first screening PSA test without a prostate cancer diagnosis was reported on a biennial follow-up questionnaire (RR = 0.76; 95% CI, 0.61–0.95).

The inverse association between current digoxin use during follow-up and prostate cancer did not differ between lean and overweight/obese men, smokers and nonsmokers, men with high and low vigorous physical activity, men with and without diabetes, and men who did and did not regularly use cholesterol-lowering drugs or aspirin (all P interaction >0.25). The inverse association was present when restricting to white men (RR = 0.76; 95% CI, 0.64–0.89) and older men (RR = 0.78; 95% CI, 0.67–0.91). However, the magnitude of the inverse association differed by family history (P interaction = 0.02); among men without a history (156 cases in 19,870 person-years in current digoxin users and 3,837 cases in 698,425 person-years in nonusers) the RR was 0.84 (95% CI, 0.65–0.99), and among those with a history (19 cases in 2,494 person-years in digoxin users and 990 cases in 95,052 person-years in nonusers) the RR was 0.48 (95% CI, 0.30–0.76).
Digoxin and Prostate Cancer

**Table 3. Association between digoxin use and prostate cancer by disease aggressiveness**

|                      | Regular digoxin use at baseline* | Current digoxin use during follow-up* |
|----------------------|----------------------------------|---------------------------------------|
|                      | RR (95% CI)                       | RR (95% CI)                           |
|                      | Prostate cancer cases (n)^b       | Multivariable-adjusted^c               | Prostate cancer cases (n)^b       | Multivariable-adjusted^c               |
|                      |                                   | Additionally adjusted for use of other medications^d |                                   |                                   |
|器官 confined        |                                  |                                       |                                   |                                       |
| No                   | 3,465 (1.00 (ref))                | 1.00 (ref)                            | 3,402 (1.00 (ref))                | 1.00 (ref)                            |
|                      | (0.52–0.94)                       | (0.52–0.95)                           | (0.59–0.87)                       | (0.59–0.88)                           |
| Yes                  | 44                               | 0.70                                  | 107                              | 0.72                                  | 0.73                                  |
|                      | (0.36–0.97)                       | (0.36–0.99)                           | (0.54–1.06)                       | (0.53–1.07)                           |
| Advanced or lethal   |                                  |                                       |                                   |                                       |
| No                   | 838                              | 1.00 (ref)                            | 819                               | 1.00 (ref)                            |
|                      | (0.36–0.97)                       | (0.36–0.99)                           | (0.54–1.06)                       | (0.53–1.07)                           |
| Yes                  | 16                               | 0.59                                  | 35                               | 0.75                                  | 0.76                                  |
|                      | (0.40–1.12)                       | (0.40–1.14)                           | (0.58–1.20)                       | (0.56–1.19)                           |
| Lethal               |                                  |                                       |                                   |                                       |
| No                   | 617                              | 1.00 (ref)                            | 601                               | 1.00 (ref)                            |
|                      | (0.46–1.30)                       | (0.47–1.34)                           | (0.63–1.35)                       | (0.63–1.38)                           |
| Yes                  | 15                               | 0.67                                  | 31                               | 0.83                                  | 0.82                                  |
|                      | (0.40–1.11)                       | (0.46–1.01)                           | (0.54–0.89)                       | (0.53–0.88)                           |
| Fatal                |                                  |                                       |                                   |                                       |
| No                   | 513                              | 1.00 (ref)                            | 499                               | 1.00 (ref)                            |
|                      | (0.46–1.30)                       | (0.47–1.34)                           | (0.63–1.35)                       | (0.63–1.38)                           |
| Yes                  | 15                               | 0.78                                  | 29                               | 0.92                                  | 0.93                                  |
|                      | (0.46–1.10)                       | (0.46–1.01)                           | (0.63–1.01)                       | (0.63–1.01)                           |
| Lower grade (Gleason sum <7) |                  |                                       |                                   |                                       |
| No                   | 2,178                            | 1.00 (ref)                            | 2,142                             | 1.00 (ref)                            |
|                      | (0.47–1.01)                       | (0.46–1.01)                           | (0.54–0.89)                       | (0.53–0.88)                           |
| Yes                  | 27                               | 0.69                                  | 63                               | 0.69                                  | 0.68                                  |
|                      | (0.47–1.01)                       | (0.46–1.01)                           | (0.54–0.89)                       | (0.53–0.88)                           |
| Higher grade (Gleason sum ≥ 7) |                  |                                       |                                   |                                       |
| No                   | 1,871                            | 1.00 (ref)                            | 1,834                             | 1.00 (ref)                            |
|                      | (0.42–0.99)                       | (0.43–1.02)                           | (0.56–0.94)                       | (0.59–1.00)                           |
| Yes                  | 22                               | 0.65                                  | 59                               | 0.73                                  | 0.76                                  |
|                      | (0.35–1.44)                       | (0.36–1.51)                           | (0.50–1.24)                       | (0.51–1.29)                           |
| Very high grade (Gleason sum ≥ 8) |                 |                                       |                                   |                                       |
| No                   | 493                              | 1.00 (ref)                            | 481                               | 1.00 (ref)                            |
|                      | (0.42–0.99)                       | (0.43–1.02)                           | (0.56–0.94)                       | (0.59–1.00)                           |
| Yes                  | 8                                | 0.71                                  | 20                               | 0.79                                  | 0.81                                  |
|                      | (0.35–1.44)                       | (0.36–1.51)                           | (0.50–1.24)                       | (0.51–1.29)                           |

NOTE: Data from 47,884 men in the Health Professionals Follow-up Study, 1986–2006.

*Reference (ref): no use at baseline for regular use at baseline; not current use for current use during follow-up.

^Adjusted for calendar year, age, race, current body mass index (BMI; kg/m^2^), body mass index at age 21, height (inches), first-degree family history of prostate cancer, pack-years smoked in the past 10 years, vigorous physical activity [metabolic equivalent (MET)–hours/week], diabetes mellitus, daily intake of energy (kcal/d), energy-adjusted α-linolenic acid (g/d), energy-adjusted calcium (mg/d), bacon (servings/d), fish (servings/d), tomato sauce (servings/d), and use of a vitamin E supplement.

^Adjusted for use of cholesterol-lowering drugs, aspirin, ibuprofen, furosemide diuretics, other diuretics, beta blockers, calcium channel blockers, other antihypertensives, and antiarrhythmics.

**DISCUSSION**

Using a transdisciplinary, 2-stage approach, we first identified drugs that inhibited the proliferation of androgen-dependent and -independent prostate cancer cell lines. Digoxin, a cardiac glycoside derived from foxglove, was the leading candidate for further study because of its strong antiproliferative activity and long history of common use in treating congestive heart failure and arrhythmia. In the second stage, in a large prospective cohort study, we observed that men who used digoxin had a 25% lower risk of prostate cancer, including disease that was potentially lethal, than men who did not use digoxin. This inverse
Figure 2. Association between duration of digoxin use during the study period and prostate cancer risk in 47,884 men in the Health Professionals Follow-up Study, 1986–2006. Ref, reference.

In general, the inverse association was comparable in magnitude between strata of prostate cancer risk and protective factors, with the exception of family history. The inverse association between digoxin use and prostate cancer was stronger in men with a family history than without. We stratified by family because these men may be enriched with a genetic predisposition or may have a different screening pattern than other men. Explanations should be sought for this observation.

The potential for cardiac glycosides as cancer therapeutic agents has been discussed previously (6, 7). The mechanisms by which digoxin may influence growth of prostate cancer cells are not established, but some leads exist. Digoxin was found to cause an influx of intracellular calcium into prostate cancer cells, triggering apoptosis (8, 9), perhaps through effects on the Cdk5/p25 pathway (3). Digoxin and ouabain, which are structurally similar, activated Src/MAPK signaling, resulting in inhibition of p53 synthesis, suggesting that cardiac glycosides may be useful in treating cancers with gain-of-function p53 mutations (10). Digoxin inhibited hypoxia-inducible factor 1 (HIF-1; ref 11), which is well recognized for its role in cancer development through its influence on VEGF and, consequently, angiogenesis. However, the antiproliferative effects of the drug also acted independently of HIF-1 (11). Gynecomastia is reported to be a side effect of digoxin, possibly caused by shared structure with steroids including estrogen (12); estrogen has long been used to treat advanced prostate cancer. Interestingly, ouabain could selectively inhibit proliferation of oncogene-transformed cells compared with untransformed cells (13, 14), suggesting that a synthetic lethality paradigm may allow sparing of normal cells despite cytotoxicity of oncogene-transformed malignant cells. Whether the same differential effect would be observed for digoxin and prostate cancer cells with their array of oncogenic alterations remains to be assessed, but these findings suggest the intriguing possibility that a synthetic lethality paradigm (15) could be exploited in the development of digoxin and other cardiac glycosides as prostate cancer drugs. Finally, in vivo, digoxin reduced distant metastases in a mouse model of metastatic prostate cancer, an effect attributed to digoxin’s inhibition of Na+/K+ ATPase (16). For the treatment of congestive heart failure and arrhythmia, digoxin acts by inhibiting Na+/K+ ATPases in cardiac myocytes. That multiple cardiac glycosides showed potent inhibition of the growth of both androgen-dependent and -independent prostate cancer cell lines in our screen provides further evidence that inhibition of these enzymes may, at least in part, underlie digoxin’s effects on prostate cancer and suggests that the Na+/K+ ATPases may be a relevant target for prostate cancer treatment. Nevertheless, studies are needed to determine whether any of these or other mechanisms explains digoxin’s anti-prostate cancer activity in both stages of our study.

The only 2 prior epidemiologic studies reporting on digitalis-derived drugs and prostate cancer, one a surveillance study of drugs prescribed in a California health maintenance organization (17) and the other a record linkage study in Norway (18), reported statistically significant positive associations (RR > 1). The California study used pharmacy records from 1969 to 1973 to evaluate 215 drugs in association with 56 cancer sites, with follow-up through 1984 (17). The Norwegian study was conducted among cardiac patients who had recently started taking digitoxin, a digitalis-derived drug, and their cancer rates were compared with age-specific population rates (18). Unlike our prospective cohort study, these studies were limited by the inability to address potential observation bias and confounding resulting from differences in characteristics of users and nonusers of these drugs. Indeed, in the Norwegian study, the authors reported that the prostate cancer finding was likely to be due to bias because men who began using digitoxin had a higher risk of cancer before beginning to take the drug (18). No consistent pattern is apparent for cardiac glycosides and other cancers in the few epidemiologic studies that have been conducted (17–23). Additional large epidemiologic studies are needed that can evaluate duration of digoxin use and potentially confounding and modifying factors.
Digoxin and Prostate Cancer

Although our findings from stage 2 suggest that digoxin might reduce the risk of developing prostate cancer or might treat yet undetected prostate cancer, we do not suggest that
digoxin be tested for chemoprevention at this time. Digoxin’s therapeutic range of 0.5 to 2.5 nM for cardiac indications is narrow (24). Even though not strictly comparable because it is unknown to what extent digoxin accumulates in prostate tissue, the IC50 of digoxin in our screen was 10 times the therapeutic range in blood. However, we observed in stage 2 that digoxin as prescribed was inversely associated with prostate cancer risk, suggesting that the therapeutic range for cardiac indications may be sufficient. If future investigations confirm that digoxin may inhibit or delay prostate cancer, then the development of related molecules with lower IC50s or drug delivery systems targeting the prostate might be warranted.

Our study has several strengths that suggest our findings are not due to bias or chance. We used a 2-stage approach in which the top candidate from stage 1 was confirmed in stage 2. Stage 1 used both androgen-dependent and androgen-independent prostate cancer cell lines. Stage 2 used a prospective design, included 5,002 cases, and had rich information on risk factors. In stage 2, we conducted subanalyses diminishing the possibility that differential intensity of care, including PSA screening and diagnostic workup, between digoxin users and nonusers could explain the inverse association. The specificity of the association for digoxin, and not for digoxin users and nonusers could explain the inverse association. The specificity of the association for digoxin, and not other cardiovascular drugs, also helps rule out bias or confounding as an explanation for our findings.

We were unable to study the other nonantineoplastic top candidate drugs identified in stage 1 because those drugs are not commonly used or were not assessed in the stage 2 cohort. However, some members of our study group are pursuing some of the other top candidates from the stage 1 screen, such as disulfiram, in mechanistic, preclinical, and early clinical studies. The stage 1 assay was based on an in vitro system using 6 prostate cancer cell lines, which may not have yielded IC50s that reflect the circulating concentration needed to prevent or treat prostate cancer. Because prevalence of digoxin use is low and the number of men who have died of prostate cancer is small in the Health Professionals Follow-up Study, in stage 2 we were unable to study men who already had a prostate cancer diagnosis to determine whether digoxin users have better survival than do nonusers. This information is needed to support the testing of digoxin as a prostate cancer drug. The stage 2 analysis was based on self-reported digoxin use; however, any inaccuracy in the reports by these health professionals prior to their prostate cancer diagnosis is unlikely to explain the inverse association that we observed. We assumed continued use/nonuse when drug use information was missing in a subsequent follow-up time period; a sensitivity analysis supported that this assumption did not distort the results. We did not collect information on use of the drug prior to baseline or on the dose taken.

In summary, with an eye toward translation, our transdisciplinary team identified that digoxin was highly potent in inhibiting prostate cancer cell growth in vitro and that its use was associated with a 25% lower risk of prostate cancer. The mechanism by which digoxin may influence the development or progression of prostate cancer is uncertain but may be related to Na+/K+ ATPase inhibition. Our study illustrates the power of the transdisciplinary approach to translational cancer research. By coupling laboratory and epidemiologic methods and thinking, we reduced the probability of identifying false-positive candidate drugs for the next steps in testing. Our work should motivate additional basic science, epidemiologic, and translational research on the potential of digoxin or related molecules in the treatment of prostate cancer.

METHODS

Stage One: In vitro Screen for Drugs with Prostate Cancer Cell Cytotoxicity

Cell lines LNCaP, PC-3, CWR22Rv1, and DU-145 cell lines were obtained from the American Type Culture Collection >9 years ago. LAPC-4 and C4-2B cell lines were provided by Dr. John T. Isaacs (Johns Hopkins University, Baltimore, Maryland) in 2002. Authentication of these cell lines is routinely carried out by the Powerplex 2.1 STR genotyping assay (Promega Corporation) and was last performed at the close of these studies in late 2009.

Primary in vitro screen A growth-inhibition screen of all compounds from the Johns Hopkins Drug Library (JHDL), which includes 1,811 (57%) FDA-approved drugs among 3,187 total compounds (28% of all known drugs worldwide), was conducted using 2 commonly studied human prostate cancer cell lines, androgen-dependent LNCaP and androgen-independent PC3, propagated using previously described methods (25) in 96-well plates. Cells were treated with JHDL compounds, 1 per well, at a final concentration of 5 μM for 24 hours, and then treated with 1 μCi [3H]-thymidine for an additional 6 hours. Cells were harvested, and the amount of incorporated [3H]-thymidine was counted using the MicroBeta plate reader, providing a measure of DNA synthesis and cell proliferation (4).

Secondary in vitro screen Those compounds that inhibited LNCaP or PC3 cell proliferation by >50% were further characterized by determining the concentration resulting in IC50 in LNCaP, PC3, and 4 additional human prostate cancer cell lines; androgen-dependent LAPC4; and androgen-independent C42B, CWR22Rv1, and DU145. Digoxin emerged as one of the most potent hits for a nonchemotherapy drug (see Results). We carried digoxin forward for testing in stage 2 of this study. Other nonantineoplastic drugs passing the primary screen were not prioritized for study in stage 2 because i) participants in the cohort were not asked to report on their use; ii) the association between their use and prostate cancer risk had already been assessed in the cohort (e.g., statin drugs; ref. 26); and/or iii) they failed to show high potency (mean IC50 ≥ 10 μM) in the secondary in vitro screen.

Stage Two: Epidemiologic Study of the Leading Candidate Drug and Prostate Cancer Risk

Study population We included in the analysis participants in the Health Professionals Follow-up Study. Details have been reported previously (5). Briefly, we asked the men to complete a mailed questionnaire on their medical history, including use of medications, and lifestyle factors at baseline and then again every 2 years. We also asked them to report on their diet at baseline and then again every 4 years. We excluded men who had a cancer diagnosis (except nonmelanoma skin cancer) before baseline in 1986 (4.0%), returned an invalid food frequency questionnaire in 1986 (3.0%), or withdrew or were otherwise ineligible (0.2%), leaving 47,884 men. The Institutional Review Boards at the Harvard School of Public Health and the Johns Hopkins Bloomberg School of Public Health approved this study.
**Assessment of digoxin use and indication for use** On the baseline questionnaire, we asked the men to indicate “Current Medications (mark if used regularly).” On the follow-up questionnaires, we stated, “Please mark if you are currently using any of the following medications.” A list of medications was provided, including “Digoxin (e.g., Lanoxin).” Duration of use during the study period was estimated by summing use across the 2-year questionnaire periods. No information was available on duration of use prior to baseline; we assumed 2 years. Dose was not ascertained. We classified digoxin users by indication—arrhythmia, congestive heart failure, or both—which we inferred from reported diagnoses and other medications used.

**Ascertainment and classification of prostate cancer cases** Ascertainment of prostate cancer diagnoses and follow-up for recurrence and death were described previously (5, 27). Briefly, on each follow-up questionnaire, we asked the men to report a diagnosis of prostate cancer. We were able to obtain medical records and pathology reports pertaining to the diagnosis and treatment of 94.5% of the men who reported a prostate cancer diagnosis or for whom prostate cancer was mentioned on the death certificate. From baseline through January 31, 2006, we ascertained 5,002 cases of incident non-T1a prostate cancer in 815,664 person-years. Stage T1a cases (n = 227) were excluded to reduce the possibility of detection bias due to differential rates of surgery for benign prostatic hyperplasia. We categorized cases as organ-confined (n = 3,509; T1b to T2b and N0M0) or as advanced stage (≥T3b, N+; or M + at diagnosis, progression to metastasis, or death during follow-up; n = 854). Of those with advanced-stage or lethal disease, 528 died of prostate cancer. We abstracted the Gleason sum from the prostatectomy pathology reports for men who were surgically treated and for the biopsy otherwise and classified the cases as lower (n = 2,205; Gleason sum, <7) and higher (n = 1,893; Gleason sum, ≥7) grade. Of the latter, 501 had a Gleason sum ≥8 (“very high grade”).

**Statistical analysis** We calculated age-standardized means and proportions for demographic and other factors by regular digoxin use and by indication for use at baseline. We calculated age-adjusted and multivariable-adjusted RRa and 95% CIs using Cox proportional hazards regression. Time at risk was accumulated beginning at the month the men returned the baseline questionnaire until the month of diagnosis of prostate cancer, month of death from other causes, or the end of follow-up on January 31, 2006. The proportional hazards assumption was met. We first evaluated whether regular digoxin use at baseline (reference: nonuse at baseline) was associated with prostate cancer risk. Next, we updated digoxin use to evaluate whether current use (reference: never or former use) or ever use (reference: never use) during follow-up was associated with risk. When digoxin use was missing, information from the prior questionnaire was carried forward and a term was included in the model for whether use was imputed: 3,186 person-years of 22,359 person-years of current use were imputed, and 169,089 person-years of 793,305 person-years of nonuse were imputed. In a sensitivity analysis, we excluded follow-up time with missing information on digoxin use. Finally, we evaluated the association for updated duration of use during the study period by entering into the model 3 indicator variables: <5, 5 to 9.9, and ≥10 years of use (reference: never use). To test for trend, we entered into the model a continuous duration term and evaluated its coefficient using the Wald test. We stratified by age and calendar year and adjusted for factors that have been associated with prostate cancer risk previously in the cohort. We further adjusted for use of other medications that a priori were known or hypothesized to be associated with digoxin use: cholesterol-lowering drugs; aspirin; ibuprofen; furosemide diuretics; other diuretics; beta blockers; calcium channel blockers; other antihypertensives; including angiotensin-converting enzyme inhibitors; and antiarrhythmics.

To assess whether the association differed by prostate cancer risk factors—family history of prostate cancer, current BMI (<25, ≥25 kg/m2), cigarette smoking in the past 10 years (yes, no), vigorous exercise (high, low), diabetes (yes, no), cholesterol-lowering drug use (yes, no), and aspirin use (yes, no)—we ran stratified models and tested interaction terms using the Wald test. We also conducted subanalyses restricting to whites and older men because prescription patterns and/or PSA screening behaviors may differ by race and age. All statistical tests were 2-sided, with P < 0.05 considered statistically significant. All analyses were performed using SAS release 9.1 (SAS Institute).

**Disclosure of Potential Conflicts of Interest**
No potential conflicts of interest were disclosed.

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