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# Cost-Effectiveness of Prophylactic Surgery for Duodenal Cancer in Familial Adenomatous Polyposis

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## Abstract

Background: **Duodenal cancer is the leading cause of cancer death in familial adenomatous polyposis after colorectal cancer. The lifetime risk for developing duodenal cancer is 4% to 10%. Current treatment guidelines recommend endoscopic surveillance with a prophylactic pancreaticoduodenectomy in advanced duodenal polyposis, defined using the Spigelman staging system. Because no clinical trials have assessed this recommendation, a modeling approach was used to evaluate the cost-effectiveness of various treatment strategies.**

Methods: **A Markov model was constructed to estimate the life expectancy and cost of three different strategies: pancreaticoduodenectomy at Spigelman stage III, pancreaticoduodenectomy at Spigelman stage IV, and pancreaticoduodenectomy at cancer diagnosis. A cohort of 30-year-old familial adenomatous polyposis patients with total colectomies was simulated until age 80. The analysis was from a societal perspective. Extensive sensitivity analysis was performed to assess the impact of model uncertainty on results.**

Results: **At all stages of polyposis and all ages <80 years, prophylactic surgery at Spigelman stage IV resulted in the greatest life expectancy. Surgery at stage IV was more effective and more expensive than surgery at cancer diagnosis, with an incremental cost of $3,200 per quality-adjusted life year gained. Surgery at stage III was not a viable option. The results were robust to wide variation in model parameters but were sensitive to the post-pancreaticoduodenectomy quality of life score.**

Conclusions: **Prophylactic pancreaticoduodenectomy at stage IV duodenal polyposis in familial adenomatous polyposis is a cost-effective approach that results in greater life expectancy than surgery at either stage III or cancer diagnosis.** (Cancer Epidemiol Biomarkers Prev 2009;18(10):2677–84)

## Introduction

Familial adenomatous polyposis is an autosomal dominant disease resulting from a defect in the *adenomatous polyposis coli* gene (1). Hundreds of premalignant adenomas develop in the colon and rectum, conferring an almost 100% lifetime risk for colorectal cancer. A prophylactic colectomy is recommended in early adulthood to prevent the development of colorectal cancer.

Familial adenomatous polyposis is also associated with a number of extracolonic manifestations, including osteomas, epidermoid cysts, dental abnormalities, hypertrophy of the retinal pigment epithelium, desmoid tumors, adenomas of the upper gastrointestinal tract, and a number of malignancies (2). One of the most important of these is duodenal polyposis (3). Individuals with familial adenomatous polyposis have nearly a 100% lifetime risk of developing duodenal polyposis (4, 5). Duodenal adenomas have a similar biology to colorectal adenomas and are thought to progress to cancer through an analogous adenoma-carcinoma sequence (2, 3). Although the risk for developing duodenal cancer with familial adenomatous polyposis is 100 to 330 times that without familial adenomatous polyposis (6, 7), the absolute lifetime risk is 4% to 10% (8, 9). Nevertheless, duodenal cancer is the second leading cause of cancer death in individuals with familial adenomatous polyposis after colorectal cancer (10-14).

The degree of duodenal polyposis can be tracked by endoscopy with biopsy and quantified using the Spigelman staging scale (15). The Spigelman staging scale gives a separate score for the number, size, histology, and degree of dysplasia of the duodenal polyps. The sum of these scores is converted into a stage rating from 0 to IV, with stage 0 corresponding to no polyposis and stage IV corresponding to severe polyposis. The risk of developing cancer increases with increasing Spigelman stage (16). Currently, endoscopic screening is recommended every 5 years to 6 months, with the frequency depending on the Spigelman stage (16, 17).

The most effective intervention for reducing the risk of developing duodenal cancer is a prophylactic pancreaticoduodenectomy. Pancreaticoduodenectomy is a major operation with substantial morbidity and mortality. When deciding whether or not to undergo prophylactic surgery, patients with familial adenomatous polyposis and duodenal polyposis must balance potential risks and benefits.

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If surgery is pursued too aggressively, the patient risks surgical mortality and morbidity when cancer might not have developed. If surgery is not pursued aggressively enough, the patient risks the development of a preventable cancer.

Although the overall prevalence of familial adenomatous polyposis, estimated at 6,000 to 7,400 families in the United States, makes duodenal polyposis a rare condition, the significant morbidity these individuals face and their high rate of resource use make management of this condition a greater public health concern than might first be thought (18). To date, no clinical trial has been done to determine at what degree of polyposis, if any, prophylactic surgery should be recommended. Such a trial would be difficult to perform because duodenal cancer in familial adenomatous polyposis is a relatively rare disorder with a slow pathogenesis. We constructed a decision-analytic model to synthesize data from observational studies and used the model to evaluate the health and economic outcomes associated with three surgical management strategies for patients with familial adenomatous polyposis and duodenal polyposis.

## Materials and Methods

**Overview.** We constructed a Markov cohort model to evaluate the costs, life years, and quality-adjusted life years associated with three surgical management strategies for duodenal polyposis in familial adenomatous polyposis. The model simulates the natural history of duodenal polyposis and routine endoscopic screening in a cohort of 30-year-old individuals with familial adenomatous polyposis. Superimposed on this model is a mechanism of surgical intervention that can interrupt the natural history.

Cost-effectiveness analysis was performed, with the incremental cost-effectiveness ratio calculated as the change in total cost over the change in total effectiveness between two strategies. If a strategy is more costly and less effective than another strategy, the first strategy is said to dominate the second strategy. Although there is no explicit willingness-to-pay threshold for medical interventions in the United States, we used a threshold of $80,000 per quality-adjusted life year to determine cost-effectiveness. This represents the incremental cost-effectiveness ratio for hemodialysis, a widely cited benchmark for willingness-to-pay decisions, adjusted to 2007 U.S. dollars (19).

Our analysis followed the guidelines of the Panel on Cost-effectiveness in Health in Medicine (20). The analysis was performed from a societal perspective. All future costs and quality-adjusted life years were discounted at a 3% annual rate, and costs were expressed in 2007 U.S. dollars. Reported life years were undiscounted. The model was constructed using commercially available software (TreeAge Pro 2008 Suite Release 1.2, Treeage Software).

**Model Design.** The model structure is shown in Fig. 1. The initial cohort consisted of individuals with familial adenomatous polyposis at age 30 who had undergone a total colectomy and were considered to be at no risk for developing colorectal cancer. During each (1 mo) cycle of the model, patients could remain in the same disease state or progress to a more advanced disease state. The clinically perceived disease state was based on endoscopic and pathologic findings and was tracked separately from the underlying biological state. The perceived polyposis state advanced only with endoscopic screening. All individuals in the model underwent endoscopic screening with biopsy as per current screening recommendations (16, 17).

For the purposes of the model, the onset of cancer was defined as the time when cancer could be detected by endoscopy with biopsy. Once cancer developed, patients could present symptomatically to undergo an endoscopy in addition to their regularly scheduled endoscopic screening. All patients diagnosed with duodenal cancer received standard therapeutic and palliative care (21). The model was run until each individual died or reached age 80.

Three management strategies were evaluated: (*a*) pancreaticoduodenectomy upon diagnosis with stage III polyposis, (*b*) pancreaticoduodenectomy upon diagnosis with stage IV polyposis, and (*c*) pancreaticoduodenectomy only upon cancer diagnosis.

**Model Inputs.** Model input parameters and the values used for the base-case scenario and sensitivity analysis are summarized in Table 1. Estimates for the base-case scenario were derived from the literature.

*Disease Progression.* We derived estimates for the stage distribution at age 30 and the transition probabilities between different stages of polyposis and cancer from the published literature. Studies estimating the cumulative risk for duodenal cancer range from a low of 3% to 4% at age 70 to a high of 10% at age 60 (8, 9). We calibrated

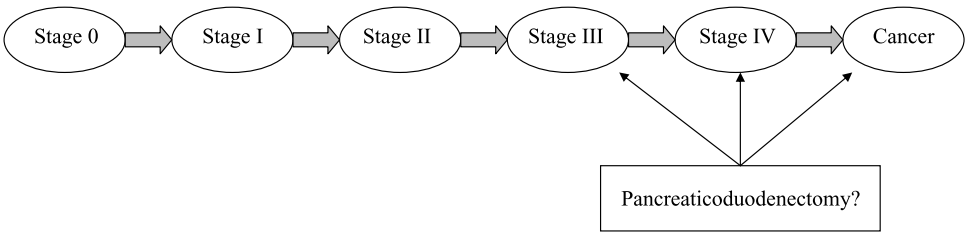


**Figure 1.** Model schematic. The model begins with a cohort of age 30 individuals with familial adenomatous polyposis and a total colectomy. They progress linearly through stages until they die or reach age 80. Perceived disease state is clinically tracked by endoscopies with biopsy, whereas the true disease state corresponds to the underlying biological disease progression. Surgery can be offered at stage III, stage IV, or cancer, depending on the management strategy. Individuals may die from surgical complications, duodenal cancer, or from other causes. Stages are based on Spigelman criteria.



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**Table 1. Model inputs and ranges for sensitivity analysis**

| Variable | Base case | Sensitivity analysis range | Reference(s) |
|---|---|---|---|
| Polyposis distribution and progression | | | |
| Stage distribution at age 30 (%) | | | See Methods |
| Stage 0 | 80 | 100/60 | |
| Stage I | 11 | 0/18 | |
| Stage II | 9 | 0/10 | |
| Stage III | 0 | 0/10 | |
| Stage IV | 0 | 0/2 | |
| Cancer | 0 | 0/0 | |
| Transition probabilities per month (%) | | | |
| Stages 0 to IV | 0.46 | 50-200% × BC | See Methods |
| Stage IV to cancer | 0.37 | 50-200% × BC | |
| Endoscopy characteristics | | | |
| Screening frequency | | | (16, 17) |
| Stage 0 | 5 y | | |
| Stage I | 5 y | | |
| Stage II | 3 y | | |
| Stage III | 1 y | | |
| Stage IV | 6 mo | | |
| Complication rate | 1.6:100,000 | 50-200% × BC | (27, 28) |
| False-negative rate (%) | 29 | 0-60 | (26) |
| Symptomatic cancer presentation (%) | 50 | 0-100 | (23, 29) |
| PD characteristics | | | |
| Eligible for curative surgery (%), age | | 25-75 | (30) |
| 30-39 | 50 | | |
| 40-49 | 66 | | |
| 50-59 | 64 | | |
| 60-69 | 60 | | |
| 70-79 | 55 | | |
| 80+ | 33 | | |
| Perioperative mortality (%) | 5 | 0-10 | (32, 33) |
| Cancer mortality per month | | | |
| Age related | 1.6 × U.S. life table | 1-2.1 × U.S. life table | (12, 35) |
| Undiagnosed cancer (%) | 0.11 | 0-1,000% × BC | (30) |
| Post-curative surgery (%), mo | | 50-200% × BC | (34) |
| 0-7 | 1.8 | | |
| 8-41 | 0.89 | | |
| 42-86 | 0.41 | | |
| 87+ | 0 | | |
| Post-palliative surgery (%), mo | | 50-200% × BC | (34) |
| 0-12 | 12 | | |
| 13+ | 5.7 | | |
| Outcome adjustments | | | |
| Utility reductions | | | |
| Endoscopy | -0.3 * 1 d | 0-0.5 | (47) |
| Endoscopy complication | -0.3 * 1 wk | 0-0.5 | (47) |
| PD | -0.3 * 4 wk | 0-0.5 | (40) |
| Quality of life adjustment factors | | | |
| Well, age | | 1 | (48) |
| 30-39 | 0.91 | | |
| 40-49 | 0.88 | | |
| 50-59 | 0.85 | | |
| 60-69 | 0.83 | | |
| 70-79 | 0.79 | | |
| 80+ | 0.75 | | |
| Post-PD | 0.98 | 0.8-1 | See Methods |
| Cancer | 0.47 | 0.25-1 | (49, 50) |
| Discount rate (%) | 3 | 0-5 | (51) |
| Costs ($) | | | |
| Cancer care | 67,565 | 50-200% × BC | (52) |
| Endoscopy | 903 | 50-200% × BC | (53) |
| Endoscopy complication | 9,355 | 50-200% × BC | (54) |
| PD | 30,568 | 50-200% × BC | (40) |
| Post-PD | 159 | 50-200% × BC | See Methods |
| Day's wages | 147 | 50-200% × BC | U.S. Bureau of Labor |

Abbreviations: BC, base-case scenario; PD, pancreaticoduodenectomy.

our model to a 4.9% cumulative risk for cancer at age 62 (see Supplemental Appendix for details).

*Endoscopic Screening.* We assumed that all patients would undergo screening endoscopy with biopsy as recommended by the American Society for Gastrointestinal Endoscopy and recent publications: endoscopy with biopsy every 5, 3, 3, 1, and 0.5 y in stages 0 to IV, respectively (16, 17). Reports of endoscopy false-negative rates for polyposis staging and cancer diagnosis range from 20% to 56% (2, 8, 22-26). We selected a false-negative rate of 29% from a representative study for the base-case scenario (26). A false-negative endoscopy resulted in a perceived stage that is one stage lower than the biological stage. We



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assumed that the perceived stage could not be greater than the biological stage and that the perceived stage would never decrease. The frequency of endoscopy complications requiring surgery was estimated from the literature (27, 28).

Fifty percent of cancer diagnoses are made after a patient presents symptomatically rather than at a scheduled screening endoscopy (8, 23, 29). To reflect this in the model, following the development of cancer, patients had a linearly increasing risk for presenting with symptoms leading to an endoscopy. The rate of symptom development was adjusted so that 50% of cancers were diagnosed following symptomatic presentation.

*Surgery.* Pancreaticoduodenectomy was used prophylactically in stage III and IV individuals, as well as therapeutically in cancer patients who were candidates for curative surgery. All stage III and IV patients were assumed to be surgical candidates for a pancreaticoduodenectomy if it was part of the management strategy. For cancer patients, surgical candidacy was a function of age based on operability data for duodenal cancer from the Surveillance Epidemiology and End Results database (30). Overall, 54% of patients were candidates for curative surgery. Individuals with inoperable cancer received palliative care. Stage III and IV patients who received a pancreaticoduodenectomy, as well as cancer patients surviving to 5 y after surgery, were considered to have no risk for future duodenal cancer.

Pancreaticoduodenectomy perioperative mortality ranges from 1% to 9%, with high volume being associated with a lower mortality rate (17). We used 5% for our base-case analysis to represent typical hospital results and enhance generalizability (31-34).

*Cancer Mortality.* Familial adenomatous polyposis increases the risk of developing a number of conditions in addition to colorectal and duodenal cancers. These include neoplastic lesions such as desmoid, brain, pancreatic, and thyroid tumors, as well as non-neoplastic lesions. To account for this, we adjusted the age-related risk of death from the 2004 U.S. life table upward by a factor of 1.6 based on a study of familial adenomatous polyposis relative mortality after excluding colorectal and duodenal cancers (12, 35). Survival curves following curative surgery and palliative care were derived from the literature (34; see Supplemental Appendix for further details).

*Outcome Adjustments.* Standard utility adjustments were made using published values (see Supplemental Appendix for details). We modeled long-term quality of life after a pancreaticoduodenectomy by assuming 15% of the surgical population would develop diabetes due to the surgery (36-38), resulting in an overall post-pancreaticoduodenectomy quality of life score of 0.98 (39). A one-time 30% utility penalty for 6 wk modeled short-term pancreaticoduodenectomy complications and perioperative recovery (40).

*Costs.* All costs were derived from published estimates adjusted to 2007 U.S. dollars using the medical care component of the Consumer Price Index (U.S. Bureau of Labor Statistics, 2007). Patient time costs, calculated from the mean daily wage based on a 7.5-h work day, were included in the cost of procedures (U.S. Bureau of Labor; see Supplemental Appendix for details).

**Model Validation.** To show model validity, we compared model outputs to independent data sets not used in its construction or calibration (see Supplemental Appendix for model-validation methodology and results.)

**Analyses.** The model was analyzed as a Markov cohort simulation using the base-case estimates. Primary outcomes included lifetime cost, life years, and quality-adjusted life years, from which we calculated incremental cost-effectiveness ratios comparing the three strategies. Secondary outcomes included the number of endoscopies and surgeries, lifetime risk for cancer, and causes of death. One-way sensitivity analysis was done to examine how assumptions about model parameters influenced results.

## Results

**Base-Case Analysis.** The results of the base-case analysis are summarized in Table 2. Pancreaticoduodenectomy at stage IV was the most cost-effective strategy, with an incremental cost-effectiveness ratio of $3,200 per quality-adjusted life year compared with pancreaticoduodenectomy at cancer diagnosis. Pancreaticoduodenectomy at stage IV was more effective and less expensive than pancreaticoduodenectomy at stage III, which was therefore considered to be dominated.

Compared with surgery at the time of cancer diagnosis, pursuing a strategy of pancreaticoduodenectomy at stage IV in a hypothetical cohort of 10,000 individuals at age 30 would prevent 1,060 cancers, 650 cancer deaths, and 49,000 endoscopies. On the other hand, an

**Table 2. Base-case results for a cohort of 30-year-olds with familial adenomatous polyposis**

| Outcome | PD at cancer | PD at stage III | PD at stage IV |
|---|---|---|---|
| Cost (U.S. $) | 12,500 | 17,900 | 13,100 |
| QALYs | 20.02 | 20.13 | 20.21 |
| ICER (U.S. $/QALY) | Reference | Dominated | 3,200 |
| Life years (undiscounted years) | 42.81 | 43.72 | 43.72 |
| Cancers diagnosed (% of cohort) | 11.7 | 0.3 | 1.1 |
| Procedures | | | |
| Endoscopies (per person) | 16.5 | 7.6 | 11.6 |
| Surgery (% of cohort) | 7.0 | 43.0 | 25.7 |
| Deaths (% of cohort) | | | |
| Surgery | 0.4 | 2.2 | 1.3 |
| Cancer | 7.2 | 0.2 | 0.7 |

NOTE: Dominated means less effective and more costly than another strategy. U.S. $ refers to discounted 2007 U.S. dollars.
Abbreviations: ICER, incremental cost-effectiveness ratio; PD, pancreaticoduocenectomy; QALY, discounted quality-adjusted life years.



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**Table 3. Results of sensitivity analysis**

| Variable | PD at stage III | | | PD at stage IV | | | PD at cancer | | |
|---|---|---|---|---|---|---|---|---|---|
| | Cost | QALY | ICER | Cost | QALY | ICER | Cost | QALY | ICER |
| Polyposis distribution and progression | | | | | | | | | |
| Stage distribution at age 30 (% stage 0/I/II/III/IV/cancer) | | | | | | | | | |
| 100/0/0/0/0/0 | 14,000 | 20.20 | Dominated | 10,300 | 20.26 | 6,400 | 9,700 | 20.17 | Reference |
| 60/18/10/10/2/0 | 26,800 | 19.96 | Dominated | 19,700 | 20.08 | 700 | 19,400 | 19.59 | Reference |
| Transition probabilities | | | | | | | | | |
| Stages 0 to IV | | | | | | | | | |
| 50% × BC | 9,800 | 20.26 | Dominated | 7,200 | 20.30 | 3,900 | 2,000 | 20.26 | Reference |
| 200% × BC | 32,800 | 19.85 | Dominated | 27,400 | 19.92 | 1,000 | 26,800 | 19.27 | Reference |
| Stages IV to cancer | | | | | | | | | |
| 50% × BC | 17,900 | 20.14 | Dominated | 13,000 | 20.23 | 25,300 | 11,200 | 20.16 | Reference |
| 200% × BC | 18,000 | 20.12 | Dominated | 13,300 | 20.18 | Reference | 14,100 | 19.88 | Dominated |
| PD characteristics | | | | | | | | | |
| Eligible for curative surgery (%) | | | | | | | | | |
| 25 | 17,900 | 20.13 | Dominated | 13,000 | 20.20 | 5,500 | 11,700 | 19.97 | Reference |
| 75 | 17,900 | 20.14 | Dominated | 13,100 | 20.21 | 1,800 | 12.800 | 20.06 | Reference |
| Perioperative mortality (%) | | | | | | | | | |
| 0 | 18,200 | 20.26 | Dominated | 13,200 | 20.27 | 3,000 | 12,500 | 20.04 | Reference |
| 10 | 17,600 | 20.01 | Dominated | 12,900 | 20.15 | 3,600 | 12,500 | 20.03 | Reference |
| Cancer mortality | | | | | | | | | |
| Age related | | | | | | | | | |
| 1 × U.S. life table | 19,100 | 20.90 | Dominated | 14,100 | 20.98 | 2,600 | 13,500 | 20.77 | Reference |
| 2.1 × U.S. life table | 17,000 | 19.57 | Dominated | 12,400 | 19.64 | 3,700 | 11,700 | 19.48 | Reference |
| Post-curative surgery | | | | | | | | | |
| 50% × BC | 17,900 | 20.14 | Dominated | 13,100 | 20.22 | 3,300 | 12,600 | 20.07 | Reference |
| 200% × BC | 17,900 | 20.13 | Dominated | 13,100 | 20.21 | 3,100 | 12,400 | 19.99 | Reference |
| Post-palliative surgery | | | | | | | | | |
| 50% × BC | 17,900 | 20.13 | Dominated | 13,100 | 20.21 | 3,300 | 12,600 | 20.04 | Reference |
| 200% × BC | 17,900 | 20.13 | Dominated | 13,100 | 20.21 | 3,100 | 12,400 | 20.03 | Reference |
| Outcome adjustments | | | | | | | | | |
| Quality of life adjustment factors | | | | | | | | | |
| Post-PD | | | | | | | | | |
| 0.8 | 17,900 | 19.69 | Dominated | 13,100 | 20.01 | Dominated | 12,500 | 20.01 | Reference |
| 1 | 17,900 | 20.18 | Dominated | 13,100 | 20.23 | 2,900 | 12,500 | 20.04 | Reference |
| Cancer | | | | | | | | | |
| 0.25 | 17,900 | 20.13 | Dominated | 13,100 | 20.21 | 2,900 | 12,500 | 20.02 | Reference |
| 1 | 17,900 | 20.14 | Dominated | 13,100 | 20.22 | 4,000 | 12,500 | 20.08 | Reference |
| Discount rate (%) | | | | | | | | | |
| 0 | 38,600 | 35.18 | Dominated | 29,400 | 35.35 | 900 | 28,900 | 34.81 | Reference |
| 5 | 11,700 | 15.07 | Dominated | 8,300 | 15.12 | 5,600 | 7,800 | 15.03 | Reference |
| Costs | | | | | | | | | |
| Cancer care | | | | | | | | | |
| 50% × BC | 17,900 | 20.13 | Dominated | 12,900 | 20.21 | 10,900 | 11,000 | 20.04 | Reference |
| 200% × BC | 18,000 | 20.13 | Dominated | 13,400 | 20.21 | Reference | 15,500 | 20.04 | Dominated |
| Endoscopy | | | | | | | | | |
| 50% × BC | 16,000 | 20.13 | Dominated | 10,400 | 20.21 | 8,000 | 9,000 | 20.04 | Reference |
| 200% × BC | 21,700 | 20.13 | Dominated | 18,400 | 20.21 | Reference | 19,500 | 20.04 | Dominated |
| PD | | | | | | | | | |
| 50% × BC | 14,700 | 20.13 | Dominated | 11,400 | 20.21 | Reference | 12,100 | 20.04 | Dominated |
| 200% × BC | 24,300 | 20.13 | Dominated | 16,400 | 20.21 | 17,500 | 13,300 | 20.04 | Reference |
| Post-PD | | | | | | | | | |
| 50% × BC | 15,100 | 20.13 | Dominated | 11,800 | 20.21 | Reference | 12,300 | 20.04 | Dominated |
| 200% × BC | 23,600 | 20.13 | Dominated | 15,600 | 20.21 | 15,700 | 12,900 | 20.04 | Reference |

NOTE: Dominated means less effective and more costly than another strategy. U.S. $ refers to discounted 2007 U.S. dollars.
Abbreviations: BC, base-case scenario; ICER, incremental cost-effectiveness ratio; PD, pancreaticoduodenectomy; QALY, discounted quality-adjusted life years.

additional 1,870 pancreaticoduodenectomy surgeries would be done, leading to 90 additional perioperative deaths. Overall, 9,100 years of life would be saved.

**Sensitivity Analysis.** An extensive sensitivity analysis was performed (Table 3). The model was robust to a wide range of changes in parameter estimates; in almost all cases, pancreaticoduodenectomy at stage IV was cost-effective relative to pancreaticoduodenectomy at cancer diagnosis and dominated pancreaticoduodenectomy at stage III. The model was not sensitive to initial stage distribution, resectability, perioperative pancreaticoduodenectomy mortality, palliative care mortality, curative care mortality, age-related mortality, or mortality from undiagnosed cancer.

There is considerable variability in literature reports of lifetime duodenal cancer risk. The transition rates between stages 0 to IV and IV to cancer were varied independently as well as simultaneously. For lifetime cancer risks of >50%, well in excess of plausible values, pancreaticoduodenectomy at stage IV dominated pancreaticoduodenectomy at stage III and pancreaticoduodenectomy at cancer diagnosis. For a lifetime cancer risk of <1%, well under all published estimates, the incremental cost-effectiveness ratio of pancreaticoduodenectomy at stage IV relative to surgery at the time of



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cancer diagnosis was <$50,000 per quality-adjusted life year gained.

Wide variation in the discount rate and all utility reductions, quality of life adjustments, and costs did not change the optimal strategy. One exception was the long-term quality of life following a pancreaticoduodenectomy. Using a willingness-to-pay threshold of $80,000 per quality-adjusted life year, pancreaticoduodenectomy at cancer diagnosis dominated pancreaticoduodenectomy at stages III and IV if quality of life after pancreaticoduodenectomy was <0.83.

To account for possible heterogeneity in optimal management strategies according to individual patient characteristics, we performed a subgroup analysis (see Supplemental Appendix for methodology and results). Regardless of the cohort's initial age or stage, pancreaticoduodenectomy at stage IV maximized life expectancy. We also performed a multiway sensitivity analysis to address simultaneous uncertainty in multiple variables (see Supplemental Appendix for methodology and results). In 99% of the multiway sensitivity trials performed, pancreaticoduodenectomy at stage IV was a cost-effective management strategy compared with surgery at cancer diagnosis (incremental cost-effectiveness ratio <$80,000 per quality-adjusted life year).

## Discussion

The results of our analysis suggest that pancreaticoduodenectomy at stage IV duodenal polyposis in patients with familial adenomatous polyposis is an effective and cost-effective management strategy compared with pancreaticoduodenectomy at cancer diagnosis or stage III polyposis. Once stage IV polyposis has been diagnosed, pancreaticoduodenectomy mortality and morbidity is substantially less than the mortality and morbidity from future cancers. Surgery at stage IV would prevent >90% of duodenal cancers. By decreasing the length of time spent in stage IV, which has frequent endoscopies, the average total number of endoscopies would decrease by almost five per person. The cost savings from performing fewer endoscopies and reducing the number of cancers would partially offset the increase in surgical costs. Although the number of individuals affected by duodenal polyposis is small in absolute terms, the results from the model highlight the large increase in life expectancy at very low marginal cost of recommending surgery at stage IV versus surgery at cancer diagnosis, making the choice of management strategy an important public health concern for this population.

Pancreaticoduodenectomy at stage III was dominated by pancreaticoduodenectomy at stage IV. However, pancreaticoduodenectomy at stage IV resulted in almost 1.1% of the model cohort developing duodenal cancer. Surgery at stage III would further reduce the lifetime risk for cancer to 0.3%. This benefit, however, comes at the cost of 43% of the cohort undergoing pancreaticoduodenectomy. The high number of surgeries would increase costs and, due to perioperative mortality and post-surgery morbidity, decrease quality-adjusted life years relative to pancreaticoduodenectomy at stage IV.

Our findings were generally insensitive to wide variations in model parameter estimates. The model was sensitive, however, to post-pancreaticoduodenectomy quality of life. A number of studies have measured the quality of life following a pancreaticoduodenectomy. Patients have equivalent quality of life scores before surgery and at 1-year following surgery and, compared with control groups, report only mildly lower quality of life overall (41-44). This supports a post-pancreaticoduodenectomy quality of life utility substantially above the threshold of 0.83 found by sensitivity analysis.

Vasen et al. (9) previously constructed a simple decision analysis model of duodenal cancer in familial adenomatous polyposis, finding that endoscopic surveillance increased life expectancy. Our model was constructed to answer the question of at what stage surgery should be recommended, assuming that endoscopic surveillance is occurring. Our analysis used a Markov model to explicitly model the underlying disease natural history and treatment states, whereas Vasen et al. (9) used a decision tree approach and did not include a cost-effectiveness analysis.

A limitation of our study, as in any modeling study, is uncertainty in the parameter estimates. Our parameter estimates were based on data from multiple sources with heterogeneous study design and populations. Future studies on familial adenomatous polyposis natural history and treatment outcomes can better inform these parameter estimates. However, the relative insensitivity of our results to a wide range of parameter estimates supports the conclusions of the model.

All disease models are a simplification of reality. The best efforts were made to construct a comprehensive model that accurately reflects clinical realities. A number of simplifying assumptions, however, were needed to make the model more understandable and transparent and to account for the availability of clinical data. We assumed that transitions between stages 0 to IV occurred at a constant rate. Although there is no underlying biological rationale that this should be the case, the literature supports this assumption as a first approximation (5, 16, 45, 46). Our model does not explicitly model transition rates as a function of age. Although such an approach might better approximate the underlying pathogenesis, sufficient clinical data were not available. Thus, at extremes of age, our model predictions may be less accurate. Disease regression is biologically supported, but there is a lack of sufficient data to quantify its effect. We felt that including it in the model would increase complexity and decrease transparency without much benefit. In addition, disease progression transition rates were calibrated to empirical data tracking disease progression in aggregate; because of this, our model implicitly includes the possibility of disease regression in its transition rates. Although not everyone in stages III and IV is a surgical candidate and prophylactic pancreaticoduodenectomy does not reduce risk for future duodenal cancer to zero, these assumptions simplify the model. Finally, we assumed perfect adherence to recommended screening protocols. If patients do not undergo screening at suggested intervals (assuming that results in cancer being diagnosed at more advanced stages), this assumption may bias the model toward delaying surgical intervention.

Several new treatment modalities for duodenal polyposis are currently being studied, including photodynamic therapy, thermal ablation, and argon plasma coagulation. The use of non-steroidal anti-inflammatory drugs in chemoprevention is also being examined. At



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present, however, the long-term outcomes of these approaches are unknown, and further study is needed to assess efficacy. These potential treatments could be valuable additions to the model in the future.

In conclusion, prophylactic pancreaticoduodenectomy at stage IV duodenal polyposis in patients with familial adenomatous polyposis is a cost-effective approach that results in greater life expectancy than surgery at either stage III or cancer diagnosis. Effective clinical decision-making requires considering this recommendation within the context of each patient's unique history and preferences to create an individually appropriate management strategy.

## Disclosure of Potential Conflicts of Interest

No potential conflicts of interest were disclosed.

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Wesley H. Greenblatt, Chin Hur, Amy B. Knudsen, et al.

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