IMPORTANCE Guidelines for clinical management in Li-Fraumeni syndrome, a multiple-organ cancer predisposition condition, are limited. Whole-body magnetic resonance imaging (WBMRI) may play a role in surveillance of this high-risk population.

OBJECTIVE To assess the clinical utility of WBMRI in germline TP53 mutation carriers at baseline.

DATA SOURCES Clinical and research surveillance cohorts were identified through the Li-Fraumeni Exploration Research Consortium.

STUDY SELECTION Cohorts that incorporated WBMRI for individuals with germline TP53 mutations from January 1, 2004, through October 1, 2016, were included.

DATA EXTRACTION AND SYNTHESIS Data were extracted by investigators from each cohort independently and synthesized by 2 investigators. Random-effects meta-analysis methods were used to estimate proportions.

MAIN OUTCOMES AND MEASURES The proportions of participants at baseline in whom a lesion was detected that required follow-up and in whom a new primary malignant neoplasm was detected.

RESULTS A total of 578 participants (376 female [65.1%] and 202 male [34.9%]; mean [SD] age, 33.2 [17.1] years) from 13 cohorts in 6 countries were included in the analysis. Two hundred twenty-five lesions requiring clinical follow-up were detected by WBMRI in 173 participants. Sixty-one lesions were diagnosed in 54 individuals as benign or malignant neoplasms. Overall, 42 cancers were identified in 39 individuals, with 35 new localized cancers treated with curative intent. The overall estimated detection rate for new, localized primary cancers was 7% (95% CI, 5%-9%).

CONCLUSIONS AND RELEVANCE These data suggest clinical utility of baseline WBMRI in TP53 germline mutation carriers and may form an integral part of baseline clinical risk management in this high-risk population.
Li-Fraumeni syndrome (LFS) was first described in 1969 as a highly penetrant cancer-prone syndrome.\(^1\) Formal diagnostic criteria for LFS have subsequently been developed, based on a family or a personal history of a broad spectrum of early-onset cancers, including sarcoma, breast cancer, adrenocortical carcinoma, and brain tumors, often with more than 1 cancer per affected individual.\(^2\) Lifetime cancer risks are reported to approach 100% for both sexes in cases identified by family history.\(^6\) The exceedingly high cancer risk in LFS often confers a high psychological and medical burden.\(^9\) Pathogenic variants in the tumor suppressor gene, TP53 (NCBI Entrez Gene 7157), were first identified and subsequently found to cause about 70% of classic LFS in 1990.\(^10\) Identification of germline TP53 mutation carriers has been augmented by increased with increased sequencing of germline and somatic DNA using gene panels and whole-exome and whole-genome testing, owing in part to the influence of precision medicine initiatives.

Although the clinical characteristics and molecular basis for LFS have been known for decades, no universally accepted approach exists for risk management. Current guidelines focus on the risk for breast cancer, primarily because organ-specific surveillance measures,\(^14\) such as magnetic resonance imaging (MRI) of the breast, are already widely used for screening in cognate high-risk syndromes. However, because breast cancer constitutes only a proportion of the surgically resectable cancers to which TP53 mutation carriers are prone, novel, effective methods for cancer surveillance are needed across a broad range of body or corporeal sites. Within the past 5 years, emerging studies have suggested improved clinical outcomes for TP53 mutation carriers with intensive screening.\(^17\)\(^-\)\(^20\) The Toronto protocol, which incorporates whole-body MRI (WBMRI) among other modalities, was associated with improved survival.\(^17\) Neonatal screening for the Brazilian TP53 founder mutation resulted in adrenocortical tumors being detected at an early, more curable stage.\(^18\) Of note, a recent UK study detected malignant neoplasms in 14% of TP53 mutation carriers at baseline WBMRI.\(^19\) Psychological benefit has also been reported from participation in an LFS surveillance program.\(^20\) However, in part because of the rarity of LFS, definitive evidence of the benefits of screening are lacking.

To generate evidence for the efficacy of WBMRI as a surveillance tool for carriers of pathogenic germline TP53 mutations, we report herein the findings of a meta-analysis of 13 prospective cohorts conducted in 6 countries. We assessed the detection rates of asymptomatic cancers using WBMRI as part of baseline assessment of TP53 mutation carriers, measured by the rate of identification of investigable lesions and new primary cancers that can be treated with curative intent.

### Key Points

**Question** Does baseline whole-body magnetic resonance imaging detect asymptomatic cancers at a curable stage in germline TP53 mutation carriers?

**Findings** In a meta-analysis of 13 cohorts that included 578 participants, the estimated overall detection rate for previously unrecognized new, localized malignant neoplasms by a single baseline scan in TP53 mutation carriers was 7%, and the false-positive rate was 42.5%. All screen-detected new cancers were treated with curative intent.

**Meaning** Baseline evaluation with whole-body magnetic resonance imaging offers important clinical utility in the management of cancer risk in TP53 mutation carriers.

### Methods

#### Study Selection

Clinical and research surveillance cohorts were identified through the Li-Fraumeni Exploration Research Consortium.\(^21\) Cohorts that were formed from January 1, 2004, through October 1, 2016, that performed WBMRI in individuals at any age were considered (eTable 1 in the Supplement). All research cohorts had ethical approval from their ethics boards, and written informed consent was obtained from participants or guardians as appropriate.

Participants were not required to be newly diagnosed for any of the studies included in this meta-analysis. All cohorts included the brain in the WBMRI scan except the Huntsman Cancer Institute cohort. All participants were asymptomatic at the time of the baseline scan. The details of imaging protocols for contributing cohorts, including the use of contrast and organ-specific sequences, are given in eTables 2 to 14 in the Supplement. All participants were known carriers of pathogenic TP53 mutations or were obligate carriers by pedigree.

#### Data Extraction and Classification

Data were extracted by investigators from each cohort and synthesized by 2 of us (M.L.B. and D.M.T.). Lesions were considered to be investigable if further clinical follow-up was required in the opinion of the study investigator, including additional imaging or biopsy. The true-positive rate for WBMRI was defined as the rate of detection of localized, primary cancers that were treated with curative intent. False-positive lesions were defined as those considered initially to be neoplastic (all neoplasms in the Figure) but that subsequently were determined on further investigation to be benign tumors, recurrences of previous cancers, or incurable metastatic cancers. Low-grade gliomas were classified as malignant. The treatment intent (curative or palliative) after diagnosis was recorded in each case.

#### Statistical Analysis

Random-effects meta-analysis methods\(^22\) for proportions were used to aggregate the data from the 13 participating cohorts. Meta-analyses were performed to estimate the proportion of participants found to have 1 or more investigable lesions, the proportion of participants found to have 1 or more new primary cancers, and the proportion of investigable lesions determined to be new primary cancers, with approximate 95% CIs.\(^23\) The between-cohort heterogeneity \(I^2\), along with the associated \(P\) value, was estimated using the DerSimonian-Laird method. A logit transformation was used to calculate the overall proportions. Cohort participants were additionally subdivided by sex and by age group (0-17, 18-40, or >40 years of age) to identify age-dependent trends in cancer detection rates and...
A flowchart outlining the disposition of participants included in the meta-analysis is given in the Figure. Of the 578 participants, 225 lesions requiring further investigation were observed in 173 participants. Forty-two malignant lesions were diagnosed in 39 individuals, with most of the diagnoses based on biopsy findings. Four of the 42 malignant lesions were brain tumors diagnosed based on imaging alone. Of the new malignant neoplasms, 35 localized primary cancers were diagnosed in 34 individuals, all of whom were treated with curative intent. The false-positive rate, defined here as the proportion of suspected neoplasms that were benign, recurrences of preexisting cancers, or newly diagnosed metastatic cancers, was 42.5% (26 of 61).

**Meta-analysis Results**

eFigure 1 in the Supplement presents the meta-analysis for the proportion of participants found to have 1 or more investigable lesions by WBMRI. Overall, 31% (95% CI, 26%-35%) of participants were estimated to have 1 or more investigable lesions. No sex differences were detected (estimated proportion of 31% in both sexes; \( P = .90 \), Cochran Q). The proportion of investigable lesions identified tended to increase with age from 29% among participants younger than 18 years to 30% among those aged 18 to 40 years and 34% among those older than 40 years, but this increase was not statistically significant (\( P = .60 \) overall, Cochran Q).

**Clinical Spectrum of New Primary Cancers**

The 35 new primary cancers identified by baseline WBMRI occurred in 34 participants (1 woman older than 40 years had a synchronous localized chromophobe renal cell carcinoma and a localized uterine leiomyosarcoma). No new primary cancers were clinically metastatic at diagnosis. The patterns of...
Table. New Localized Primary Malignant Neoplasms Detected by WBMRI

<table>
<thead>
<tr>
<th>Age Group by Participant Sex</th>
<th>Morphologic and Topographic Findings</th>
<th>Age at Diagnosis, y</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-17 y</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Male</td>
<td>Adrenocortical carcinoma</td>
<td>2</td>
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<tr>
<td></td>
<td>Osteosarcoma of the leg</td>
<td>9</td>
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<tr>
<td></td>
<td>Low-grade glioma</td>
<td>15</td>
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<tr>
<td></td>
<td>Osteosarcoma of the fibula</td>
<td>12</td>
</tr>
<tr>
<td>Female</td>
<td>Choroid plexus carcinoma</td>
<td>4</td>
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<tr>
<td></td>
<td>Low-grade glioma</td>
<td>6</td>
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<tr>
<td></td>
<td>Low-grade glioma</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td>Osteosarcoma of the chest</td>
<td>13</td>
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<td></td>
<td>Astrocytoma</td>
<td>13</td>
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<td></td>
<td>Papillary thyroid cancer</td>
<td>17</td>
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<td></td>
<td>Renal carcinoma</td>
<td>17</td>
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<td></td>
<td>Spinal chordoma</td>
<td>17</td>
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<tr>
<td>18-40 y</td>
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<tr>
<td>Male</td>
<td>Osteosarcoma of the rib</td>
<td>29</td>
</tr>
<tr>
<td></td>
<td>Colorectal cancer</td>
<td>21</td>
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<tr>
<td></td>
<td>Osteosarcoma of the rib</td>
<td>29</td>
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<tr>
<td>Female</td>
<td>Renal and liver epithelioid angiomyolipomas</td>
<td>24</td>
</tr>
<tr>
<td></td>
<td>Chondrosarcoma of the sacroiliac joint</td>
<td>29</td>
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<tr>
<td></td>
<td>Undifferentiated pleomorphic sarcoma of the shoulder</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>Astrocytoma</td>
<td>33</td>
</tr>
<tr>
<td></td>
<td>Chordoma of the clivus</td>
<td>40</td>
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<tr>
<td></td>
<td>Thyroid carcinoma</td>
<td>40</td>
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<td>&gt;40 y</td>
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<tr>
<td>Male</td>
<td>Prostate adenocarcinoma</td>
<td>41</td>
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<td></td>
<td>Prostate adenocarcinoma</td>
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<td></td>
<td>Lung adenocarcinoma</td>
<td>54</td>
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<tr>
<td></td>
<td>Leiomyosarcoma of the bowel</td>
<td>63</td>
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<tr>
<td>Female</td>
<td>Low-grade spindle cell sarcoma of the chest</td>
<td>41</td>
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<tr>
<td></td>
<td>Lung adenocarcinoma</td>
<td>54</td>
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<td></td>
<td>Chromophobe renal cell carcinoma and uterine leiomyosarcoma</td>
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<td></td>
<td>Ductal carcinoma in situ of the breast</td>
<td>49</td>
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<tr>
<td></td>
<td>Abdominal myxosarcoma</td>
<td>51</td>
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<td>Well-differentiated liposarcoma of the lumbar region</td>
<td>52</td>
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<tr>
<td></td>
<td>Lung adenocarcinoma</td>
<td>64</td>
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<tr>
<td></td>
<td>Invasive ductal carcinoma of the breast</td>
<td>66</td>
</tr>
<tr>
<td></td>
<td>Lung adenocarcinoma</td>
<td>43</td>
</tr>
</tbody>
</table>

Abbreviation: WBMRI, whole-body magnetic resonance imaging.

* Currently under surveillance with short-interval MRI, with the intent to resect at a later stage.

cancers observed vary by age and sex (Table). All 7 bone sarcomas were observed in participants younger than 40 years, with no sex difference, whereas 5 of 7 soft-tissue sarcomas arose in participants older than 40 years. A single adrenocortical tumor was found in a child, as was a choroid plexus carcinoma. The diversity of cancers to which TP53 mutation carriers are prone was evident. Other cancers identified included carcinomas of the lung (4 participants, all aged >40 years), kidney (1 female participant in each age group), thyroid (1 female participant aged <18 years and 1 aged 18-40 years), prostate (2 male participants aged >40 years), and bowel (1 male partici-

Discussion

This meta-analysis provides, to our knowledge, the first statistically robust estimate of the potential clinical utility of WBMRI in screening TP53 mutation carriers. Overall, 1 in 14 participants undergoing their first WBMRI was found to have a primary malignant neoplasm, which was then treated with curative intent. The rate of detection of localized malignant neoplasms was remarkably consistent between individual cohorts, studies of which were conducted across 6 countries and 13 institutions. The rate at which cancers were identified appeared to be highest among children and lowest among young adults and increased again among older adults. The spectrum of cancers shifts with age, with a greater number of brain tumors and bone sarcomas in children and a range of epithelial malignant neoplasms in older adults. All screen-detected cancers were treated with curative intent, although the follow-up of those participants in whom cancers were identified and treated curatively was too short to assess long-term outcomes. Whole-body MRI does not reliably identify brain tumors in TP53 mutation carriers. Another important outcome of WBMRI is the detection of benign but clinically significant lesions that are medically actionable, for example, by causing organ damage through local growth or undergoing malignant transformation in this high-risk population.

The absence of breast cancers in this screened population was notable. Breast cancer is the most common diagnosis among women with TP53 mutations who are younger than 40 years, but only 2 women with breast cancer were identified in this meta-analysis (both aged >40 years). This finding may reflect the high percentage of women who had undergone unilateral or bilateral mastectomy before study entry (127 of 264 [48.1%]), the inability of WBMRI to detect small breast lesions, or the routine use of dedicated breast MRI in women at high risk for breast cancer.

Abbreviation: WBMRI, whole-body magnetic resonance imaging.
To put the results of this meta-analysis of WBMRI in TP53 mutation carriers into the context of current clinical genetics practice, we compared these results with those achieved through screening using dedicated breast MRI in women at high risk for breast cancer owing to germline BRCA1/2 mutations. Breast MRI is widely approved, recommended, and reimbursed for early detection of cancer in women at high risk for breast cancer.14-16 The Ontario Breast Screening Program26 screened 2207 women at high risk for breast cancer by using mammography or breast MRI. The detection rate of breast MRI was 1% in that series, consistent with rates of previous large-scale studies.27,28 The rate of screen-detected cancers in other series was similar.29 However, specific incidence rates for TP53 mutation carriers can be as high as 4.4%,30 and the results are often premalignant comedo with histologic findings for ductal carcinoma in situ.30

An important aspect of population screening is the false-positive rate because the investigation of lesions that are subsequently clinically insignificant is a source of potential psychological distress, medical morbidity, and cost. Almost 1 in 3 participants in this WBMRI meta-analysis were found to have an investigable lesion, and nearly 1 in 5 lesions (18%) were malignant and appropriately treated with curative intent. Comparison with breast MRI is useful. The false-positive rate for the combination of breast MRI with mammography has been variably reported to range from 4% to 30%,27-29 rates lower than that observed in our series (42.5%). A recent report on the acceptability of WBMRI in the population with LFS observed that screening reduces anxiety for participants and may provide psychological benefit.20

Limitations
Important limitations and unanswered questions arise from this study. The surveillance protocols used in each cohort were heterogeneous. Subgroup meta-analyses such as these can be challenging to interpret because the meta-analysis estimates are calculated by incorporating estimated weights for each cohort rather than by pooling data across studies. Weighting is a valuable part of meta-analyses because it reduces the influence of cohorts with small amounts of data while these data can still be included in the aggregated analysis. Incorporation of study weights calculated independently in each subgroup or combined analysis may lead to observations such as ours that cancer diagnosis rates in the aggregate of participants aged 18 to 40 years is lower among male and female participants combined than among either group alone.

Other important questions involve the optimal use of WBMRI in relation to participant age and sex because the nature and incidence of cancers vary substantially in TP53 mutation carriers. The excess of female to male participants in our study may be attributable to the greater engagement of women in health care.31 In addition, when WBMRI or other components of a surveillance program should be introduced as part of follow-up for patients with an existing cancer diagnosis is unclear. Most cohorts contributing to this meta-analysis did not use contrast; however, the question of the importance of contrast as an effective component of a WBMRI protocol remains open. Careful follow-up will be required to fully document any safety issues associated with WBMRI screening. Opportunity exists for optimization of WBMRI protocols with faster acquisition sequences and improved imaging technologies. In this meta-analysis, individual cohorts varied widely in eligibility criteria regarding time since curative treatment for a previous cancer, although only 7 malignant neoplasms detected by WBMRI were recurrences of previous malignant neoplasms.

Finally, we cannot estimate the false-negative rate for WBMRI from our data because this meta-analysis describes the results of a single baseline scan. Only follow-up will determine whether occult cancers were missed by WBMRI. Longitudinal follow-up of TP53 mutation carriers is very limited, with only 1 study reported to date.17 Longer-term follow-up of these patients will be essential to reveal the rate of cancer development in these cohorts, identify the optimal scheduling of WBMRI, and determine whether early detection of cancers in TP53 mutation carriers will translate into decreased morbidity and better survival. Estimates of the cost-effectiveness of WBMRI also lie beyond the scope of the present study but will be important to implementation in clinical practice.

Conclusions
Cancer screening in germline TP53 mutation carriers is especially challenging because of the wide spectrum of associated malignant neoplasms. Baseline WBMRI identified a new and treatable malignant neoplasm in as many as 7% of TP53 mutation carriers, confirming that this modality enables clinically useful early detection of cancer in this highly cancer-prone population across a broad range of health systems. The meta-analysis presented herein suggests that WBMRI adds significantly to the armamentarium available to clinicians seeking to improve the likelihood of early tumor detection and subsequent improved outcomes. Although further research is required, our findings suggest that WBMRI may be a useful component of the routine baseline assessment of TP53 mutation carriers in children and adults.
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Dr Ballinger and Best served as equal first authors. Drs Thomas and Savage served as equal senior authors. Drs Ballinger and Savage had full access to all data and take responsibility for data integrity and analysis.

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Acquisition, analysis, or interpretation of data:

Savage.

Statistical analysis:

Savage.

Critical revision of the manuscript for important intellectual content: All authors.

Administrative, technical, or material support: Mai, Khincha, Santiago, O’Neill, Rujis, Naumer, Kohlmann, Bojadzieva, Koepe, Nehoray, Walsh, Villani.

Study supervision: Thomas, Savage.

Conflict of Interest Disclosures:

None reported.

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