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Long-term efficacy and safety of thalamic stimulation for drug-resistant partial epilepsy

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ABSTRACT

Objective: To report long-term efficacy and safety results of the SANTE trial investigating deep brain stimulation of the anterior nucleus of the thalamus (ANT) for treatment of localization-related epilepsy.

Methods: This long-term follow-up is a continuation of a previously reported trial of 5- vs 0-V ANT stimulation. Long-term follow-up began 13 months after device implantation with stimulation parameters adjusted at the investigators' discretion. Seizure frequency was determined using daily seizure diaries.

Results: The median percent seizure reduction from baseline at 1 year was 41%, and 69% at 5 years. The responder rate (≥50% reduction in seizure frequency) at 1 year was 43%, and 68% at 5 years. In the 5 years of follow-up, 16% of subjects were seizure-free for at least 6 months. There were no reported unanticipated adverse device effects or symptomatic intracranial hemorrhages. The Liverpool Seizure Severity Scale and 31-item Quality of Life in Epilepsy measure showed statistically significant improvement over baseline by 1 year and at 5 years ($p < 0.001$).

Conclusion: Long-term follow-up of ANT deep brain stimulation showed sustained efficacy and safety in a treatment-resistant population.

Classification of evidence: This long-term follow-up provides Class IV evidence that for patients with drug-resistant partial epilepsy, anterior thalamic stimulation is associated with a 69% reduction in seizure frequency and a 34% serious device-related adverse event rate at 5 years.
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GLOSSARY

ANT = anterior nucleus of the thalamus; **CI** = confidence interval; **DBS** = deep brain stimulation; **LSSS** = Liverpool Seizure Severity Scale; **QOLIE-31** = 31-item Quality of Life in Epilepsy; **SAE** = serious adverse event; **SANTE** = Stimulation of the Anterior Nucleus of the Thalamus for Epilepsy; **SUDEP** = sudden unexpected death in epilepsy; **VNS** = vagus nerve stimulation.

Approximately 3 million people in the United States have epilepsy and approximately 30% remain resistant to medical treatment. Some of these patients are candidates for resective surgery.[1,2] For those who are not surgical candidates, or who continue to have seizures after surgery, neuromodulation may offer a viable therapeutic option. Several pilot studies,[3–6] and recent trials including the Stimulation of the Anterior Nucleus of the Thalamus for Epilepsy (SANTE) trial[7] and a trial of responsive cortical stimulation,[8] have demonstrated reduction in seizures. The SANTE trial in 110 subjects with localization-related epilepsy found that seizures were significantly reduced by stimulation.[7] We now report the 5-year efficacy and safety outcomes of this trial.

METHODS The SANTE trial[7] utilized a design with a 3-month baseline, 1-month postoperative recovery, followed by 3 months of double-blind treatment randomized to 5 V or 0 V of stimulation, then an open-label conversion of all subjects to 5-V stimulation for 9

Supplemental data at Neurology.org

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Go to Neurology.org for full disclosures. Funding information and disclosures deemed relevant by the authors, if any, are provided at the end of the article.

additional months. The long-term follow-up reported here began at 13 months and continued for an additional 4 years. The primary research question was whether seizure frequency continued to improve over time with open-label anterior thalamic stimulation.

Subjects were 18 to 65 years old with at least 6 partial or secondarily generalized seizures per month who had failed at least 3 antiepileptic drugs (AEDs) because of lack of efficacy. Subjects with IQ <70, inability to complete neuropsychological testing, or progressive neurologic deficits were excluded. Subjects were seen every 6 months in addition to daily diary collection and monthly telephone contact. Efficacy analyses were performed on the 109 subjects randomized in the original study. One subject who was implanted but not randomized is included for safety analyses only. The outcome measures included efficacy (seizure diary), Liverpool Seizure Severity Scale (LSSS), and 31-item Quality of Life in Epilepsy (QOLIE-31). Safety was addressed by adverse event collection and neuropsychological measures.

Standard protocol approvals, registrations, and patient consents. This study was approved by all study center institutional review boards, and subjects provided written informed consent before participation. The study is registered on clinicaltrials.gov, identifier NCT00101933.

Statistical analysis. The required sample size was determined for the randomized portion of the study; no additional sample size requirements were associated with long-term follow-up. Device longevity was determined through Kaplan-Meier survival analysis, and sudden unexpected death in epilepsy (SUDEP) confidence intervals (CIs) were based on the Poisson distribution. Appropriate summary statistics are reported for all other measures. Change from baseline was tested using a paired t test or Wilcoxon signed rank test as appropriate. Statistical tests were examined for significance at the 0.05 level, with no adjustments for multiple comparisons. SAS software (version 9.2; SAS Institute, Cary, NC) was used for all analyses.

Seizure frequency reduction was determined via daily seizure diaries and is reported as percentage change from baseline. Sensitivity analyses were completed to show the robustness of the main analysis.

This long-term follow-up provides Class IV evidence that for patients with drug-resistant partial epilepsy, anterior thalamic stimulation is associated with a 69% reduction in seizure frequency and a 34% serious device-related adverse event rate at 5 years.

RESULTS The mean age was 36.1 years (range 18.2–60.9 years). The average number of years with epilepsy was 22.3 (range 2–60 years) and the median monthly seizure frequency during baseline was 19.5 (range 6–604). A total of 105 subjects entered the long-term follow-up phase beginning 13 months after implant (figure 1). There were 30 discontinuations in the long-term follow-up phase, including 5 deaths (1 each due to drowning, suicide, SUDEP, cardiac arrest, and liver cancer). SANTE subjects have received stimulation for 441 years of follow-up at 5 years and 623 years including all follow-up.

Between implant and year 5, 61 of the 110 implanted subjects added at least one AED that was not present at baseline. Each subject could have added more than one AED. Medications added were lacosamide (28 subjects), pregabalin (24), levetiracetam (8), lamotrigine (7), clonazepam (6), and 15 others in 4 or fewer subjects. A similar reduction in seizure frequency was seen for subjects who had at least one medication added vs those subjects who did not add medications (figure e-1 on the *Neurology*® Web site at Neurology.org). Not surprisingly, subjects with less improvement were more likely to add a medication. Over most of the follow-up, however, the curves of improvement were parallel, such that subjects who added medicines did not improve faster than those who did not. No significant link was detected for using a specific medication and seizure improvement. Most subjects continued to take medications; when looking at changes relative to the previous year, 6 to 8 subjects per year were on a decreased number or dosage of AEDs at the year 1 to 5 visits.

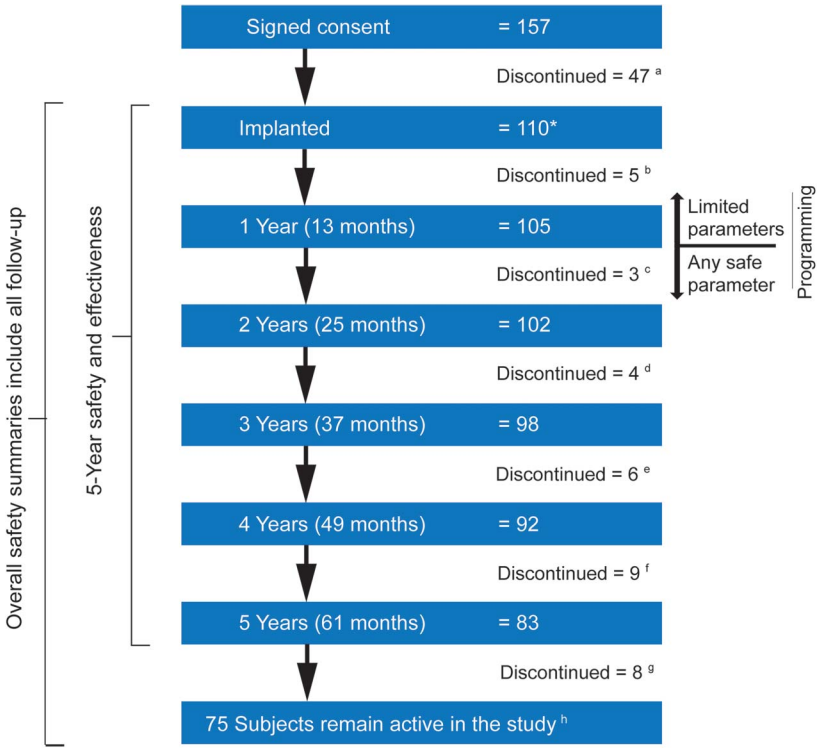
Neurostimulator battery life is directly related to stimulation parameters (parameters shown in table e-1), which varied over time and across subjects. Half of the subjects needed their first battery replacement after an average of 35.0 months (2.9 years). No formal statistical analysis of stimulation parameters was performed to identify the most efficacious parameters, as parameters were not assigned experimentally. Stimulation parameters for responders and nonresponders at year 2 to 5 were compared using descriptive statistics. However, no trend was found to favor any one stimulation parameter. Some investigators judged that rapid cycling and higher amplitude in some subjects appeared to improve outcome, although numbers were small.

Long-term follow-up efficacy. Figure 2 shows the seizure frequency change from baseline at 1 to 5 years for subjects with at least 70 days of diary entries. The median change from baseline was 41% at 1 year and 69% at 5 years ($p < 0.001$ for both). Sensitivity analyses shown in the figure demonstrate the robustness of the results. The cohort that completed diaries for every annual visit until the last observation (constant cohort) showed a gradual seizure frequency reduction with median reduction from baseline of 49% at 1 year and 69% at 5 years ($n = 74$, $p < 0.001$ for both). Figure 3 shows the distribution of individual responses to treatment at 5 years. The responder rate was 43% at 1 year ($n = 99$) and 68% at 5 years ($n = 59$).

Each subject identified a seizure type as the "most severe" at the initial baseline visit. Using subjects who experienced at least one most severe seizure during baseline with at least 70 days of diary, seizure reductions for the most severe seizure type were 39% at year 1 ($n = 74$) and 75% at year 5 ($n = 42$) ($p < 0.001$ for year 1–5).

Seizure freedom. In the 5 years after implant, 16% (17/109) of randomized subjects reported a

Figure 1 Participant timeline



The number of subjects who completed, or discontinued before, each visit is indicated in the figure. Reasons for discontinuation between phases are as follows. [a]Preimplant discontinuations: have been described in detail by Fisher et al.[7] [b]One year: device explant (4: implant site infection in 2 subjects, discomfort, involuntary muscle contractions); SUDEP (1). [c]Two years: device explant (2: implant site infection, therapeutic product ineffective); drowning (1). [d]Three years: device explant (3: anxiety, cognitive disorder, meningitis); withdrawal of consent (1). [e]Four years: device explant (4: therapeutic product ineffective in 2 subjects, psychotic disorder, undesirable change in stimulation); completed suicide (1); physician choice (1). [f]Five years: device explant (5: therapeutic product ineffective in 4 subjects, implant site infection); withdrawal of consent (2); SUDEP (1); physician choice (1). [g]More than 5 years: device explant (4: anxiety, convulsion, implant site infection, therapeutic product ineffective); withdrawal of consent (2); cardiac arrest (1); liver cancer (1). [h]Subjects have been followed through 6 (80 subjects), 7 (41), 8 (31), and 9 (6) years. *One hundred nine of 110 implanted subjects were randomized, but all subjects continued to be followed. Statistical imputation is based on 109 randomized subjects.

seizure-free interval of at least 6 months and 6 subjects were seizure-free for more than 2 continuous years during that time. In addition, 6 subjects had 2 or more seizure-free intervals of at least 6 months. At the 5-year assessment, 11 subjects were seizure-free for at least 6 months.

LSSS and QOLIE-31. The mean improvement from baseline in the LSSS was 13.4 (n = 103) at 1 year and 18.3 (n = 81) at 5 years ($p < 0.001$ for both, figure 4). The mean improvement from baseline in QOLIE-31 scores at 1 year was 5.0 (n = 102) and at 5 years was 6.1 (n = 80, $p < 0.001$ for both, figure 4). The percentage of subjects experiencing at least a 5-point change from baseline in QOLIE-31 scores, which has been reported to be clinically significant,[9] was 46% at year 1 (n = 102) and 48% at year 5 (n = 80).

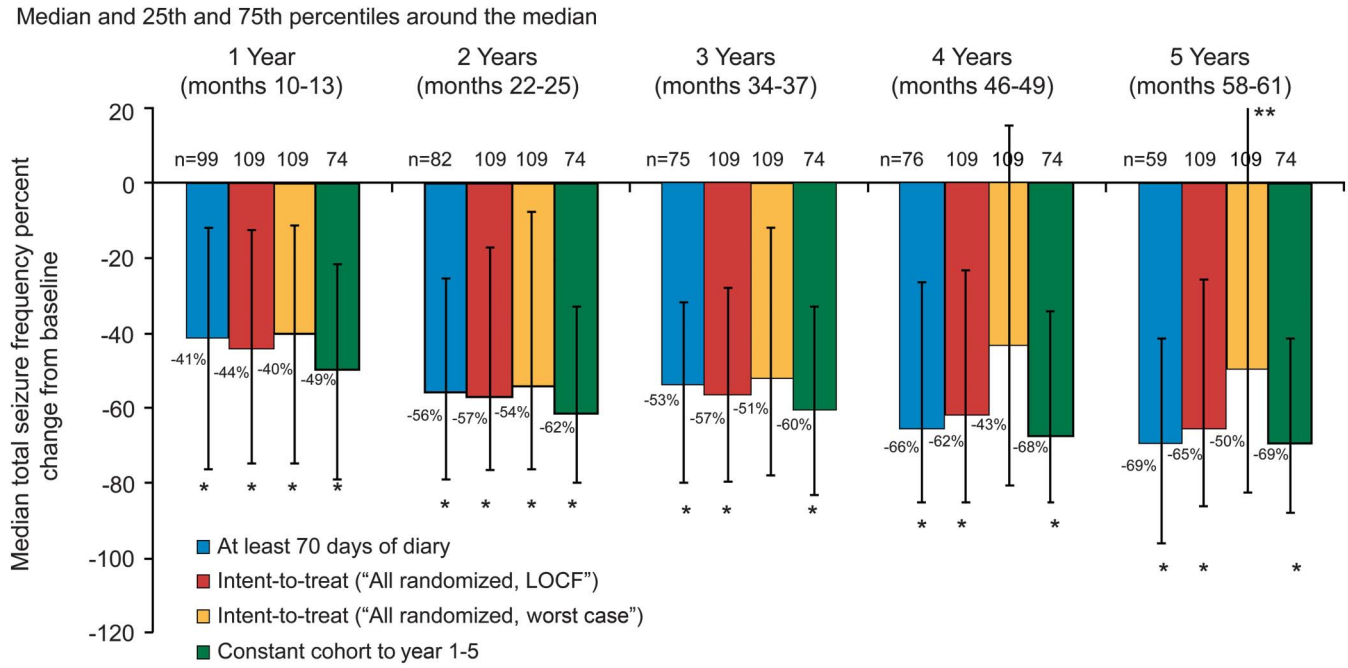
Subgroup analysis. Median seizure reduction was also determined for subgroups of subjects. Reduction by seizure onset zone was computed for temporal lobe seizures, frontal lobe seizures, and all other seizure onset zones. The median reduction for temporal lobe seizures was 44% at 1 year (n = 59, $p < 0.001$) and 76% at 5 years (n = 33, $p < 0.001$), and 53% at 1 year (n = 25, $p = 0.001$) and 59% at 5 years (n = 17, $p = 0.005$) for frontal lobe seizures. The remaining seizure onset locations experienced a median reduction of 34% at 1 year (n = 22, $p = 0.012$) and 68% at 5 years (n = 13, $p = 0.124$).

Previous vagus nerve stimulation (VNS) and history of resective surgery were also used to create subgroups. The median seizure reduction from baseline for subjects who previously tried VNS was 40% at 1 year (n = 45, $p < 0.001$) and 69% at 5 years (n = 25, $p < 0.001$), and 45% at 1 year (n = 54, $p < 0.001$) and 69% at 5 years (n = 34, $p < 0.001$) for those without prior VNS. Those subjects who underwent previous resective surgery had a median reduction of 53% at 1 year (n = 24, $p < 0.001$) and 67% at 5 years (n = 14, $p < 0.001$).

Neuropsychological outcome. Selected neuropsychological test results are presented in figure 5; the scores are expressed as composites across several tests within a given domain. There was a gradual improvement from baseline in several neuropsychological composites. Neuropsychological test composite scores showed statistically significant gains from baseline to 5 years including attention ($p < 0.001$), executive function ($p < 0.001$), depression ($p = 0.039$), tension/anxiety ($p = 0.027$), total mood disturbance ($p = 0.0016$), and subjective cognitive function ($p < 0.001$). Individual neuropsychological test scores are provided in table e-2.

Device-related adverse events. The most frequent device-related adverse events at any time after implantation were implant site pain in 23.6% (20.9% in 5 years), paresthesias including tingling, vibration, or shocking sensations at the stimulator implant site in 22.7% (22.7%), implant site infection in 12.7% (12.7%), therapeutic product ineffective in 10.0% (8.2%), discomfort in 9.1% (9.1%), lead(s) not within target in 8.2% (8.2%), sensory disturbance in 8.2% (8.2%), memory impairment in 7.3% (6.4%), implant site inflammation in 7.3% (7.3%), dizziness in 6.4% (6.4%), postprocedural pain in 6.4% (6.4%), extension fracture in 5.5% (4.5%), and neurostimulator migration in 5.5% (5.5%). Of the 14 subjects who experienced implant site infection, there were 17 events (3 subjects experienced 2 events) of infection. Of those, 5 led to full system explants and 4 led to partial system explants. None included osteomyelitis, meningitis, or infections of the brain.

Figure 2 Percentage seizure reduction over time



The graph shows seizure reduction for those subjects who had at least 70 days of diary in the 3 months before each annual visit (blue bars) as well as sensitivity analyses allowing diaries as short as 28 days, and using either last observation carried forward (red bars) or a worst case (100% worsening from baseline, yellow bars) data imputation methodology for subjects with fewer than 28 diary days. Also shown is seizure reduction for those subjects who had at least 28 days of diary in the 3 months before each and every annual visit, elucidating whether, in the most diary-compliant subgroup of subjects, seizure reductions change over time (constant cohort, green bars). *Wilcoxon signed-rank, $p < 0.001$; **25th percentile bar extends to 100% since more than 25% of 109 subjects were imputed to or had greater than 100% median percent change in total seizure frequency from baseline.

Device-related serious adverse events. Overall, 39 of the 110 implanted subjects (35.5%) had a device-related serious adverse event (SAE) in the study (33.6% in 5 years), with the majority occurring in the first few months following implant. After the blinded phase, 13.6% experienced an SAE. The most frequent SAEs reported any time after implant were implant site infection in 10.0% (10.0% in 5 years) and lead(s) not within target in 8.2% (8.2% in 5 years), with all others reported in 1.8% or less.

Other adverse events. ***Depression.*** Depression events were reported in 37.3% (32.7% in 5 years) at some time after implant. Three events in 3 subjects were considered device-related. Of the 41 subjects who reported depression, 66% had a history of depression.

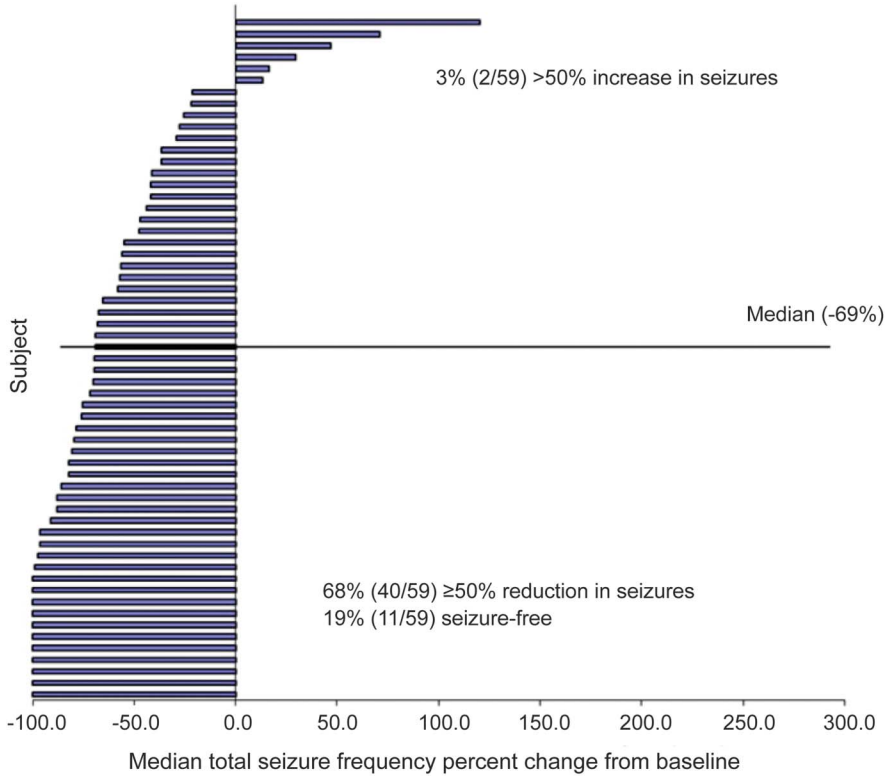
Suicide. After implantation, 11.8% (13 subjects) (8.2% in 5 years) reported at least one instance of suicidal ideation. One subject committed suicide approximately 4 years after implant, not judged by the site investigator or data monitoring committee to be device-related. Ten of the 13 subjects, including the one who completed suicide, had a history of depression. Causes for suicidal ideation were multifactorial and none of the episodes of suicidal ideation were considered by the treating physician to be device-related.

Memory impairment. Memory impairment was reported in 27.3% of subjects at some time after implant (25.5% in 5 years). None of the events were considered serious. Of the 30 subjects who had an adverse event of memory impairment, 50% had a history of memory impairment. Approximately a third of memory impairment events were confirmed with a change from baseline in neuropsychological testing. It did not appear that memory impairment was related to seizure control or to any particular stimulation parameter.

Status epilepticus occurred in 7 subjects (6.4%) during the study. Four of the 7 events were nonconvulsive in nature. Six of the 7 subjects required hospitalization for their status epilepticus. Three of the 7 events occurred in subjects who were not receiving stimulation.

Sudden unexpected death in epilepsy. To evaluate the SUDEP rate, the 7 deaths during the study were considered. None were considered by the investigator or data monitoring committee to be device-related. One probable SUDEP occurred in the baseline phase, and 2 definite and 1 possible SUDEP occurred after implant, none occurring after 5 years. The remaining 3 deaths were due to suicide, cardiorespiratory arrest, and liver cancer. Including

Figure 3 Distribution of individual subject response to treatment

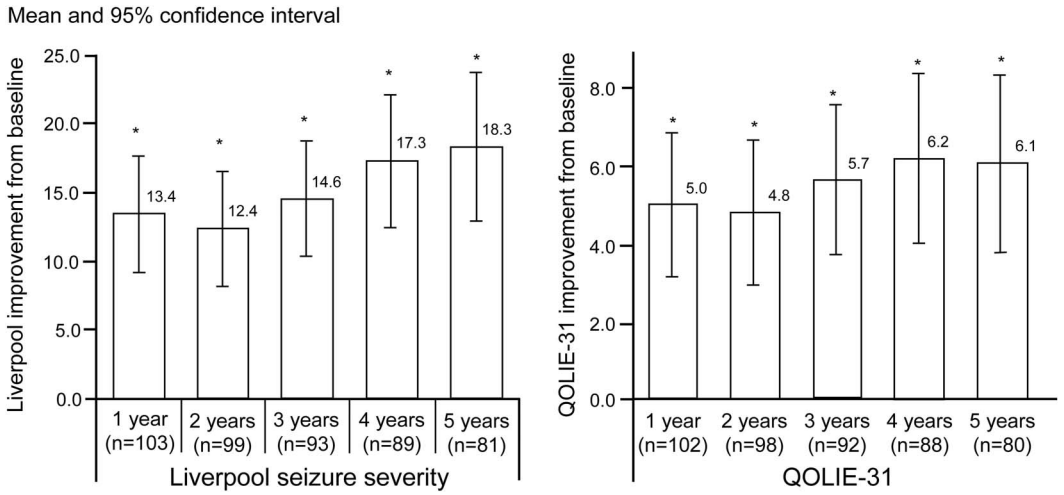


The graph shows the by-subject distribution of total seizure frequency percent change from baseline at 5 years for subjects who had at least 70 days of diary in the 3 months before the year 5 visit. Negative values indicate a seizure frequency reduction compared with baseline.

the pilot studies, SUDEP rate of definite/probable SUDEP was 2.9 per 1,000 patient-years (95% CI: 0.3, 10.4), which is lower than published SUDEP rates as high as 9.3 per 1,000 patient-years in epilepsy surgical candidates.[10] The SUDEP rate excluding subject follow-up after 5 years is 3.9 per 1,000 patient-years (95% CI: 0.5, 14.01).

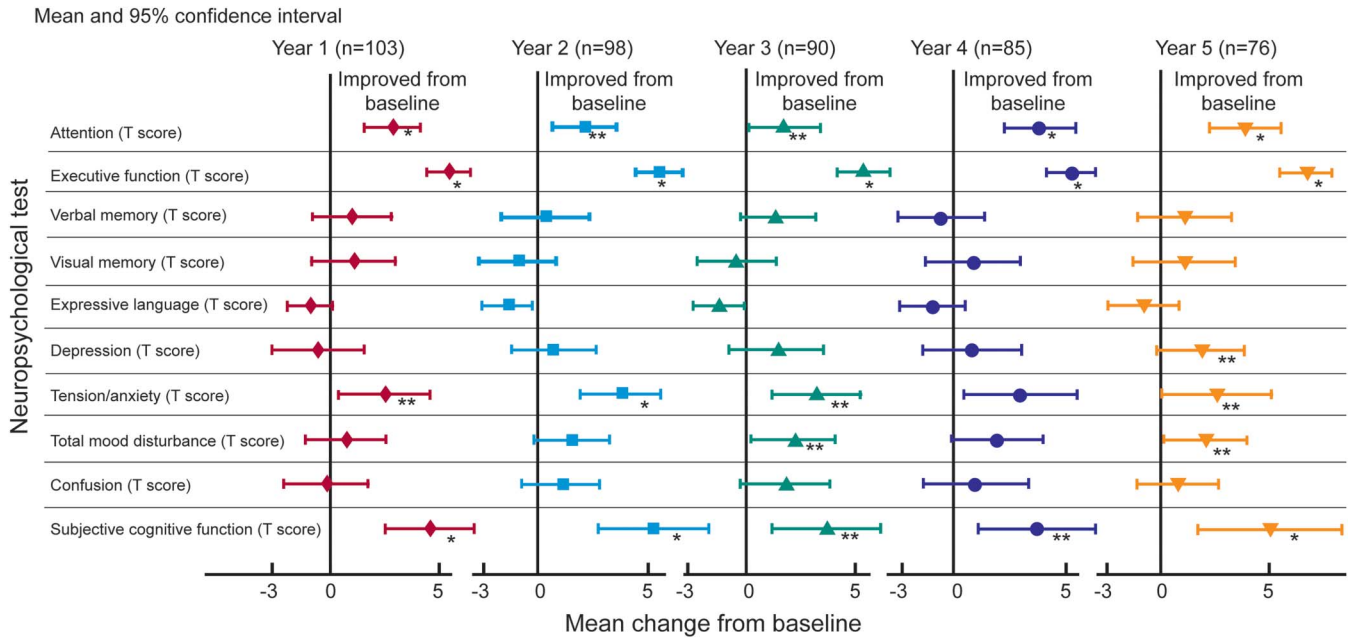
DISCUSSION Long-term deep brain stimulation (DBS) for epilepsy showed a sustained and statistically

Figure 4 Seizure severity and quality of life



The graph shows responses to the Liverpool Seizure Severity Scale and the 31-item Quality of Life in Epilepsy (QOLIE-31) scale for all subjects who completed the respective questionnaire at each annual visit. Higher values reflect improvement in both charts. A QOLIE-31 change of at least 5 points is considered clinically meaningful.[9] *Paired *t* test, $p < 0.001$.

Figure 5 Neuropsychological outcomes



The graph shows composited T scores across several neuropsychological tests within each given domain, over time. Positive values represent an improvement in each outcome. *$p < 0.001$, **$p < 0.05$, Wilcoxon signed-rank nonparametric test.

significant seizure frequency reduction from baseline after 1, 2, 3, 4, and 5 years of stimulation. Also showing significant improvement were responder rates, seizure severities, quality of life, and reductions in most severe seizures. Certain subgroups improved over baseline, including those with temporal or frontal seizure origin, those with or without prior VNS, and those with prior epilepsy surgery. Seizures originating in lobes other than frontal or temporal showed trends toward improvement, but small sample size and variability precluded achieving significance.

Several clinical markers improved in addition to seizure frequency. Five years after implantation, nearly half of the subjects experienced a clinically meaningful improvement in quality of life. Likewise, improvement of 18.3 in the LSSS at 5 years is in the range of changes considered to be clinically significant.[11,12]

Because all subjects received active stimulation at month 4, all subsequent evaluations were unblinded and compared with an earlier baseline, rather than with a parallel control group. We therefore cannot rule out factors other than the stimulation as the cause for the improvement. It is nonetheless encouraging that the benefits observed during the blinded phase did not diminish and in fact seemed to increase over time.

An obvious question is whether long-term results are better because those doing poorly discontinued from the trial. Even making a worst case assumption of 100% seizure increase in those discontinued, seizure frequency was still approximately 50% of baseline at 5 years. These data strongly suggest that discontinuations for lack of efficacy do not account for much of the improvement over time. Medication changes, which were not analyzed in detail during the long-term follow-up phase, also could account for some improvement. Two points argue against this being a major effect. First, subjects had been tried on at least 3 AEDs before entry without major benefit. Second, medications were kept constant in almost all subjects from month 4 through month 13 of the trial, and improvement was evident during this phase. Furthermore, subjects treated with new medications and stimulation did not improve faster than those with stable medications and stimulation.

Steady improvement over several years of neurostimulation has been reported for both VNS and responsive neurostimulation.[8,13] Our results now add thalamic DBS to this list. It is interesting by way of contrast that DBS for Parkinson disease affects tremor and bradykinesia within minutes of initiation. The differences of location of stimulation and underlying disorder likely have a large role in this difference. The mechanisms of progressive improvement with neurostimulation are unknown.

Most adverse events associated with neurostimulation occur around the time of device implantation. As detailed in the randomized phase of the SANTE trial,[7] device-related implantation problems were reversible and as expected with this surgical procedure. The percentage of subjects in this study with implant site pain (most common device-related

adverse event) is consistent with rates reported for prospective DBS studies in Parkinson disease.[14] At 5 years after device implantation, there was a high subject retention rate of 75%, and 73% of subjects also indicated they were satisfied with the therapy, suggesting that stimulation was well-tolerated in this study population.

An interpretive difficulty arises because of the high prevalence of depression and memory problems in people with refractory epilepsy. Our follow-up included depression in 37.3% of subjects, memory impairment in 27.3%, status epilepticus in 6.4%, and suicidal ideation in 11.8%, with one suicide. However two-thirds of the subjects reporting depression had a history of depression, and half of the subjects reporting memory impairment had a history of memory impairment.

Prevalence of depression in people with epilepsy in community settings has been reported to range from 12% to 37%. A recent systematic review and meta-analysis of depression in 29,891 people with epilepsy showed an overall prevalence of active depression of 23.1%.[15]

Cognitive impairment has long been associated with intractable epilepsy. A study in 136 patients with refractory epilepsy found that "cognitive decline was severe and occurred across a wide range of cognitive functions."[16] Favorable effects on cognition have also been reported for thalamic stimulation. A case series study[17] reported 9 patients with intractable epilepsy treated with continuous anterior nucleus of the thalamus (ANT) DBS who underwent cognitive testing before implantation and more than 1 year after surgery. The mean seizure reduction after DBS was 57.9% and was accompanied by favorable cognitive test results for verbal fluency tasks and a significant improvement in delayed verbal memory. The authors hypothesized that these improvements may be attributable to bilateral activation of fronto-limbic circuits during DBS.[17]

Some subjects reported mood and memory problems, but objective neuropsychological testing of the overall study group showed improved attention, executive function, depression, tension/anxiety, mood disturbance, and subjective cognitive function compared with baseline. It remains to be determined whether there are individual risk factors predisposing to emergence or worsening of depression and cognition during ANT stimulation.

Repeated electrical stimulation of the brain in animal models of epilepsy can produce kindling.[18] It is reassuring that no evidence of kindling and increasing seizures/status epilepticus over time was seen in the 5 years of our observation, although this does not rule out problems with neurostimulation beyond 5 years. However, 41, 31, and 6 subjects have been observed respectively at 7, 8, and 9 years with no evidence of stimulation-linked seizures or increased rate of status epilepticus.

Despite limited understanding of the mechanisms of benefit for DBS in epilepsy, our observation is that long-term ANT DBS is well-tolerated and associated with a significant and sustained reduction in the frequency and severity of seizures in a very refractory patient population.

AUTHOR CONTRIBUTIONS

V. Salanova: conception or study design, analysis or interpretation of the data, drafting or revising the manuscript for intellectual content, acquisition of data. T. Witt: drafting or revising the manuscript for intellectual content, acquisition of data. R. Worth: drafting or revising the manuscript for intellectual content. T. Henry: conception or study design, analysis or interpretation of the data, drafting or revising the manuscript for intellectual content, acquisition of data. R. Gross: drafting or revising the manuscript for intellectual content. J. Nazzaro: drafting or revising the manuscript for intellectual content. D. Labar: analysis or interpretation of the data, drafting or revising the manuscript for intellectual content. M. Sperling: drafting or revising the manuscript for intellectual content, acquisition of data. A. Sharan: analysis or interpretation of the data, drafting or revising the manuscript for intellectual content. E. Sandok: analysis or interpretation of the data, drafting or revising the manuscript for intellectual content, acquisition of data, local study supervision or coordination. A. Handforth: analysis or interpretation of the data, drafting or revising the manuscript for intellectual content, local study supervision or coordination. J. Stern: drafting or revising the manuscript for intellectual content, acquisition of data, local study supervision or coordination. S. Chung: drafting or revising the manuscript for intellectual content, acquisition of data, local study supervision or coordination. J. Henderson: drafting or revising the manuscript for intellectual content, acquisition of data. J. French: analysis or interpretation of the data, drafting or revising the manuscript for intellectual content. G. Baltuch: conception or study design, drafting or revising the manuscript for intellectual content, acquisition of data. W. Rosenfeld: drafting or revising the manuscript for intellectual content, acquisition of data, local study supervision or coordination. P. Garcia: analysis or interpretation of the data, drafting or revising the manuscript for intellectual content. N. Barbaro: drafting or revising the manuscript for intellectual content, acquisition of data, local study supervision or coordination. N. Fountain: drafting or revising the manuscript for intellectual content, acquisition of data, local study supervision or coordination. W. Elias: drafting or revising the manuscript for intellectual content, acquisition of data, local study supervision or coordination. R. Goodman: drafting or revising the manuscript for intellectual content. J. Pollard: analysis or interpretation of the data, drafting or revising the manuscript for intellectual content, local study supervision or coordination. A. Tröster: conception or study design, analysis or interpretation of the data, drafting or revising the manuscript for intellectual content. C. Irwin: analysis or interpretation of the data, statistical analysis. K. Lambrecht: analysis or interpretation of the data, drafting or revising the manuscript for intellectual content. N. Graves: conception or study design. R. Fisher: conception or study design, drafting or revising the manuscript for intellectual content.

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DISCLOSURE

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