Longevity decoded: Insights from power consumption analyses into device construction and their clinical implications

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Abstract

Introduction: The longevity of a cardiac implantable electronic device (CIED) depends on how quickly the powers consumed by the device’s functions exhaust its usable battery energy. A mathematical model for CIED power consumptions was developed and validated against longevity data from manufacturers.

Methods: The programmable parameters for the Resonate X4 cardiac resynchronization therapy defibrillators (CRT-Ds) on the Boston Scientific (St. Paul, MN, USA) online longevity calculator were designated as independent terms in the sum for the total power consumption. The reciprocal of longevity was plotted against variations in these terms. Linear and nonlinear regression analyses were used to fit the plots. The power consumed by pacing was theoretically derived and used as the calibrating tool for estimating the powers consumed by other functions and the usable battery energy. The same methodology was applied to the longevity data of other manufacturers’ CRT-Ds.

Results: Single chamber 100% pacing at 60 beats/min, 2.5 V, 0.4 ms, 500 Ω consumes ≈ 144 J/year. Shock therapy is 45–85% energy efficient. Multichamber pacing modes and maintaining readiness to pace a chamber consume power even if no pacing is delivered. Switching voltage regulation is theoretically more energy efficient than linear voltage regulation for powering pacing.

Conclusions: The powers consumed by therapy functions are dictated by the patient’s clinical needs, but healthcare professionals can extend device longevity by switching off dormant functions and simplifying the pacing mode. Choosing a device model with large usable battery energy, low background power, and energy efficient pacing and shock therapy for implantation will increase the probability of a long service lifespan.

Keywords: background power, linear regulation, longevity, power consumption, regression analyses, switching regulation, usable battery energy, voltage multiplication-division

1 | INTRODUCTION

The longevity of cardiac implantable electronic devices (CIEDs) should be an important if not the primary performance attribute in model choice, as battery depletion is the dominant cause of device replacement, which entails not only fiscal cost but also risk of infection and lead failure. The longevities quoted by manufacturers for their latest generation of device models are inevitably projections (typically based on nonuniform settings) and have historically turned out to be overestimates in clinical practice, even after correction for use conditions. The observed longevities reported in single/multicenter studies, registries, and product performance reports (PPRs) can only pertain to previous generations of device models, which have become technologically obsolete and may no longer be...
available for new implantation by the time significant clinical experience has accrued. Confronted with a bewildering array of conflicting claims and estimates, implanters cannot readily base model choice on longevity, which is an especially important clinical concern for implantable cardioverter-defibrillators (ICDs) and cardiac resynchronization therapy defibrillators (CRT-Ds).

Boston Scientific (BSc; St. Paul, MN, USA) is the first CIED manufacturer to provide an open access online device longevity calculator. Data from the calculator can be used to deduce the functional (and structural) components of BSc CIEDs and their power consumptions. That knowledge was used to develop a mathematical model that produced reasonably accurate longevity projections for any arbitrary settings. The same methodology was also successfully applied to device models by other CIED manufacturers despite many fewer longevity projections were listed in the publicly available information sources. Even from the limited information released by manufacturers, valuable insights can be gained into the construction and power consumptions of their devices to guide device selection and programming.

2 | METHODS

See Table 1 for a list of the symbols and abbreviations.

2.1 | Relationships between longevity, battery energy, and power consumptions

If a CIED has usable battery energy \( W^u \), its longevity in service \( t^p \) is given by:

\[
 t^p = \frac{W^u}{P^n} \quad (1a)
\]

\[
P^n = \sum n P_n \quad (1b)
\]

where \( P^n \) is the sum of the average powers \( P_n \)'s consumed by the different functions/components (assumed to be independent and additive). While some functions are performed continuously (e.g., running the device's operating system, heart rhythm monitoring), other functions are performed periodically (e.g., remote transmission, high-voltage capacitor reformation, battery conditioning), intermittently (e.g., pacing), or sporadically (e.g., shocks).

2.2 | Pacing impulse energy

The energy of a pacing impulse \( W_p \) (in joule, J) of duration \( \tau_p \) (in second) depends on whether switching regulation (SR) or linear regulation (LR) is used to produce the (peak) output amplitude \( V_p \) (in volt, V) (see Appendix A)\(^{14} \):

\[
\langle W_p \rangle_{SR} = \frac{C_p V_p^2}{2} \left[ 1 - \exp \left( -\frac{2}{C_p} \frac{\tau_p}{Z_p + a_p} \right) \right] \approx \frac{V_p^2 \tau_p}{Z_p + a_p} \left( 1 - \frac{1}{C_p Z_p + a_p} \right) \approx \frac{V_p^2 \tau_p}{Z_p + a_p},
\]

where \( P^n \) is the sum of the average powers \( P_n \)'s consumed by the different functions/components (assumed to be independent and additive). While some functions are performed continuously (e.g., running the device's operating system, heart rhythm monitoring), other functions are performed periodically (e.g., remote transmission, high-voltage capacitor reformation, battery conditioning), intermittently (e.g., pacing), or sporadically (e.g., shocks).

\[
\langle W_p \rangle_{LR} = \frac{C_p V_p^2}{2} \left[ 1 - \exp \left( -\frac{2}{C_p V_p} \frac{V_p \tau_p}{Z_p + a_p} \right) \right] \approx \frac{V_p C_p V_p}{Z_p + a_p} \left( 1 - \frac{1}{C_p V_p Z_p + a_p} \right) \approx \frac{V_p V_p}{Z_p + a_p}. \quad (2)
\]

See Table 1 for a list of the symbols and abbreviations.

### Table 1: List of symbols and abbreviations

| Symbol/abbreviation | Meaning |
|---------------------|---------|
| CIED | Cardiac implantable electronic device |
| ICD | Implantable cardioverter defibrillator |
| CRT-D | Cardiac resynchronization therapy defibrillator |
| SR | Switching (voltage) regulation/regulator |
| LR | Linear (voltage) regulation/regulator |
| \( W^u \) | Usable battery energy |
| \( t^p \) | Device longevity |
| \( P^n \) | Total device power consumption |
| \( P_{bg} \) | Device background power consumption |
| \( W_p (W_k) \) | Pacing impulse energy (for a particular cardiac chamber) |
| \( \langle (W_p)_p \rangle_{SR} \) | Pacing impulse energy (switching voltage regulation) |
| \( \langle (W_p)_p \rangle_{LR} \) | Pacing impulse energy (linear voltage regulation) |
| \( f_p \) | Pacing frequency (base rate) |
| \( \eta_p (\%_p) \) | Percentage of pacing (for a particular cardiac chamber) |
| \( V_b \) | Battery voltage |
| \( V_p (V_k) \) | Peak pacing output amplitude (for a particular cardiac chamber) |
| \( V_C (V_k) \) | Peak pacing capacitor voltage (for a particular cardiac chamber) |
| \( \tau_p (\tau_k) \) | Pacing pulse width (for a particular cardiac chamber) |
| \( Z_p (or Z_k) \) | Pacing load impedance (for a particular cardiac chamber) |
| \( a_p (a_k) \) | Pacing internal impedance (for a particular cardiac chamber) |
| \( C_p (C_k) \) | Pacing capacitance (for a particular cardiac chamber) |
| \( \eta_p (\%_p) \) | Pacing energy efficiency (for a particular cardiac chamber) |
| \( P_{exp} (P_{sk}) \) | Average pacing power (for a particular cardiac chamber) |
| \( W_s \) | Shock energy |
| \( f_s \) | Shock frequency |
| spyr | Shocks per year |
| \( \eta_s \) | Shock energy efficiency |
| \( P_s \) | Average shock therapy power |
| \( m \) | Slope of linear regression line |
| \( x_0 \) | Horizontal intercept of linear regression line |
| \( Y_0 \) | Vertical intercept of linear regression line |
| \( \lambda \) | Scale factor for variable in linear regression against \( 1/t^p \) |
| \( k \) | An integer referring to a particular cardiac chamber |
where $Z_p$ (in ohm, Ω) is the load impedance, $a_p$ (in Ω) is the internal resistance, $C_p$ (in farad, F) is the pacing capacitance, and $V_C$ (in V) is the (peak) capacitor voltage. ($V_C$ may be below, equal to, or above the device’s battery voltage $V_b$).

$a_p$ and $C_p$ can be estimated from limited longevity data (see Appendices B and E), which then allows $W_p$ to be calculated for different pacing parameters. $W_p$ can be used as an “energy unit” to estimate the powers consumed by other functions and the usable battery energy $W^*$ (see below). In clinical practice, $f_p$ is typically expressed in ms. Pacing capacitance $C_p$ is thus more conveniently expressed in millifarad (mF) rather than the more commonly used microfarad ($\mu$F) as the term $f_p/C_p(Z_p + a_p)$ will automatically be a dimensionless value without scaling. With the same convention on units, the terms $C_p V_p^2$, $C_p V_p^2 f_p/(Z_p + a_p)$, and $V_C V_p f_p/(Z_p + a_p)$ will have the unit of millijoule (mJ). Equation (2)/(3) allows the pacing impulse energy $W_p$ to be calculated exponentially, quadratically, or linearly.

### 2.3 Pacing power consumption

For pacing frequency (base rate) $f_p$, and percentage $\%_p$, the power consumed $P_p$ is:

$$P_p = \frac{f_p \%_p W_p}{\eta_p} = \frac{f_p \%_p W_p}{\eta_p} (V_p, f_p, Z_p, a_p, C_p, V_C)(4)$$

where $\eta_p > 0$ is the energy efficiency of pacing after allowing for the internal resistance $a_p$.

In clinical practice, $f_p$ is typically expressed in beats/min, whereas the reciprocal of device longevity $1/t^*$ is in year$^{-1}$ (yr$^{-1}$).

$$1 \text{ yr} = 365 \times 24 \times 60 \text{ min} = 525600 \text{ min} \Rightarrow \frac{1 \text{ min}}{525600 \text{ yr}} = \frac{1}{525600 \text{ yr}}$$

$$1 \text{ beats/min} \cdot \% = \frac{1 \text{ min}}{525600 \text{ yr}} \cdot \frac{1}{100} = \frac{525600 \text{ yr}}{100} \cdot \frac{1}{100} = 5256 \text{ yr}^{-1}.$$  

With the units used clinically, $W_p$ has the unit of mJ. $P_p$ thus has the unit of:

$$5256 \text{ yr}^{-1} \times 10^{-2} \text{ J} = 0.5256 \text{ J/yr},$$

$$1 \text{ J/yr} = \frac{1 \text{ J}}{365 \times 24 \times 60 \text{ s}} = 3.17 \times 10^{-8} \text{ J/s}^{-1} = 0.0317 \text{ μW}.$$  

Battery capacity is typically quoted in ampere-hour (A-h). Assuming an average voltage of 2.9 V for a lithium anode primary battery used to power CIEDs:

$$1 \text{ A} \cdot \text{h} \times 2.9 \text{ V} = 3600 \times 12.9 \text{ J} = 40440 \text{ J}.$$  

### 2.4 Shock therapy power consumption

The (average) power consumed by (sporadic) shock therapy $P_s$ is:

$$P_s = f_s \frac{W_s}{\eta_s},$$  

where $W_s$ is the energy (in J) stored on (generally not completely delivered by) the high-voltage capacitor for each shock, $f_s$ is the shock frequency (in shocks per year, or spyr), and $\eta_s > 0$ is the shock energy efficiency. With these units, $P_s$ has the unit of J/yr.

### Table 2

| Function (component) | Symbol | Formula | $\Delta(1/yr)$ for Resonate X4 |
|----------------------|--------|---------|-------------------------------|
| Running the operating system | $P_0$ | $P_0$ | 0.058 |
| Pacing | $P_1$ | $P_{1k} = \frac{f_k \%_k W_k}{\eta_k}$ | variable |
| Shock therapy | $P_2$ | $P_{2} = f_s \frac{W_s}{\eta_s}$ | 1spyr = 0.0021 for $f_s < 4$  
1spyr = 0.0042 for $f_s > 4$ |
| Brady mode | $P_3$ | $\sum_{k=0}^{3} P_{3k} 1_{3k}$ | $P_{30} = 0$  
$P_{31} = 0.0037$  
$P_{32} = 0.0057$  
$P_{33} = 0.0065$  
$P_{34} = 0.0067$ |
| Ventricular chambers paced | $P_4$ | $\sum_{k=0}^{2} P_{4k} 1_{4k}$ | $P_{40} = 0$  
$P_{41} = 0.0011$  
$P_{42} = 0.0041$  
$P_{43} = 0.0011$ |
| Multisite pacing | $P_5$ | $P_{50} 1_{50}$ | $P_5 = \mu_{0.012}$ |
| Remote monitoring | $P_6$ | $P_{60} 1_{60}$ | $P_6 = \mu_{0.033}$ |
| Minute ventilation | $P_7$ | $P_{70} 1_{70}$ | $P_7 = \mu_{0.003}$ |
| Heart failure sensor suite | $P_8$ | $P_{80} 1_{80}$ | $P_8 = \mu_{0.006}$ |
| SonR | $P_9$ | $P_{90} 1_{90}$ | \(—\) |

Note: A = atrial; CRT-D = cardiac resynchronization therapy defibrillator; LV = left ventricular; RV = right ventricular. Turning the brady mode off and pacing no ventricular chamber are assumed to consume no power (i.e., $P_{30} = 0$ and $P_{40} = 0$). Figures in the last column pertain only to the Resonate X4 G447 CRT-D. (See Table 1 for meanings of the symbols and notations).

### 2.5 Other power consumptions

As the CRT-D has the largest set of programmable functions for CIEDs and the BSC online longevity calculator was the most accessible tool for longevity projection study, the Resonate X4 G447 was used to build the basic list of power consumptions $P_k$’s (Table 2). Functions common to all CIEDs were assigned lower indices in the list. Functions unique to particular device models (e.g., minute ventilation, heart failure suite, SonR) were assigned higher indices. The list so generated should thus be general enough to be applicable to most CIED models.

Substituting Eqs. (4) and (5) into Eq. (1b):

$$P^* = P_0 + f_p \sum_{k=0}^{2} \%_k W_k + f_s \frac{W_s}{\eta_s} + \sum_{k=3}^{4} \sum_{l=0}^{k} P_{lk} 1_{lk}.$$  

$P_0$ is the minimum power needed to operate the device. The $P_{lk}$’s are the powers consumed by pacing the atrium (A), right ventricle (RV), left ventricle (LV), and a second LV site (LV₂), $P_2$ is the power consumed...
by shock therapy. The $P_{sk}$’s are the powers consumed by the pacing modes. The $P_{sk}$’s are the powers consumed by maintaining readiness to pace the ventricular chambers. $(P_{sk})$ is not available in the BSc online longevity calculator but was assumed if pacing the RV, LV, or both makes no difference to $1/t^s$, as for the OOO or AAi(R) mode.) The $P_{n0}$’s ($n \geq 5$) are single-option binary (“on-off”) functions ($f_0 = 0$ in Eq. (6)). The $1_{nk}$’s ($n \geq 3$) are indicator functions that take the value of 0 or 1 depending on whether the corresponding functions are off or on.

### 2.6 Estimation of usable battery energy and power consumptions

Inverting Eq. (1a) and substituting Eqs. (4) and (6) into Eq. (1b) give:

$$\frac{1}{t^s} = \frac{1}{W^s} \left( P_{p0} + f_p \sum_{k=0}^3 \frac{a_k}{\eta_k} W_k (V_k, \tau_k, Z_k, a_k, C_k, V_{ck}) + f_{sk} \frac{\sum_{n=1}^5 \sum_{k=0}^4 P_{nk} \eta_k}{\eta_s} \right).$$  \(7\)

Equation (7) is a linear equation in multiple variables (which may be derivatives of one or more parameters). Changing only one of these variables $x$ at a time and lumping the terms containing all the other constant variables into a background power $P_{p0}$, Eq. (7) becomes:

$$\frac{1}{t^s} = \frac{1}{W^s} (P_{p0} + \lambda x).$$  \(8\)

By Eq. (8), a plot of $1/t^s$ against $x$ will be a straight line of slope $m = \lambda / W^s$, vertical intercept $y_0 = P_{p0} / W^s$, and horizontal intercept $x_0 = -P_{p0} / \lambda$. The values of $m$, $y_0$, and $x_0$ can be readily estimated with linear regression from any suitable data set. Once these regression coefficients are known, other variables in Eq. (8) can be estimated:

- If $\lambda$ is known: $W^s = \lambda / m$  
- $P_{p0} = -\lambda x_0$  
- If $W^s$ is known: $\lambda = mW^s$  
- $P_{p0} = y_0 W^s$.  \(9\)

A pacing power $P_{sk}$ depends on nine variables: $f_p$, $\%_k$, $V_k$, $\tau_k$, $Z_k$, $a_k$, $C_k$, $V_{ck}$ (Eq. (4)). The first five variables can change significantly in clinical use, whereas the last four may be regarded as fixed and their values estimated from available longevity data (see Appendices B and E). From Eqs. (2)/(3) and (7), if $x$ is $P_{sk}$, $f_p$, $\%_k$, $V_k$ (or $V_{ck}$), it will have a linear relationship with $1/t^s$. The value of $\lambda$ can be calculated from Eqs. (2)/(3) and (4). This means $W^s$ and $P_{p0}$ can be estimated from the linear regression coefficients with Eqs. (9a) and (9b). Once $W^s$ has been estimated for a device, it can be used to estimate the $\lambda$ and $P_{p0}$ for a different regression line (from another variable-background power pair) with Eqs. (9c) and (9d).

From Eq. (7), $f_s$ has a linear relationship with $1/t^s$ with $\lambda = W_s / \eta_s$. Since $W_s$ (generally assumed to be the maximum shock energy possible) is always supplied by the manufacturer, if $W^s$ is known, from Eq. (9c):

$$\lambda = \frac{W_s}{\eta_s} = mW^s \Rightarrow \eta_s = \frac{W_s}{mW^s}. \quad (10)$$

Shock energy efficiency can also be estimated by establishing the equivalence (in terms of impact on longevity) between shock and pacing powers. If a rise in shock frequency $\Delta f_s$ has the same impact on device longevity as a rise in pacing power $\Delta P_p$, then:

$$\Delta \left( \frac{1}{t^s} \right) = \frac{\Delta P_p}{W^s} = \frac{\Delta P_p}{W^s} \Rightarrow \Delta f_s = \frac{W_s}{\eta_s} = \frac{\Delta f_s \cdot W_s}{\Delta P_p}. \quad (11)$$

If $x = 1_{nk}$, then $\lambda = P_{nk}$ and:

$$P_{nk} = \frac{1}{t^s} (1_{nk} = 1) - \frac{1}{t^s} (1_{nk} = 0) = \Delta \left( \frac{1}{t^s} \right)_{nk}. \quad (12)$$

Equation (12) means the power of a programmable function $P_{nk}$ can be estimated from the difference in the reciprocal of longevity between switching the function on and off, and this difference is well-defined and independent of the background power $P_{p0}$ (i.e., $\Delta (1/t^s)_{nk}$ will not have different values depending on $P_{p0}$). If $W^s$ is constant for a device model, $\Delta (1/t^s)_{nk}$ can be used as a surrogate measure of $P_{nk}$.

### 2.7 Validation of mathematical model

To assess the powers consumed by pacing, one out of five parameters ($f_p$, $\%_k$, $V_k$, $\tau_k$, $Z_k$) for one or more cardiac chambers was altered at a time. The plot of $1/t^s$ against the varying parameter or its derivative (e.g., $V_k^2$, $1/Z_k$, $\tau_k/Z_k$) was inspected for a possible algebraic (linear, quadratic, or exponential) relationship, and regression analysis was performed whenever a reasonable fit could be achieved. The regression coefficients were used to estimate the internal resistance $a_k$ and pacing capacitance $C_k$ (see Appendices B and E), which would in turn be used to calculate the pacing power $P_p$ by Eqs. (2)/(3) and (4). Once $P_p$ is known, the other terms in Eq. (7) were calculated using Eqs. (8)–(12).

### 2.8 Numerical analyses

All regression analyses were performed by the least-square criterion with a statistical package (Prism, GraphPad Software, San Diego, CA, USA).

### 2.9 Device models and data sources for longevity and power consumption analyses

Only CRT-D models were analyzed. For BSc, the Resonate X4 G447 was chosen (data source: online longevity calculator). For Abbott (Abt, formerly St. Jude Medical, Sylmar, CA, USA), the Quadra Assura MP model CD3369–40Q was chosen (data source: PPR 2018, 1st edition; manufacturer’s technical support). For Microport (Mcp, formerly LivaNova, Clamart, France), the Platinum 4LV SonR model 1844 was chosen (data source: online device longevity stimulator, http://www.cardiacdevicelongevity.com/longevity/, manufacturer’s technical
FIGURE 1  Effects of RV pacing parameters on Resonate X4 longevity. Plots produced with figures obtained from the online longevity calculator provided by Boston Scientific for the Resonate X4 G447 CRT-D. The reciprocal of longevity is linearly related to the base rate (A) and percentage (B) of pacing, and the square of the output amplitude (C) and (D). The reciprocal of longevity appears to be related to the reciprocal of impedance (E) and pulse width (pw) (F) through an inverted negative exponential rise to a plateau, and the two factors affect each other’s relationship. RV = right ventricular [Color figure can be viewed at wileyonlinelibrary.com]

support). For Biotronik (Btk, Berlin, Germany), the Intica 7 HF-T (QP) was chosen (data: manual). For Medtronic (Mdt, Minneapolis, MN, USA), the Viva Quad XT model DTBA1QQ was chosen (data source: manual; a previous publication 15).

3 | RESULTS

3.1 | SR for pacing

The Resonate X4 was set to VVIR (P31) and RV-only pacing (P41), with no shock therapy and all nonessential functions off on the BSc online longevity calculator. The default values were: $f_p = 60 \text{ beats/min}; \%_1 = 100\%; V_1 = 2.5 \text{ V}; \tau_1 = 0.4 \text{ ms}; Z_1 = 500 \Omega$. The $1/t^\circ - f_p$ and $1/t^\circ - %_1$ plots are straight lines (Figures 1A and B). The $1/t^\circ - V_1^2$ plot is a parabola (Figure 1C) but the $1/t^\circ - V_1^2$ plot is a straight line (Figure 1D), which suggests SR (see Appendices A and B).

The $1/t^\circ - 1/Z_1$ and $1/t^\circ - \tau_1$ plots are a series of convex upward curves for different values of the other variable (Figures 1E and F). When $1/t^\circ$ is plotted against $\tau_1/Z_1$, both sets of curves become better but still not perfectly aligned (Figures 2A and B). However, the “iso-longevity” curves of $(\tau_1, Z_1)$ pairs giving rise to the same longevity (with linear interpolation between adjacent data points when the exact longevity figure was not given by the online calculator) are straight lines (Figure 2C), which suggests $t^\circ$ is dependent on $(\tau_1, Z_1)$ only through their ratio $\tau_1/(Z_1 + \alpha_1)$, where $\alpha_1 \approx 60 \Omega$ corrects for the negative intercept on the $Z_1$ axis by the iso-longevity lines (Figure 2C). When $1/t^\circ$ is plotted against $\tau_1/(Z_1 + \alpha_1)$, both sets of curves become perfectly aligned and in fact overlapping (Figures 2D and E). When
FIGURE 2 Effects of the pw: impedance (with or without adjustment for internal resistance) ratio on Resonate X4 longevity. (A) and (B) For a fixed pacing amplitude, the pw: impedance ratio does not consistently predict the reciprocal of longevity. (C) Iso-longevity curves suggest a correction term, an internal resistance, needs to be added to the load impedance to give an adjusted impedance. (D) and (E) The pw: adjusted impedance ratio consistently predicts the reciprocal of longevity. (F) The plot of the reciprocal of longevity against the total pacing power for the settings in the Viva Quad XT manual incorporating the estimated internal resistance and pacing capacitance is a straight line. The slope of the line is the reciprocal of the usable battery energy $1/W^\circ$. The horizontal intercept is the negative value of the background power $P_0$. pw = pulse width [Color figure can be viewed at wileyonlinelibrary.com]

the two sets of curves were regressed for an exponential model (general equation $y = y_0 + (y_1 - y_0)(1 - e^{-\kappa x})$), the vertical intercepts $y_0$ (0.05852 and 0.05874), vertical spans $y_1 - y_0$ (0.0612 and 0.0613), and rate constants $\kappa$ (244.5 and 239.8) are similar. From Eq. (2):

$\frac{2}{C_1} = \kappa = 240 \Rightarrow C_1 = 0.008 \text{ mF}$.

Figures 2C–E give a graphical way of estimating internal resistance $a_1$ and capacitance $C_1$, but their values can also be estimated analytically (see Appendix B). For $a_1 = 100 \text{ }\Omega$ and $C_1 = 0.01 \text{ mF}$, $\langle W_p \rangle_{SR} = 0.0039 \text{ mJ}$ (see Appendix A). By Eq. (4), assuming $\eta_1 = 0.85$:

$P_p = f_p \eta_1 \frac{W_p}{\eta_0} = 5.256 \times 60 \times 100 \times \frac{0.0039}{0.85} \frac{J}{\text{yr}} = 144 \frac{J}{\text{yr}}$.

For the variables with a linear relationship with $1/t^\circ$ ($f_p$, $\%_1$, and $V_1^2$, Figures 1A, B, and D), the slope $m$ and horizontal intercept $x_0$ of the regression line were used to estimate $W^\circ$ and $P_0$ (Table 3). Using
the same values for the internal resistance, capacitance, and energy efficiency for all three pacing channels, the total pacing power $P_1 = \sum_{k=0}^{2} P_{1k}$ for the settings in the Viva Quad XT CRT-D manual (which involve simultaneous changes in the amplitude and impedance of all three pacing channels) was calculated (see Appendix C). The $1/t_s^{-1} P_1$ plot is a straight line (Figure 2F), validating Eqs. (2) and (4) used in $P_1$’s calculation (Table 3).

### 3.2 | LR for pacing

The longevity data supplied by the manufacturer of the Quadra Assura MP assumed 100% A, RV and LV pacing at 60 beats/min, 3 spyr, daily alert, and remote follow-up every 3 months. A and RV pacing were fixed at 2.5 V, 0.5 ms, and 500 Ω. The LV pacing parameters varied: 0.5–7.5 V for amplitude $V_2$, 0.5–1.5 ms for pulse width $t_2$, and 400–1500 Ω for load impedance $Z_2$.

Keeping $t_2$ and $Z_2$ fixed, the $1/t_s^{-1} V_2$ plot comprises three rising steepening straight line segments separated by widening abrupt jumps at $V_2 = 2.5, 5$, and 7.5 V, with a common $1/t_s^{-1}$ intercept and slopes proportional to the $V_2$ value at their upper ends (i.e., 2.5, 5, and 7.5, Figure 3A). Quadratic regression for the upper ends of the three straight line segments produces a parabola that also shares their common $1/t_s^{-1}$ intercept. The $1/t_s^{-1} V_2^2$ plot comprises three rising flattening convex curve segments separated by widening abrupt jumps and whose upper ends lie on a straight line (Figure 3B). The pattern is consistent with LR with peak pacing capacitor voltage $V_{C2} = 2.5, 5$, and 7.5 V (see Appendices A and B). When $V_{C2} = V_{p}$, LR impacts longevity like SR (Figure 1D).

Keeping $V_2$ and $Z_2$ fixed, the $1/t_s^{-1} V_2$ plot appears to be a straight line but has only four points (Figure 3C). Keeping $t_2$ fixed at 1.5 ms (chosen for accentuation of any deviation from linearity), the $1/t_s^{-1} - 1/Z_2$ plot is a series of convex upward curves with curvature positively correlated with $V_2$ (Figure 3D). There were not enough data points to conduct iso-longevity analysis as in Figure 2C. Instead, the slopes of the linear $1/t_s^{-1} V_2$ plot (Figure 3A) for different values of $Z_2$ were used to estimate the internal resistance $a_2 (\approx 120 \Omega)$ (see Appendix B). The $1/t_s^{-1} - 2/Z_2 + a_2$ plot is still a series of convex upward curves but has many more data points on each due to the larger number of $(r_2, Z_2 + a_2)$ combinations (Figure 3E).

### 3.3 | Shock therapy power

The data available only allowed shock therapy power analyses on three device models (Table 4).

For the Resonate X4, the $1/t_s^{-1} f_s$ plot for VV(I)R with 0% RV pacing comprises straight lines of different slopes intersecting at $f_s = 4$ (Figure 5A). The $1/t_s^{-1} V_2^2$ plots (100% RV pacing at 0.4 ms and 500 Ω) for $f_s = 0, 4$, and 8 are three parallel lines with the same slope but different $1/t_s^{-1}$-intercepts (Figure 5B). The estimated shock energy efficiency $\eta_s$ is $\approx 1.5$ for $f_s < 4$ and $\approx 0.75$ for $f_s > 4$ (Table 4).

For the Platinium 4LV SonR, the $1/t_s^{-1} f_s$ plot for VVI 100% biventricular (BiV) pacing comprises straight lines of different slopes intersecting at $f_s = 2$ (Figure 5C). The $1/t_s^{-1} P_{12}$ (LV pacing power) plots (for 100% BiV pacing, RV amplitude 2.5 V at 0.35 ms and 500 Ω) for $f_s = 0, 2, 4$ and 8 are three parallel lines with the same slope but different $1/t_s^{-1}$-intercepts (Figure 5D). The estimated shock energy efficiency $\eta_s$ is $\approx 2.4$ for $f_s < 2$ and $\approx 0.45$ for $f_s \geq 4$ (Table 4).

For the Intica 7 HF-T (QP), the only data available for the study were two tables in the device’s manual showing how combinations of percentage of triple chamber pacing $\%_p$ (2.5 V, 0.4 ms, 500 Ω) and shock frequency $f_s$ affect longevity. The table for no multipoint LV pacing was
FIGURE 3 Effects of LV pacing amplitude, pulse width (pw), and impedance (with or without adjustment for internal resistance) on the longevity of the Quadra Assura MP CRT-D. The parameters of pacing were altered from the default values of 2.5 V, 0.5 ms, and 500 Ω. (A) The plot of the reciprocal of longevity against LV amplitude comprises three rising steepening straight line segments separated by widening abrupt jumps. The line segments have a common vertical intercept and slopes proportional to the LV amplitude at their upper ends, which lie on a parabola. (B) The plot of the reciprocal of longevity against the square of LV amplitude comprises three rising flattening convex curve segments separated by widening abrupt jumps and whose upper ends lie on a straight line. (C) The reciprocal of longevity is linearly related to the LV pw. (D) The plots of the reciprocal of longevity against the reciprocal of LV impedance are a series of convex upward curves with curvature positively with the LV amplitude. (E) The plots of the reciprocal of longevity against the pw: adjusted LV impedance (with the addition of an estimated internal resistance) are still a series of convex upward curves, but have many more data points on each due to the larger number of combinations of pw and adjusted LV impedance pairs. Modeling these curves as parabolas allows capacitance to be estimated. (F) The plot of the reciprocal of longevity against the calculated total pacing power is a straight line for the four data points available in the model’s performance report (black circles). The slope of the line is the reciprocal of the usable battery energy $1/\text{W}$. The horizontal intercept is the negative value of the background power $P_0$. These two values allow the longevity of the Quadra Assura MP to be estimated for the same pacing settings chosen for the settings in the Viva Quad XT manual (red circles). CRT-D = cardiac resynchronization therapy defibrillator; LV = left ventricular; pw = pulse width [Color figure can be viewed at wileyonlinelibrary.com]

3.4 Pacing modes, paced ventricular chambers, and other nonessential functions

The powers (measured with $\Delta(1/t^0)$) consumed by different combinations of binary functions with 0% pacing and 0 shocks for the Resonate X4 estimated with the Bsc online longevity calculator are summarized in Table 5. Even with no actual pacing delivered, the dual-chamber
pacing modes (DDD(R) and DDI(R)) consume 60% more power than VVI(R), which in turn consumes 20% more power than AAI(R). Maintaining readiness for RV-only and LV-only pacing consumes the same power, and less than for BIV pacing (see Appendix A). Maintaining readiness for multisite pacing and remote monitoring consume 1/3 and 2/3 the power of VVI(R). The heart failure sensor suite consumes 20% of the power consumed by remote monitoring. One of the first four shocks in a year consumes ≈20% of the energy consumed by 100% pacing at 2.5 V, 0.4 ms, and 500 Ω.

The combination of VVI(R) with no ventricular chamber (P31 + P40) is not available on the BSc online longevity calculator for the Resonate X4. Assuming VVI(R) consumes the same power as AAI(R) (i.e., P31 = P32) and P40 = 0, then maintaining readiness for RV pacing consumes 0.001 in Δ(1/t°) (i.e., P41 = (P31 + P41) − (P32 + P40), Table 5). This allows figures to be assigned to all the programmable states in Table 2. (Similar analyses were also possible for the Platinium 4LV SonR but they were not performed.)

3.5 | Longevity projection simulation

The longevities projected for the Resonate X4 by the mathematical model in Eq. (7) and estimates in Table 2 for various settings were compared with those by the BSc online longevity calculator (Table 6).

3.6 | Comparison of CRT-D models

For the Viva Quad XT, the only source of longevity data available to the study was its manual. Based on a previous publication, pacing appears to be powered by LR with transition at Vp = 2.5, 3.5, 5, 7.5, and 8 V. Assuming internal resistance αp = 100 Ω, pacing capacitance Cp = 0.01 mF, and pacing efficiency ηp = 0.85 for all channels, the total pacing power P1 according to the settings in its manual was calculated (see Appendix G). The 1/t°–P1 plot comprises two lines with the same 1/t° intercept but different slopes (ratio 1.08; LV amplitude = 4 V for all the points on the less steep line; Figure 6A).
TABLE 4  Estimation of shock energy efficiency by two different methods for three different CRT-D models

| (a) Impact of shock frequency on longevity |
|------------------------------------------|
| Device Groups | Resonate X4 | Platinium 4LV SonR | Intica 7 HF-T (QP) |
| Shocks per year | % triple chamber pacing |
| 0 – 4 | 15 | 0.00216 | 0.00074 | 0.000073 |
| 4 – 10 | 20 | 0.00153 | 0.000074 | 0.000074 |

| Scale factor | 0.00172 | 0.00174 | 0.00176 | 0.000074 | 0.000074 | 0.000073 | 0.00011 | 0.00011 | 0.00011 |
| x-intercept $x_0$ | –33.55 | –38.3 | –47.74 | –869.9 | –906.3 | –1091 | –939.7 | –1088 | –1314 | –1734 |
| Slope $\lambda$ | 23.09 | 23.09 | 23.09 | 1 | 1 | 1 | 1 | 1 |

| Usable battery energy $W^*$ | 13410 | 13290 | 13583 | 13610 | 9500 | 9500 | 9500 | 9500 |
| Background power $P_{00}$ | 775 | 884 | 1102 | 870 | 906 | 1091 | 940 | 1088 | 1314 | 1734 |
| $\Delta x_0$ | 4.75 | 9.44 | 36 | 185 | 148.3 | 226 | 420 |
| $\Delta P = \lambda \cdot \Delta x_0$ | 110 | 218 | 36 | 185 | 148.3 | 226 | 420 |
| $\Delta f_s$ (spry) | 4 | 4 | 2 | 2 | 4 | 4 | 8 |
| Shock energy $W_s (J)$ | 41 | 41 | 42 | 42 | 41 | 41 | 41 |
| Shock energy efficiency $\eta_s$ | 1.5 | 0.75 | 2.31 | 0.45 | 1.11 | 0.73 | 0.78 |

| (b) Equivalence between shock and pacing powers |
|-----------------------------------------------|
| Device | Resonate X4 (Figure 4B) | Platinium 4LV SonR (Figure 4D) | Intica 7 HF-T (QP) (Figure 4F) |
| Shock frequency $f_s$ (spry) | 4 | 8 | 12 | 20 |
| Slope | 0.00172 | 0.00174 | 0.00176 | 0.000074 | 0.000074 | 0.000073 | 0.00011 | 0.00011 | 0.00011 |
| $1/t^\alpha$-intercept $y_0$ | 0.05775 | 0.06652 | 0.08405 | 0.06405 | 0.06663 | 0.08008 | 0.09922 | 0.1192 | 0.1398 | 0.1817 |

Postulating the LV channel was more energy efficient for output amplitude $> 3.5 \text{ V}$, $\eta_p$ was set to 0.8 for A/RV/LV amplitude $\leq 3.5 \text{ V}$ and 0.9 for LV amplitude $> 3.5 \text{ V}$ and that aligns the two lines (see Appendix G; Figure 6B). The estimated usable battery energy $W^*$ is 6932 $J$ ($\approx 0.66 \text{ A-h}$) and the background power $P_{00}$ 696 $\text{J/yr}$ (22.1 $\mu\text{W}$) for the Viva Quad XT. The total pacing powers of other CRT-D models for the Viva Quad XT settings were calculated and plotted against longevity projected by either the manufacturers (BSc, Mcp) or Eq. (7) (Abt, Btk) (Table 7, Figure 6B).

4 | DISCUSSION

Longevity projections reported in publicly available sources are for settings chosen by the manufacturers. For particular settings, users generally need to request the longevity estimates specifically from the manufacturers. The situation changed when BSc launched its online longevity calculator. For the first time in CIED history, users can freely “experiment” with the possible combinations of device settings and independently assess their impact on device longevity. The input and output data of these “experiments” allow inferences to be drawn on the structure and functions of CIEDs and they can have implications for clinical practice. The BSc and Mcp online longevity calculator and simulator are different from the Mdt online longevity calculator, which estimates the remaining longevity based on the previous clinical use experience (the implantation date and the battery voltage at a subsequent date) and does not allow the user to alter the device settings.

4.1 | Validity of the mathematical model

The equations in the article and Appendices A and B are derived from fundamental principles of electric energy with some basic assumptions about the structure and operation of the CIED. The mathematical model explains, agrees with (especially Figures 2F and 6B), and predicts (Table 6) the impact on longevity by pacing, shock therapy, and other functions (either individually or in combination), proving its validity.

4.2 | Power supply for pacing

If SR is used to power pacing, the $1/t^\alpha - V_p$ plot is a parabola and the $1/t^\alpha - V_p^2$ plot is a straight line (Figures 1C and D). If LR is used, the $1/t^\alpha - V_p$ plot comprises rising steepening straight line segments separated by widening abrupt jumps and whose upper ends lie on a parabola (Figures 3A and 4A), and the $1/t^\alpha - V_p^2$ plot comprises rising flattening convex curve segments separated by widening abrupt jumps and whose upper ends lie on a straight line (Figures 3B and 4B). The straight line segments of $1/t^\alpha - V_p$ plot share a common $1/t^\alpha$ intercept (constant background power) and have slopes proportional to the $V_p$ values at their upper ends (Figures 3A and 4A).
The deviation of the $1/t^\circ - V_p$ and $1/t^\circ - V^2_p$ plots from the parabola and straight line "backbones" represents the theoretical energy inefficiency of LR compared to SR. The energy inefficiency increases with each successive jump (becomes wider) and diminishes when the pacing amplitude $V_p$ approaches the peak pacing capacitor voltage $V_C$. Even though SR may be more energy efficient than liner regulation for pacing, it has its disadvantages (e.g., generation of electromagnetic noise from switching, vulnerability to electromagnetic interference during magnetic resonance imaging, see Appendix A) and the pacing energy efficiency advantage decreases if LR is implemented with finer increments for $V_C$ (e.g., 1 V instead of 2.5 V, compare Figures 4A/b with Figures 3A/B). The different types of voltage regulation are not mutually exclusive and can be used in conjunction (see Appendices A and E).

4.3 Shock energy efficiency

Manufacturers may quote several shocks per year in the publicized materials on the longevity of their ICD and CRT-D models, but it is not always clear whether these shocks include the periodic high-energy discharges for high-voltage capacitor reformation or battery conditioning. For the Resonate X4 and Platinium 4LV SonR, energy of the first four and two shocks in a year may be offset against the energy included in the background power consumption for high-voltage capacitor reformation/battery conditioning, leading to an apparent shock energy efficiency $>1$ (Table 4) and lower than expected rises in background power when pacing power is modified by shock frequency (Figures 5B and D). Battery conditioning may consume less energy than...
TABLE 5  Powers consumed by functions (components) of the Resonate X4 CRT-D

| State       | Code          | $t^*$ | $1/t^*$ | Pacing mode | $\Delta(1/t^*)$ | V chamber | $\Delta(1/t^*)$ | Others | $\Delta(1/t^*)$ |
|-------------|---------------|-------|---------|-------------|-----------------|-----------|-----------------|--------|-----------------|
| OOO-no V    | $P_0+P_{30}+P_{40}$ | 18.5  | 0.054054 |             |                 |           |                 |        |                 |
| VVIR+RV     | $P_0+P_{31}+P_{41}$ | 17    | 0.058824 | (VVIR+RV)-(OOO-no V) | 0.0047695 |           |                 |        |                 |
| VVIR+BV     | $P_0+P_{31}+P_{42}$ | 16.3  | 0.06135 | BIV-RV      | 0.002526 |           |                 |        |                 |
| VVIR+LV     | $P_0+P_{31}+P_{43}$ | 17.1  | 0.05848 | BIV-LV      | 0.00287 |           |                 |        |                 |
| AAIR-no V   | $P_0+P_{32}+P_{40}$ | 17.3  | 0.057803 | (VVIR+RV)-(AAIR-no V) | 0.0010201 |           |                 |        |                 |
| VDDR+RV     | $P_0+P_{33}+P_{43}$ | 16.5  | 0.060606 | VDDR-VVIR   | 0.0017825 |           |                 |        |                 |
| VDDR+BV     | $P_0+P_{33}+P_{42}$ | 15.7  | 0.063964 | VDDR-VVIR   | 0.0023446 | BIV-RV    | 0.003088 |        |                 |
| VDDR+LV     | $P_0+P_{33}+P_{43}$ | 16.5  | 0.060606 | VDDR-VVIR   | 0.0021265 | BIV-LV    | 0.003088 |        |                 |
| DDIR+RV     | $P_0+P_{34}+P_{41}$ | 16.3  | 0.06135 | DDIR-VVIR   | 0.002526 |           |                 |        |                 |
| DDIR+BV     | $P_0+P_{34}+P_{42}$ | 15.5  | 0.064516 | DDIR-VVIR   | 0.0031664 | BIV-RV    | 0.003166 |        |                 |
| DDIR+LV     | $P_0+P_{34}+P_{43}$ | 16.3  | 0.06135 | DDIR-VVIR   | 0.0028702 | BIV-LV    | 0.003166 |        |                 |
| DDDR+RV     | $P_0+P_{35}+P_{41}$ | 16.2  | 0.061728 | DDDR-VVIR   | 0.0029049 |           |                 |        |                 |
| DDDR+BV     | $P_0+P_{35}+P_{42}$ | 15.5  | 0.064516 | DDDR-VVIR   | 0.0031664 | BIV-LV    | 0.002788 |        |                 |
| DDDR+LV     | $P_0+P_{35}+P_{43}$ | 16.2  | 0.061728 | DDDR-VVIR   | 0.0032489 | BIV-LV    | 0.002788 |        |                 |
| VVIR+BV+MSP | $P_0+P_{31}+P_{42}+P_{5}$ | 15.9  | 0.062893 | MSP         | 0.0015434 |           |                 |        |                 |
| VVIR+LV+MSP | $P_0+P_{31}+P_{43}+P_{5}$ | 16.7  | 0.05988 | BIV-LV      | 0.003013 | MSP       | 0.0014007 |        |                 |
| VDDR+BV+MSP | $P_0+P_{33}+P_{42}+P_{5}$ | 15.4  | 0.064935 | VDDR-VVIR   | 0.002042 | MSP       | 0.0012408 |        |                 |
| VDDR+LV+MSP | $P_0+P_{33}+P_{43}+P_{5}$ | 16.2  | 0.061728 | VDDR-VVIR   | 0.0018482 | BIV-LV    | 0.003207 | MSP       | 0.0011223 |
| DDIR+BV+MSP | $P_0+P_{34}+P_{42}+P_{5}$ | 15.2  | 0.065789 | DDIR-VVIR   | 0.0028964 | MSP       | 0.0012733 |        |                 |
| DDIR+LV+MSP | $P_0+P_{34}+P_{43}+P_{5}$ | 15.9  | 0.062893 | DDIR-VVIR   | 0.0030128 | BIV-LV    | 0.002896 | MSP       | 0.0015434 |
| DDDR+BV+MSP | $P_0+P_{35}+P_{42}+P_{5}$ | 15.2  | 0.065789 | DDDR-VVIR   | 0.0028964 | MSP       | 0.0012733 |        |                 |
| DDDR+LV+MSP | $P_0+P_{35}+P_{43}+P_{5}$ | 15.9  | 0.062893 | DDDR-VVIR   | 0.0030128 | BIV-LV    | 0.002896 | MSP       | 0.0011647 |
| OOO-no V+RM | $P_0+P_{30}+P_{40}+P_{6}$ | 17.4  | 0.057471 | RM          | 0.0034172 |           |                 |        |                 |
| VVIR+RV+RM  | $P_0+P_{31}+P_{41}+P_{6}$ | 16.1  | 0.062112 | (VVIR+RV)-(OOO-no V) | 0.0046405 | RM       | 0.0032863 |        |                 |
| AAIR-no V+RM | $P_0+P_{32}+P_{40}+P_{6}$ | 16.3  | 0.06135 | AAIR-OOO   | 0.0038784 | RM       | 0.0035462 |        |                 |
| OOO-no V+MV | $P_0+P_{30}+P_{40}+P_{7}$ | 17.5  | 0.057143 | MV          | 0.0030888 |           |                 |        |                 |
| VVIR+RV+MV  | $P_0+P_{31}+P_{41}+P_{7}$ | 16.3  | 0.06135 | (VVIR+RV)-(OOO-no V) | 0.0042068 | MV       | 0.0025262 |        |                 |
| AAIR-no V+MV | $P_0+P_{32}+P_{40}+P_{6}$ | 16.4  | 0.060976 | AAIR-OOO   | 0.0038328 | MV       | 0.0031721 |        |                 |
| OOO-no V+HFS| $P_0+P_{30}+P_{40}+P_{8}$ | 18.2  | 0.054945 | HFS         | 0.000891 |           |                 |        |                 |
| VVIR+RV+HFS | $P_0+P_{31}+P_{41}+P_{8}$ | 16.9  | 0.059172 | (VVIR+RV)-(OOO-no V) | 0.0042265 | HFS      | 0.0003481 |        |                 |
| AAIR-no V+HFS| $P_0+P_{32}+P_{40}+P_{8}$ | 17.1  | 0.05848 | AAIR-OOO   | 0.0035345 | HFS      | 0.0006761 |        |                 |
| OOO+1 spyr  | $P_0+P_{30}+P_{40}+1$ spyr | 17.8  | 0.05618 | 1 spyr     | 0.0021257 |           |                 |        |                 |
| VVIR+RV+<P_p> | $P_0+P_{31}+P_{41}+<P_p>$ | 14.6  | 0.068493 | $<P_p>$    | 0.0096696 |           |                 |        |                 |

Note: 0% atrial and ventricular pacing and 0 shocks generally assumed; $t^*$ = device longevity; $\Delta(1/t^*)$ difference in reciprocal of device longevity; ($P_p$) = power of 100% RV pacing at 2.5 V at 0.4 ms and 500 Ω; BIV = biventricular; CRT-D = cardiac resynchronization therapy defibrillator; HFS = heart failure suite; LV = left ventricular; MSP = multi-site pacing; MV = minute ventilation; RM = remote monitoring; RV = right ventricular; spyr = shocks per year.

4.4 | Longevity, usable battery energy, background power, and pacing power supply

Clinical discussion on device longevity has often focused on battery capacity (usable battery energy $W^n$) and neglected background power $P_0$ and pacing power supply. Figure 6B provides a graphical illustration of the interplay of the three factors. The $1/t^* - P_1$ (total pacing power) plot is entirely determined by the horizontal intercept.
### TABLE 6  Comparison of longevity projections by mathematical model and online calculator for the Resonate X4 CRT-D

| Programmable states (setting) | Power (1/t) | DDD + 15% A pacing + 100% RV-only pacing | DDD + 50% A pacing + 50% RV-only pacing + 2 shocks per year | DDD + 20% A pacing + 80% RV-only pacing + 6 shocks per year | DDD + 20% A pacing + 90% LV pacing + 90% MSP LVb pacing@2.5V | DDD + 15% A pacing + 80% RV pacing + 90% LV pacing@3.5V + 90% MSP LVb@4.5V + 8 shocks per year + RM |
|-----------------------------|-------------|-------------------------------------|-------------------------------------------------|-------------------------------------------------|-------------------------------------------------|-------------------------------------------------|
| P0                          | 0.058       | 0.058                               | 0.058                                           | 0.058                                           | 0.058                                           | 0.058                                           |
| P10                         | 0.0097      | 0.001455                            | 0.00485                                         | 0.00194                                         | 0.00194                                         | 0.00194                                         | 0.002425                                       |
| P11                         | 0.0097      | 0.0097                              | 0.00485                                         | 0.00776                                         | 0.00873                                         | 0                                              | 0.00776                                        |
| P12                         | 0.0097      | 0                                  | 0                                               | 0                                               | 0.00873                                         | 0.009778                                       | 0.017111                                       |
| P13                         | 0.0097      | 0                                  | 0                                               | 0                                               | 0                                               | 0.017382                                       | 0.028285                                       |
| P2 (fs ≤ 4)                 | 0.0021      | 0                                  | 0                                               | 0                                               | 0.0084                                          | 0                                               | 0.0084                                        |
| P2 (fs > 4)                 | 0.0042      | 0                                  | 0                                               | 0                                               | 0.0084                                          | 0                                               | 0.0168                                        |
| P30                         | 0           | 0                                  | 0                                               | 0                                               | 0                                               | 0                                               | 0                                             |
| P31                         | 0.0037      | 0                                  | 0                                               | 0                                               | 0                                               | 0                                               | 0                                             |
| P32                         | 0.0037      | 0                                  | 0                                               | 0                                               | 0                                               | 0                                               | 0                                             |
| P33                         | 0.0057      | 0                                  | 0                                               | 0                                               | 0                                               | 0                                               | 0                                             |
| P34                         | 0.0065      | 0                                  | 0                                               | 0                                               | 0                                               | 0                                               | 0                                             |
| P35                         | 0.0067      | 0.0067                             | 0.0067                                          | 0.0067                                          | 0.0067                                          | 0.0067                                          | 0.0067                                        |
| P40                         | 0           | 0                                  | 0                                               | 0                                               | 0                                               | 0                                               | 0                                             |
| P41                         | 0.001       | 0.001                              | 0.001                                           | 0.001                                           | 0                                               | 0                                               | 0                                             |
| P42                         | 0.004       | 0                                  | 0                                               | 0                                               | 0.004                                           | 0                                               | 0.004                                         |
| P43                         | 0.001       | 0                                  | 0                                               | 0                                               | 0                                               | 0.001                                           | 0                                             |
| P5                          | 0.0012      | 0                                  | 0                                               | 0                                               | 0                                               | 0.0012                                          | 0.0012                                       |
| P6                          | 0.0033      | 0                                  | 0                                               | 0                                               | 0                                               | 0.0033                                          | 0.0033                                       |
| P7                          | 0.003       | 0                                  | 0                                               | 0                                               | 0                                               | 0                                               | 0                                             |
| P8                          | 0.0006      | 0                                  | 0                                               | 0                                               | 0                                               | 0                                               | 0                                             |
| Sum(1/t)                    | 0.076855    | 0.0796                             | 0.0922                                          | 0.0868                                         | 0.096                                           | 0.153981                                       |                                               |
| Longevity                   | 13.7        | 13.1                                | 11.2                                            | 11.7                                            | 10.7                                            | 6.5                                             |                                               |

Note: f<sub>p</sub> = shock frequency; CRT-D = cardiac resynchronization therapy defibrillator; MSP = multisite pacing; RM = remote monitoring; RV = right ventricular.

### TABLE 7  Projected longevities for five CRT-D models standardized to the settings in the Viva Quad XT manual

| %A pacing | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 |
|-----------|----|----|----|----|----|----|----|----|
| A amplitude (V) | 2  | 2  | 2.5 | 2.5 | 2.5 | 2.5 | 2.5 | 2.5 |
| % RV pacing | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| RV amplitude (V) | 2  | 2  | 2.5 | 2.5 | 2.5 | 2.5 | 2.5 | 2.5 |
| % LV pacing | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| LV amplitude (V) | 2.5 | 4  | 2.5 | 4  | 2.5 | 4  | 2.5 | 4  |
| Impedance (ohm) | 500 | 500 | 500 | 500 | 500 | 500 | 500 | 500 |

| Usable battery energy | Background power | Longevity |
|-----------------------|------------------|-----------|
| Platinum 4LV SonR     |                  | 13843 J (≈ 1.33 A h) | 799 J/yr (25.3 μW) | 131 | 13.1 | 12.1 | 11.7 | 9.4 | 10.6 | 8.5 | 13.5 | 10.7 | 12.6 | 12.3 | 10.1 | 11.2 | 9.2 |
| Resonate X4           |                  | 13619 J (≈ 1.30 A h) | 918 J/yr (29.1 μW) | 11.6 | 9.8 | 11.1 | 10.5 | 9.4 | 9.8 | 8.4 | 12 | 10.2 | 11.5 | 11 | 9.9 | 10.3 | 9 |
| Quadra Assura MP      |                  | 11774 J (≈ 1.13 A h) | 1059 J/yr (33.6 μW) | 8.4 | 6.5 | 8.2 | 6.9 | 6.4 | 7.2 | 5.8 | 8.7 | 6.9 | 8.5 | 7.3 | 6.8 | 7.6 | 6.2 |
| Intica 7 HF-T (QP)    |                  | 9471 J (≈ 0.907 A h) | 940 J/yr (29.8 μW) | 7.8 | 6.1 | 7.6 | 6.5 | 6 | 5.7 | 5.5 | 8 | 6.5 | 7.8 | 6.8 | 6.4 | 7 | 5.8 |
| Viva Quad XT          |                  | 6932 J (≈ 0.664 A h) | 696 J/yr (22.1 μW) | 7 | 5.4 | 6.8 | 6.1 | 5.3 | 5.8 | 4.7 | 7.3 | 5.8 | 7.1 | 6.4 | 5.6 | 6.1 | 5 |

Note: Base rate: 60 beats/min. Pulse width: 0.35 ms (Platinum 4LV SonR); 0.4 ms (Resonate X4; Intica 7 HF-T(QP); Viva Quad XT); 0.5 ms (Quadra Assura MP). CRT-D = cardiac resynchronization therapy defibrillator; LV = left ventricular; RV = right ventricular.
The logical circuits for regulating pacing need to run continuously, even if no pacing is actually delivered. The more chambers are sensed and paced, the more steps are in the logical circuits, and the more power is consumed. In this light, for patients who are unlikely to require significant pacing support, it would be advisable to choose VVI(R) over DDD(R) even if the ICD is a dual chamber one in order to conserve energy. (The atrial channel can still be used for ventricular tachyarrhythmia diagnosis.) For the same pacing mode, reducing the number of paced chambers conserves energy (even if no pacing is actually delivered). To maximize device longevity, dormant nonessential functions should be switched off.

4.6 Extended or shortened device longevity—whose credit and whose fault?

When a CIED lasts longer or shorter than expected, the manufacturer often takes the credit and the blame. How long a device lasts in clinic use depends on the: (1) usable battery energy, (2) the minimum operational power, (3) the therapies delivered, and (4) other activated non-essential functions. The first two items are controlled by the...
manufacturer, but the two last items are determined by the patient’s clinical needs and programming by healthcare professionals. Device therapies can consume more power than the background operations. Premature (significantly earlier than projected by the manufacturer) device failure due to battery depletion in clinical use is probably mostly driven by the patient’s clinical needs for therapy, partially due to suboptimal programming by healthcare professionals, and unlikely to be the manufacturer’s fault unless component failure can be clearly identified.20,21

4.7 | Conclusions

Longevity has become a major focus of attention for a CIED’s clinical performance, but is in fact a direct consequence of how quickly the powers consumed by the device’s functions and components exhaust its finite usable battery energy store. A mathematical model for CIED power consumptions was derived from fundamental principles of electric energy and validated against longevity data from multiple manufacturers. Compared to longevity estimated for a single set of standardized settings,6 the methodology described in the article allows the user to make multiple longevity projections for clinically relevant settings freely without further input from manufacturers. The power consumed by pacing can be theoretically derived and used for estimating the background power, shock therapy energy efficiency, the powers consumed by other functions, and the usable battery energy of CIEDs. The powers consumed by therapy functions are dictated by the clinical needs of the patient, but healthcare professionals can reduce power consumption by switching off dormant functions and reducing the clinical needs for device therapies such as by catheter ablation of ventricular tachycardia.22–25 As power consumption of a device in clinical use may not be reliably anticipated or modified, the surest way to extend a device’s duration in service is to implant a model with a large usable battery energy, a low background power, and energy efficient pacing and shock therapy.

5 | LIMITATIONS

Because longevity is typically expressed in years to one decimal point, and regression analysis is done on its reciprocal, the regression parameters may be subjected to error and instability, especially when power consumption is high and longevity is low. The mathematical model described in this article tries to “reverse-engineer” the mathematical models used by manufacturers to project the longevity of their products rather than predict their actual service lifespan in clinical use. The mathematical model fits the data from the BSc online longevity calculator remarkably well, but may not accurately reflect how the calculator is programmed by the manufacturer. The inferences drawn from the mathematical model on device construction and function cannot be verified. Lead insulation breach can lower pacing impedance drastically and invalidate the approximations in Eqs. (2) and (3) (and Eqs. (B3) and (B4) in Appendix B). A single clinical shock defers the next high-voltage capacitor reformation/battery conditioning by the same duration as multiple shocks in quick succession, making it hard to offset shock therapy against high-voltage capacitor reformation/battery conditioning in longevity projection. Equations (6), (7), (10), and (11) assume all shocks are at the same (maximum) output, which may be not true in clinical practice. The methodology described in this study permits the user more freedom in choosing the settings for longevity projection, but still requires a minimum (“training”) set of data from the manufacturers to implement. Manufacturers make disparate assumptions about storage time before implantation, amount of radiofrequency communication during implantation, and frequency of remote monitoring in their longevity projections.

CONFLICTS OF INTEREST

EWL: consultancy (Abbott).

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SUPPORTING INFORMATION
Additional supporting information may be found online in the Supporting Information section at the end of the article.

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