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Visual prosthesis wireless energy transfer system optimal modeling

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Abstract

Background: Wireless energy transfer system is an effective way to solve the visual prosthesis energy supply problems, theoretical modeling of the system is the prerequisite to do optimal energy transfer system design.

Methods: On the basis of the ideal model of the wireless energy transfer system, according to visual prosthesis application condition, the system modeling is optimized. During the optimal modeling, taking planar spiral coils as the coupling devices between energy transmitter and receiver, the effect of the parasitic capacitance of the transfer coil is considered, and especially the concept of biological capacitance is proposed to consider the influence of biological tissue on the energy transfer efficiency, resulting in the optimal modeling's more accuracy for the actual application.

Results: The simulation data of the optimal model in this paper is compared with that of the previous ideal model, the results show that under high frequency condition, the parasitic capacitance of inductance and biological capacitance considered in the optimal model could have great impact on the wireless energy transfer system. The further comparison with the experimental data verifies the validity and accuracy of the optimal model proposed in this paper.

Conclusions: The optimal model proposed in this paper has a higher theoretical guiding significance for the wireless energy transfer system's further research, and provide a more precise model reference for solving the power supply problem in visual prosthesis clinical application.

Keywords: Biological capacitance, Optimal modeling, Visual prosthesis, Wireless energy transfer, Planar spiral coils

Background

Visual prosthesis is one of the hot research issues in biomedical field and how to solve the energy supply problem of implantable visual prosthesis is particularly important. To reduce the patient's pain of multiple surgical implantable battery replacement, in recent years wireless energy transfer become scholar's accepted method [1-9]. Many scholars have done some research on wireless energy transfer of the coupling coils, but the models built in these papers are too ideal, for example the internal resistance of power source and the parasitic capacitance of the coil are neglected, and most of them are based on air medium [1-3]. Part of the literatures have considered the biological tissue influence on energy transfer, but they all are based on the analysis of the simulation software such as Ansoft-HFSS without establishing more accurate mathematical model on the basis of the physical properties of biological tissue [4-8]. In this paper, we focus on the optimal modeling of visual prosthesis wireless energy transfer system, During the modeling, on one hand, the factors that may affect the wireless energy transfer are fully considered without taking many ideal assumptions. On the other hand, the influence of biological tissue, the coupling medium between primary coil and secondary coil, is fully taken account.

Methods

The ideal modeling of wireless power transfer system

Figure 1 shows the model of ideal wireless energy transfer (wireless power transfer, WPT) system [1], in which the internal resistance of power source r_s and the coil parasitic capacitance are ignored. Energy transfer is achieved by the coupling of the primary inductance coil L_1 and the secondary inductance coil L_2. Usually the mutual inductance (factor) M or the coupling coefficient K_{12} characterizes the coupling degree of two coils, and the formula is $K_{12} = \frac{M}{\sqrt{L_1 L_2}}$. In Figure 1, V_s means the energy source. Z_1 means the equivalent impedance of the primary coil circuit, which is composed by the reactance $j\omega L_1$ of the primary coil L_1 (where ω is the energy transfer angular frequency) and equivalent series resistance r_1 , that is $Z_1 = r_1 + j\omega L_1$. Z_2 means the equivalent impedance of the secondary coil circuit, which is composed by the reactance $j\omega L_2$ of the secondary coil L_2, the equivalent series resistance r_2 and the load Z_L ($Z_L = R_L + j\omega X_L$), that is $Z_2 = r_2 + j\omega L_2 + Z_L$.

According to the energy conservation law, the total energy supplied by the energy source V_s is consumed by r_1,r_2 and R_L jointly, and the reactance parts of L_1,L_2 and X_L do not involved in energy consumption. Therefore, the energy transfer efficiency η of the wireless energy transfer system can be defined as the ratio of the energy consumed by the load and the total energy provided by the energy source. That is:

$$\eta = \frac{P_{R_L}}{P_{R_L} + P_{r_2} + P_{r_1}} \tag{1}$$

In Formula (1),

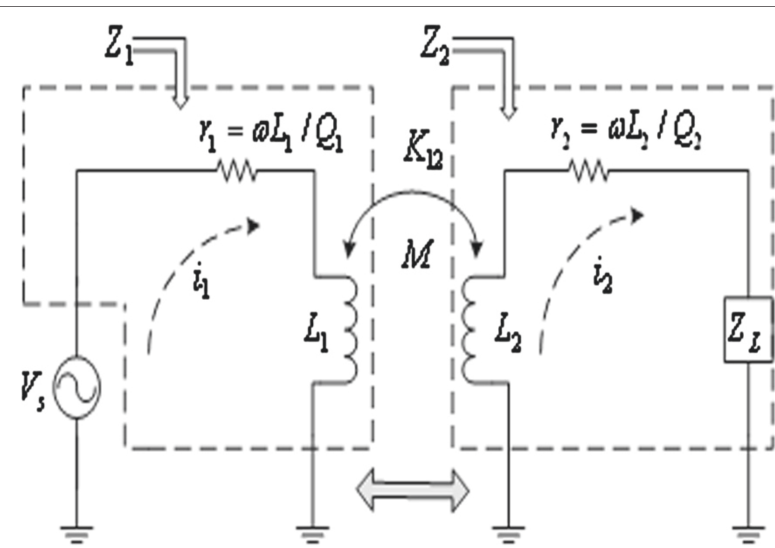

Figure 1 The model of ideal wireless energy transfer system. Figure 1 shows the model of ideal wireless energy transfer (wireless power transfer, WPT) system.

$P_{R_L} = i_2^2 R_L$, which is the energy obtained (consumed) by the load, i_2 is the secondary coil loop current. $P_{r_2} = i_2^2 r_2$, which is the energy consumption of the equivalent series resistance r_2 in the secondary coil. $P_{r_1} = i_1^2 r_1$, which is the energy consumption of the equivalent series resistance r_1 in the primary coil, i_1 is the primary coil loop current.

$$i_1 = \frac{Z_2 V_s}{Z_1 Z_2 + (\omega M)^2} \tag{2}$$

$$i_2 = \frac{-j\omega M V_s}{Z_1 Z_2 + (\omega M)^2} \tag{3}$$

So, the ideal mathematical model of the wireless energy transfer system can be summarized as follows:

$$\eta = \frac{\omega M^2 \frac{R_L}{L_1}}{\omega M^2 \frac{R_L}{L_1} + \omega M^2 \frac{r_2}{L_1} + \left[(\omega L_2 + X_L)^2 + (r_2 + R_L)^2\right] \frac{r_1}{\omega L_1}} \tag{4}$$

Modeling optimization of visual prosthesis wireless energy transfer system

During the modeling optimization in this paper, the impacts of the physical parameters in the actual circuits to the wireless energy transfer are fully considered without taking ideal assumptions, and especially the impact of biological tissue is taken account. Figure 2 shows the equivalent circuit of the perfect visual prosthesis wireless energy transfer system proposed in this paper. Compared with the ideal model shown in Figure 1, the internal resistance of power source r_s and the parasitic capacitance of the primary coil C_p are added in the primary coil circuit impedance Z_1. It's worth to note that in this paper we will use the vector network analyzer to measure the wireless energy transfer efficiency of the system, for the characteristics of the equipment, here we have $r_s = R_L = 50\Omega$, and for the actual application, the load resistance R_L should be the equivalent load of the circuit in vivo. In the secondary coil circuit impedance Z_2, the biological capacitance C_p' proposed in this paper is added. When the secondary coil is implanted into the body, the air medium is replaced by the biological tissue medium (the relative dielectric constant of

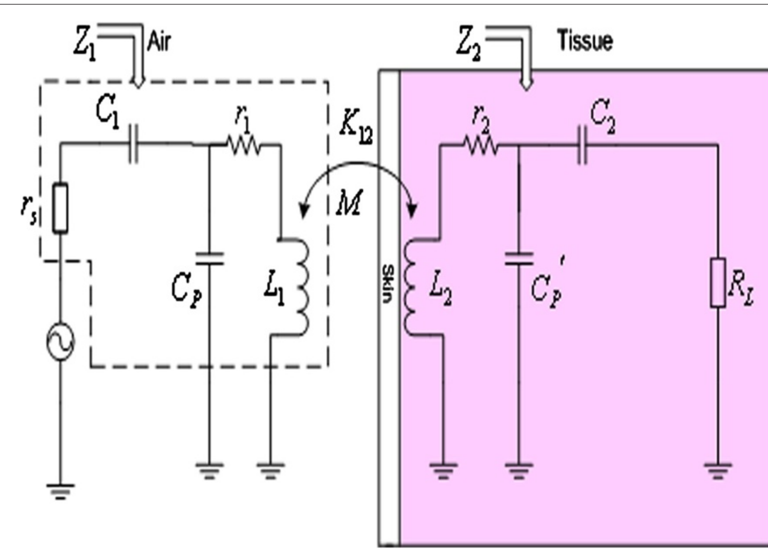

Figure 2 The visual prosthesis wireless energy transmission system. Figure 2 shows the equivalent circuit of the visual prosthesis wireless energy transfer system proposed in this paper.

human biological medium $\varepsilon_m >> 1$), in this paper the capacitance produced by the biological medium is defined as the biological capacitance. In addition, in order to improve the energy transfer efficiency, the resonant match capacitances C_1 and C_2 are added in the primary side and the secondary side respectively.

The modeling of the planar spiral inductance coil L

The coupling coils used in this system are the planar spiral inductance coils, the shape is shown in Figure 3.

Such Inductance coils are widely used in wireless charger, card reader, IC, ID card, which have the following physical properties:

1. They can be manufactured conveniently and they are economical and durable;
2. Good flexibility, easy to be implanted.

Based on large number of experimental data statistics, the planar spiral coil inductance empirical formula [10] is adopted here:

$$L = \frac{r^2 n^2}{(2r + 2.8d) * 10^5} \tag{5}$$

From above formula (5), we can get that the parameters affecting the coil inductance can be summarized as:

Coil winding turns n;

Average coil winding radius r (the average of the outer radius and inner radius, unit: m);

Coil winding depth d (outer radius minus inner radius, unit: m).

In this paper, the size of the primary and secondary spiral coil (Figure 3) is the same. Number of turns n is 8, average winding radius r is 17.08mm, and winding depth d is 4.34mm. According to the proposed model we can obtain the planar spiral coil inductance that is $L_1 = L_2 = 4.031\mu$H.

Figure 3 The planar spiral inductance coil. The coupling coils used in this system are the planar spiral inductance coils.

The modeling of the mutual inductance M

When the central axis of the primary coil and the secondary coil are aligned, according to Maxwell's equation, the mutual inductance value M_{ij} between any pair of parallel single-turn coils with the radius of r_i, r_j can be expressed as equation (6) [6]:

$$M_{ij} = \frac{2\mu}{\alpha}\sqrt{r_i.r_j}\left[\left(1-\frac{\alpha^2}{2}\right)K(\alpha) - E(\alpha)\right] \tag{6}$$

where $\alpha = 2\sqrt{\frac{r_i.r_j}{(r_i+r_j)^2+D^2}}$;

$K(\alpha)$ and $E(\alpha)$ are class I and II of complete elliptic integral respectively;

Class I of elliptic integral expression is: $K(\alpha) = \int_0^1 \frac{dt}{\sqrt{(1-t^2)(1-\alpha^2 t^2)}}dt$

Class II of elliptic integral expression is: $E(\alpha) = \int_0^1 \frac{\sqrt{1-\alpha^2 t^2}}{\sqrt{1-t^2}}dt$

D is the distance between the coils; μ is the transfer medium magnetic permeability between the coils.

In summary, when the turns of the primary coil are n_1, the turns of the secondary coils are n_2, the mutual inductance M between two coils can be expressed as:

$$M = \sum_{i=1}^{n_1}\sum_{j=1}^{n_2} M_{ij}(r_i, r_j, D) \tag{7}$$

As the coil is shown in Figure 3, the inner diameter is 14.91mm; the diameter of each turn is 0.62mm; the vacuum magnetic permeability is $\mu_0 = 4\pi * 10^{-7}H/m$; the relative magnetic permeability of air and biological tissue is $\mu_r \approx 1$. Substituting into this model, when the distance between the coils D=1cm, the mutual inductance $M = 1.0209\mu$H; when the distance between the coils D=2cm, the mutual inductance $M = 0.42134\mu$H.

The modeling of the inductance coil high-frequency equivalent series resistance R

Under high frequencies condition, because the inductance coil resistance is influenced by the skin effect, the proximity effect, the eddy current effect and many other effects, the impedance is much larger than the intrinsic resistance of coil at DC. Typically, the coil loss resistance under high frequency can break down into Ohm loss resistance R_o and radiation loss resistance R_r [3,11]. In this paper, the energy transfer frequencies are in 1-50MHz, resulting in $R_r << R_o$, so the radiation loss impedance R_r can be negligible.

$$R_o = \sqrt{\frac{\omega\mu_0}{2\sigma}}\frac{l}{2\pi r'} = \sqrt{\frac{\omega\mu_0}{2\sigma}}\frac{nr}{r'} \tag{8}$$

In above formula, μ_0 is the vacuum magnetic permeability; σ is the conductivity; l is the wire length; r' is the radius of the wire; n is the number of the coil turns; r is the average radius of the coils; ω is the angular frequency.

In our system, the coil conductivity $\sigma = 5.9 * 10^7$S/m; the average radius $r = 17.08$mm; turns $n = 8$; the equivalent series resistance is changed with frequency, for example, when $\omega = 35.35534$rad/s that is $f = 5.63$MHz, the coil equivalent series resistance R_o= 0.2705Ω.

The Modeling of the inductance coil parasitic capacitance C_p

Figure 4 is the cross-sectional view between two adjacent turns of the coils. In the figure, D_c means the bare wire diameter, D_o means the wire diameter with the insulating layer,

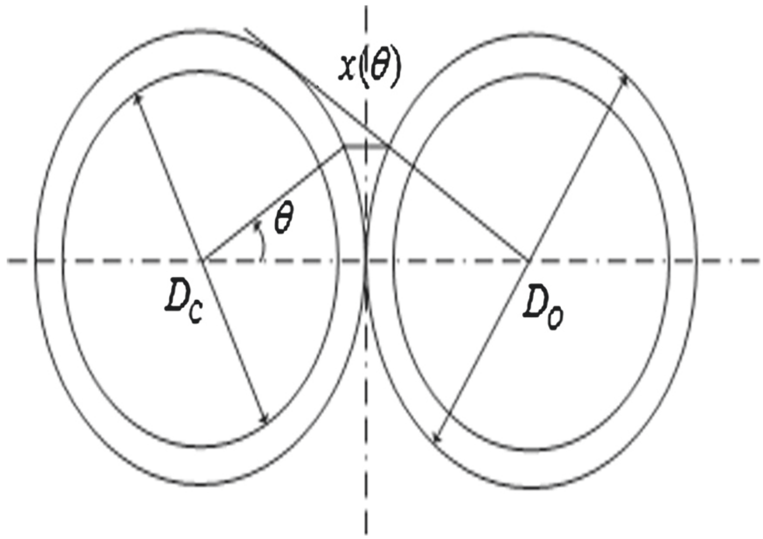

Figure 4 The cross-sectional view between two adjacent turns of the coil.

and $x(\theta)$ means the air gap between two adjacent wires. The relationship between $x(\theta)$ and other parameters could be given as

$$x(\theta) = D_o(1 - \cos\theta) \tag{9}$$

The parasitic capacitance C_{tt} between two adjacent turns of the coil can be equivalent to the insulation layer dielectric equivalent capacitance C_{ttc} in series with the inter-insulation layer air medium equivalent capacitance C_{ttg} [12].

The insulation layer dielectric equivalent capacitance per unit angle can be expressed as:

$$dC_{ttc} = \frac{\varepsilon_r \varepsilon_0 l_t}{2\ln\frac{D_o}{D_c}} d\theta \tag{10}$$

ε_r is the relative dielectric constant of the insulation layer;
l_t is the corresponding effective length of two adjacent turns of the coil;

The inter-insulation layer air medium equivalent capacitance per unit angle can be expressed as:

$$dC_{ttg} = \varepsilon_0 \frac{l_t D_o}{2x(\theta)} = \varepsilon_0 \frac{l_t}{2(1-\cos\theta)} d\theta \tag{11}$$

The equivalent capacitance per unit angle can be expressed as:

$$dC_{eq}(\theta) = \frac{dC_{ttc} dC_{ttg}}{dC_{ttc} + dC_{ttg}} = \frac{\varepsilon_0 l_t}{2} \frac{1}{1 + \frac{1}{\varepsilon_r}\ln\frac{D_o}{D_c} - \cos\theta} d\theta \tag{12}$$

The equivalent capacitance between two adjacent turns of the coil can be expressed as:

$$C_{tt} = 2\int_0^{\frac{\pi}{6}} \frac{\varepsilon_0 l_t}{2} \frac{1}{1 + \frac{1}{\varepsilon_r}\ln\frac{D_o}{D_c} - \cos\theta} d\theta\, du$$

$$= \varepsilon_0 l_t \frac{2\varepsilon_r \arctan\left[\frac{\left(-1+\sqrt{3}\right)\left(2\varepsilon_r + \ln\frac{D_o}{D_c}\right)}{\left(1+\sqrt{3}\right)\sqrt{\ln\frac{D_o}{D_c}\left(2\varepsilon_r + \ln\frac{D_o}{D_c}\right)}}\right]}{\sqrt{\ln\frac{D_o}{D_c}\left(2\varepsilon_r + \ln\frac{D_o}{D_c}\right)}} \tag{13}$$

By measuring the selected planar spiral coil in this paper we can get the bare wire diameter $D_c = 0.575$mm, the wire diameter including the insulation layer $D_o = 0.620$mm, the vacuum dielectric constant $\varepsilon_0 = 8.85 * 10^{-12}$F/m, the enameled wire insulation layer relative dielectric constant $\varepsilon_r \approx 3.5$ [13], the innermost effective corresponding length between two adjacent turns of the coil $l_t = 97.3871$mm. According to the model, the parasitic capacitance between the innermost two turns of the coil can be obtained $C_{tt} = 9.9399$pF; Similarly, the parasitic capacitance between each two adjacent turns of the coil can be evaluated.

The equivalent parasitic capacitance between each two adjacent turns of the multi-turn coil also can be expressed as equation (13), and the capacitances between the turns of the coil are connected in series, in other words, the lumped equivalent capacitance of the n-turn coil equals to the n-1 inter-turn capacitances in series.

$$C_p = \frac{1}{\frac{1}{C_{12}} + \frac{1}{C_{23}} + \ldots + \frac{1}{C_{(n-1)n}}} \tag{14}$$

The Modeling of the Biological Capacitance C'_p

The biological capacitance C'_p can be equivalent to the insulation layers dielectric equivalent capacitance C_{ttc} in series with the inter-insulation layer biological tissue dielectric equivalent capacitance C_{ttm}(the relative dielectric constant of the biological tissues is represented by ε_m). The inter-insulation layer biological tissue dielectric equivalent capacitance per unit angle could be expressed as:

$$dC_{ttm} = \varepsilon_0 \varepsilon_m \frac{l_t D_o}{2x(\theta)} = \varepsilon_0 \varepsilon_m \frac{l_t}{2(1-\cos\theta)} d\theta \tag{15}$$

Connect it in series with the insulation layer dielectric equivalent capacitance per unit angle C_{ttc}, then the biological capacitance per unit angle can be obtained:

$$dC'_{eq}(\theta) = \frac{dC_{ttc} dC_{ttm}}{dC_{ttc} + dC_{ttm}} = \frac{\varepsilon_0 l_t}{2} \frac{1}{\frac{1}{\varepsilon_m} + \frac{1}{\varepsilon_r} \ln \frac{D_o}{D_c} - \frac{1}{\varepsilon_m} \cos\theta} d\theta \tag{16}$$

The biological capacitance between two adjacent turns of the coil is expressed as:

$$C'_{tt} = 2\int_0^{\frac{\pi}{6}} dC'_{eq}(\theta) = \varepsilon_0 l_t \frac{2\varepsilon_r \varepsilon_m \arctan\left[\frac{\left(-1+\sqrt{3}\right)\varepsilon_m \ln\frac{D_o}{D_c}}{\left(1+\sqrt{3}\right)\sqrt{\left(2\varepsilon_r + \varepsilon_m \ln\frac{D_o}{D_c}\right)\varepsilon_m \ln\frac{D_o}{D_c}}}\right]}{\sqrt{\left(2\varepsilon_r + \varepsilon_m \ln\frac{D_o}{D_c}\right)\varepsilon_m \ln\frac{D_o}{D_c}}} \tag{17}$$

The value of relative dielectric constant of the biological tissues is different for each one and it could be decrease slowly with the increase of the frequency when the frequency arrives several MHz [13,14]. In this paper we take the relative dielectric constant $\varepsilon_m \approx 54$ [14], the biological capacitance of the innermost two turns C'_{tt}=20.192pF. Similarly,

$$C'_p = \frac{1}{\frac{1}{C'_{12}} + \frac{1}{C'_{23}} + \ldots + \frac{1}{C'_{(n-1)n}}} \tag{18}$$

So, the modeling built in this paper can be available not only for the general air medium wireless energy transfer system but also for the biological tissue medium wireless energy transfer system. Formula (14) is used in general air medium and formula (18) is used in biological tissue medium.

Results

Simulation and analysis

Using the optimal visual prosthesis energy transfer model proposed in this paper, we get the energy transfer efficiency at different frequency point (the distance of the primary coil and the secondary coil is 1cm), the "Frequency - Efficiency" curves about the ideal model, the optimal model of air medium and biological medium are shown in Figure 5.

The three curves in Figure 5 show energy transfer efficiency versus the frequency by using the resonance method. Among them, the first one is the curve of the ideal model, the second one is the curve of the optimal model with air medium, and the third curve is the optimal model with biological tissue medium.

From Figure 5 we can find that at the low frequencies, the three curves are almost overlapped, while with the increase of frequency, the difference between each other is increasing. The reason is that when the coil inductance is fixed, the resonance frequency in the low frequency band needs the larger coupling capacitance, the influence of the air medium inductance parasitic capacitance and the biological capacitance is negligible, so, the energy transfer efficiency of the model before and after optimization is basically equal. However, with the resonant frequency increases, the required matching capacitance gradually reduces, when it reduces to a certain extent, the influence of the inductance parasitic capacitance and its biological capacitance becomes significant, so the trend of three curves become discrete.

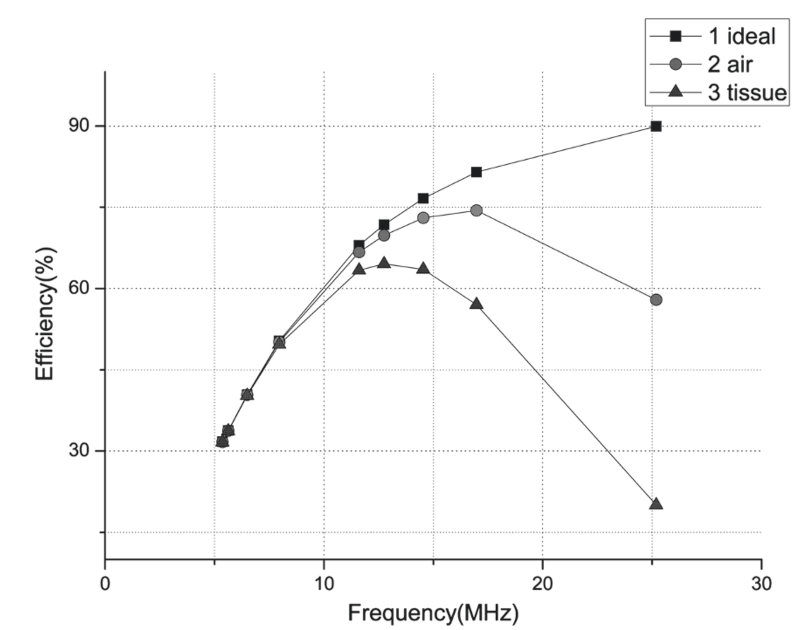

Figure 5 The comparison chart of the energy transfer efficiency simulation (the distance between the coils D = 1cm). The "Frequency - Efficiency" curves about the ideal model, the optimal model of air medium and biological medium are shown in Figure 5.

Experimental verification

The photos of the experimental devices for measurement is shown in Figure 6, the energy transfer efficiency is measured by the vector network analyzer Agilent E5071C. The influence of the human biological tissue on the energy transfer efficiency is simulated by using the fresh lean from the intraday slaughtered pig wrapping tightly around the secondary coil.

Figure 7 is the situation that the energy transfer efficiency varies with the frequency. In order to reflect the versatility of this model, in Figure 7 the distance between the primary coil and the secondary coil is changed into 2cm. Figure 7A is the comparison chart of the ideal model, the optimal model in the air medium and the measured data. It can be seen from Figure 7A that the modeling simulation results (curve 2) in the air medium is more consistent with the experimental data (the point curve 3). The ideal model (curve 1) which ignores the parasitic capacitance is basically consistent with the measured data at the low frequencies, but the extent of error in the high frequency band cannot be tolerated, therefore the optimization modeling theory of this paper is closer to the actual situation. Figure 7B is the comparison chart of the simulation data in the biological media and the measured data, we can see that the trend of the two curves basically coincide, the extent of error range is within the reasonable range, which verifies the correctness of the model.

The inductance values of the planar spiral inductance coils used in this paper are $L_1 = L_2 = 4.031\mu$H, when the match capacitances are 22pF and 47pF, the resonant frequencies are 16.97MHz and 11.61MHz respectively. Figure 8 shows that the energy transfer efficiency in the air medium and in the biological tissue medium varies with the transfer distances at two different frequencies 16.97MHz and 11.61MHz. From Figure 8 we can find that the air medium modeling highly coincides with the actual measurement data, the biological tissue medium modeling also basically coincides with the measured data within the distance of 1-2cm. According to clinical medicine experience, the distance between the secondary visual prosthesis reception coil which implant into the patient's body and the primary coil outside the body is usually 1-2cm. Therefore, this model meets the requirements of the implantation depth range for the actual clinical application.

Conclusions

Based on the physical characteristics of the biological tissue, optimization modeling of the visual prosthesis wireless energy transfer system is established in this paper.

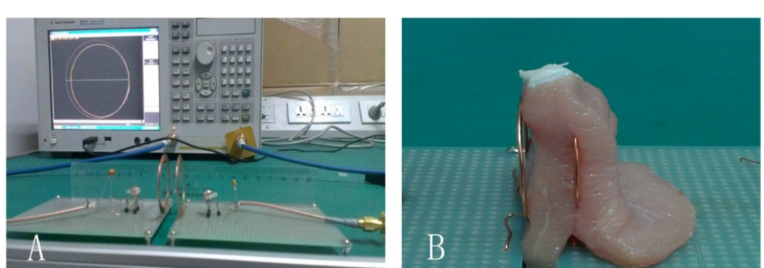

Figure 6 The photos of the experimental device for measurement. A-The experimental instrument and the vector network analyzer Agilent E5071C; **B**-The picture of the secondary coil embedded by biological tissue.

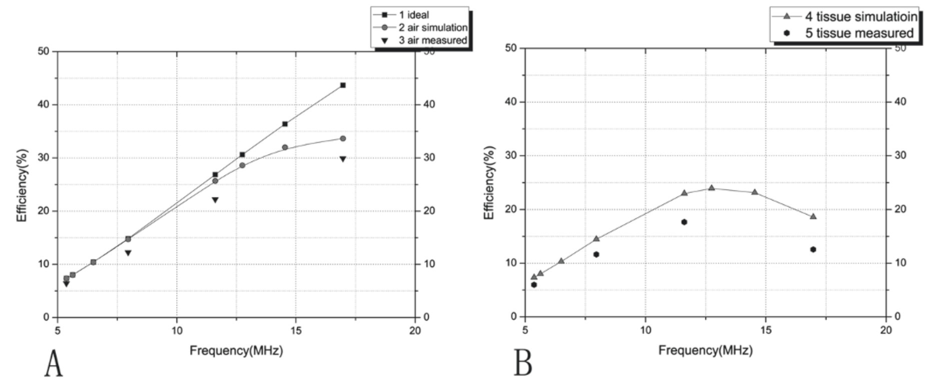

Figure 7 The comparison chart of the simulation and the experimental measurement (D=2cm). A-The comparison of measurement data in air medium with simulation data using ideal model and optimal model; **B**-The comparison of measurement data in biological medium with simulation data using optimal model simulation.

During the optimization modeling, the influence of the parasitic capacitance of the coil and the biological capacitance to the energy transfer efficiency is considered fully, which greatly improves the matching degree of the theoretical modeling and the measured data. The optimal modeling has a higher guiding significance for the actual system design.

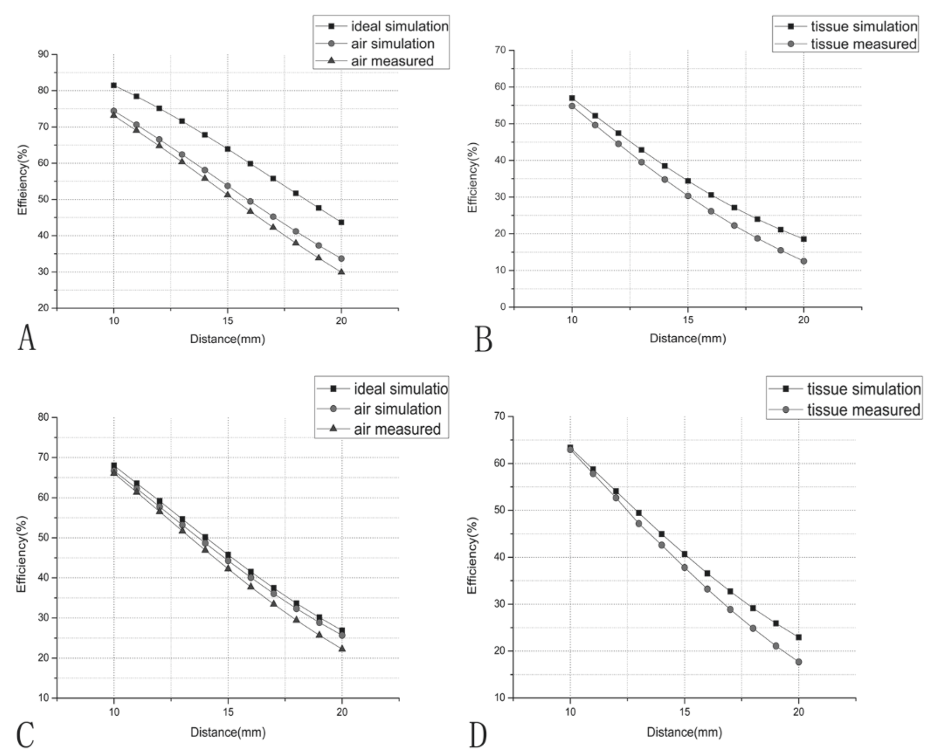

Figure 8 The diagram of the energy transmission efficiency vs. the distance between the coils. A-The curves in the air medium at 16.97MHz; **B**-The curves in the biological medium at 16.97MHz; **C**-The curves in the air medium at 11.61MHz; **D**-The curves in the biological medium at 11.61MHz.

Competing interests
The authors declare that they have no competing interests.

Authors' contributions
LXP, YY and GY have equally contributed to the manuscript; both were also involved in the design of the modeling study and data analysis. All authors read and approved the final manuscript.

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LXP is a lecturer and doctoral candidate in Xi'an University of Technology. His research subjects are Visual prosthesis wireless energy and data transfer. YY is a professor in Xi'an University of Technology. And she is also the vice dean of graduate school of the university. She is supported by National Natural Science Foundation of China. GY is a professor and academic leader of electronics science and technology subject in Xi'an University of Technology.

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References
1. Chen CJ, Chu TH, Lin CL, Jou ZC: **A study of loosely coupled coils for wireless power transfer.** *IEEE Trans Circuits Syst* 2010, **57:**536–540.
2. Zhu Chunbo, Yu Chunlai, Yinhua M, Qingquan C: **Analysis of the loss of magnetic resonant wireless power transfer.** *Trans China Electrotechnical Soc* 2012, **27:**13–17.
3. Fu WZ, Zhang B, Qiu DY, Wang W: **Maximum Efficiency Analysis and Design of Self-resonance Coupling Coils for Wireless Power Transmission System.** *Proc CSEE* 2009, **29:**21–26.
4. Xue RF, Cheng KW: **High-efficiency wireless power transfer for biomedical implants by optimal resonant load transformation.** *IEEE Trans Circ Syst* 2012, **60:**1–7.
5. Jow UM, Ghovanloo M: **Modeling and optimization of printed spiral coils in air, saline, and muscle tissue environments.** *IEEE Trans Biomed Circ Syst* 2009, **3:**339–346.
6. Jow UM, Ghovanloo M: **Design and optimization of printed spiral coils for efficient transcutaneous inductive power transmission.** *IEEE Trans Biomed Circ Syst* 2007, **3:**193–201.
7. Jegadeesan R, Guo YX: **Topology selection and efficiency improvement of inductive power links.** *IEEE Trans Antennas Propagation* 2012, **60:**4846–4853.
8. Zargham M, Gulak PG: **Maximum achievable efficiency in near-field coupled power-transfer systems.** *IEEE Trans Biomed Circ Syst* 2012, **6:**228–244.
9. Danilov AA, Itkin GP, Ustinov AO: **Experimental setup for studying wireless energy transfer using magnetic coupling in auxiliary circulation systems.** *Biomed Eng* 2012, **45:**218–220.
10. Physics Teaching and Research Section: *Physics Experiment Course, 162*. Guangzhou: Zhongshan University Press; 2004.
11. Solja cic M, Kurs A, Karalis A, et al: **Wireless power transfer via strongly coupled magnetic resonances.** *Sciencexpress* 2007, **112:**1–10.
12. Massarini A, Kazimierczuk MK: **Self-capacitace of inductance coils.** *IEEE Trans Power Electron* 1997, **12:**671–676.
13. RUAN Fm, Tomasz D, GAO Yg: **Cylindrical model algorithm for calculation of human body impedance.** *ACTA ELECTRONICA SINICA* 2010, **38:**469–472.
14. Li G, Chen Y, Lei G: **The measurement of the permittivity of a kind of phantom muscle tissue at microwave frequency.** *Chinese J Med Phys* 1995, **12:**243–245.

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