Research Article

New Exact Traveling Wave Solutions of Fractional Time Coupled Nerve Fibers via Two New Approaches

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Received 2 November 2020; Revised 23 December 2020; Accepted 16 January 2021; Published 27 January 2021

Academic Editor: Kottakkaran Sooppy Nisar

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In this paper, we obtain new soliton solutions of one of the most important equations in biology (fractional time coupled nerve fibers) using two algorithm schemes, namely, \( \exp(\psi(\xi)) \) expansion function method and \( \frac{\theta'(\xi)}{\theta^2(\xi)} \) expansion methods. The equation and the solution methods have free parameters which help to make the obtained solutions are dynamics and more readable for dealing with fractional parameter and the initial and boundary value problem. As a result, various new exact soliton solutions for the considered model are derived which include the hyperbolic, rational, and trigonometric functions, and other solutions are obtained. In addition, the obtained results proved that the used methods give better performance compared with existing methods in the literature.

1. Introduction

Differential equations attained great importance with several applications in nature and live environment [1–19]. Differential equations were widely used in the modeling and simulation of the biological system long time ago, for example, population dynamics and spreading and transmission of viruses. Nerve conduction is one of the most important phenomena in biological systems. Several studies have attempted to provide an interpretation to the nature of the nerve conduction. These studies started in the early last century in 1925 and seemed to indicate that local circuit currents were involved in the longitudinal propagation of activity [20–23]. This study presents a model of action potential propagation in bundles of myelinated nerve fibers. The nature of the conduction process on an isolated nerve axon is studied numerically and compared with the theoretical models [24]. Reutskiy et al. introduced a new model that combines the single-cable formulation of Goldman and Albus (1967) with a basic representation of the ephaptic interaction among the fibers. The conduction velocity (CV) behavior is investigated in the presence of various conductance parameters and temperatures [25].

Recently, the fractional calculus plays a major role in various fields, such as fluid mechanics, plasma physics, optical fibers, solid state physics, chemical kinematics, and chemical physics, and geochemistry [26–33] is the specific one which attracts our attention. Many effective methods for obtaining exact solutions of FNLEEs have been presented [34–42]. In the present work, we propose a system which is governed by a fractional order derivative. The fractional order derivative is a concept that has been known since the early 17th century [43–45]. The model studied here is the ephaptically coupled myelinated nerve fibers. The myelinated nerve fibers might be responsible for diagnostic dilemmas in cases of visual loss [46–48]. They allow an increase in the speed of a nerve impulse while decreasing the diameter of the nerve fiber. The first work concerning myelinated nerve fibers was developed by Rushton [49].

The primary content of the article is organized as follows. In section 2, the governing equations of the model are introduced. The properties of conformable fractional derivatives are given in Section 3. Two algorithms of the proposed analytical method, namely, \( \exp(-\psi(\xi)) \) expansion function method and \( \frac{\theta'(\xi)}{\theta^2(\xi)} \) expansion method for solving the reduced equation for fractional time coupled nerve fibers are
introduced in Section 4. Finally, we briefly make a conclusion in Section 5.

2. Governing Model and Mathematical Analysis

To consider the equations for the coupled nerve fibers, consider their electrical analogy as in [50, 51]:

\[ M_n^j - M_n^{j+1} = (R_i + R_0)N_n^j + R_0 \left[AN_n^j + (1 - A)N_n^{j-1}\right], \]
\[ M_n^j - M_n^{j-1} = (R_i + R_0)N_n^j + R_0 \left[AN_n^j + (1 - A)N_n^{j+1}\right], \]
\[ N_n^j - N_n^j = N_{C,n}^j + N_{ion,n}^j, j = 1, 2, \ldots \quad (1) \]

where \( n \) represents successive active nodes, \( M_n \) represents the voltage across the membrane, \( N_n \) represents the current flowing longitudinally through the fiber from node \( n \) to node \( n + 1 \), \( R_i \) and \( R_0 \) are the inside and outside resistances, \( N_{C,n} \) is the current supplying the capacity of the active node \( n \), while \( N_{ion,n} \) is the ionic current, comprising both sodium and potassium components. According to [51–53], the complex impedance of a capacitor reads:

\[ Z_C = \frac{1}{C(j\omega)^\alpha}, \quad (2) \]

Then, the ionic current becomes

\[ N_{ion,n}^j = C \frac{d^\alpha M_n^j}{dt^\alpha}. \quad (3) \]

The ionic current is given by the following relation:

\[ N_{ion,n}^j = \frac{G}{M_b(M_b - M_a)}(M_{a}^j - M_b^j)(M_b^j - M_a^j), \quad (4) \]

where \( M_a \) and \( M_b \) are the threshold voltage at sodium current and potential at the current returns to zero. By setting \( v_n = (M_a^j/M_b), i_n = R f (N_{a}^j/M_a), a = (M_b^j/M_a), r = R_i + R_f, \eta = (R_0/R), D = (R_f/R), \beta = R_f G (1 - a) \), equation (1) can be rewritten as

\[ D[(1 - \eta)(v_{n+1} - 2v_n + v_{n-1}) - \eta(w_{n+1} - 2w_n + w_{n-1})] - R_f C \frac{d^\alpha v_n}{dt^\alpha} - \beta v_n(v_n - a)(v_n - 1), \]
\[ D[(1 - \eta)(w_{n+1} - 2w_n + w_{n-1}) - \eta(v_{n+1} - 2v_n + v_{n-1})] - R_f C \frac{d^\alpha w_n}{dt^\alpha} - \beta w_n(w_n - a)(w_n - 1), \quad (5) \]

where \( v_n^1 = v_n \) and \( v_n^2 = w_n \).

As long as \( \delta_n \) tends to \( \chi \), equation (5) admits to

\[ D\left[ (1 - \eta)\beta \frac{d^3 v}{dx^3} - \eta \beta \frac{d^3 w}{dx^3} \right] - R_f C \frac{d^\alpha v}{dt^\alpha} - \beta v(v - a)(v - 1), \]
\[ D\left[ (1 - \eta)\beta \frac{d^3 w}{dx^3} - \eta \beta \frac{d^3 v}{dx^3} \right] - R_f C \frac{d^\alpha w}{dt^\alpha} - \beta w(w - a)(w - 1). \quad (6) \]

3. Conformable Fractional Derivatives and Its Properties

For a given \( \chi: (0, \infty) \rightarrow R \), some definition and useful properties about conformable fractional derivatives can be written as follows [22, 23]:

\[ w_a(\chi)(t) = \lim_{\varepsilon \to 0} \frac{\chi(t + \varepsilon t^{1-a}) - \chi(t)}{\varepsilon}, \quad t > 0, 0 < a < 1, \]
\[ w_a(\chi) + ch = Bw_a(\chi) + Cw_a(h), \quad B, C \in R, \]
\[ w_a t^\lambda = \lambda t^{1-a}, \quad \lambda \in R, \]
\[ w_a \chi = \chi w_a(h) + hw_a(\chi), \]
\[ w_a \left( \frac{\chi}{h} \right) = \frac{hw_a(\chi) - \chi w_a(h)}{h^2}, \quad (7) \]
and \( w_n(\chi)(t) = t^{1-n} (d\chi/dh) \).

In the limiting case \( \chi: (0,\infty) \to R \), then

\[
\phi(v, D^2_v v, D^3_v v, D^4_v v, D^5_v v, D^6_v v, D^7_v D^2_v v, D^8_v D^3_v v, \ldots = 0, \quad 0 < \alpha, \beta, \delta < 1.
\]

\[
\psi_4(\xi) = \ln \left( \frac{2\alpha^2 \xi + c_1^2 + 1}{\lambda (\xi + c_1)} \right)
\]

where \( c_1 \) is constant.

The parameters \( a_i, \mu, \lambda, c, k, \) and \( \delta \) can be found by inserting equations (11) and (12) in equation (9) and taking some approximations for the parameters of \( \exp(-\psi(\xi)) \) and making them equal to zero. This will produce a group of equations which can be solved to find equation parameters. The exact solution of equation (9) can be found by inserting the parameter values in equation (11).

4.2. The Extended \( \left( \theta' \right. \left/ \theta^2 \right) \) Expansion Method. In view of the \( \left( \theta' \right. \left/ \theta^2 \right) \) expansion method, the quick gain of this method is the solution of

\[
V(\xi) = \alpha \sum_{i=1}^{N} \left( \theta' \left( \xi \right) \right)^i, \quad (18)
\]

where \( \lambda, \mu \) are constants and will be computed with the flow of the paper. The integer \( N \) is determined by balancing between the highest order derivative. The solutions of equation (12) read.

\[
\psi_4(\xi) = \ln \left( \frac{2\alpha^2 \xi + c_1^2 + 1}{\lambda (\xi + c_1)} \right)
\]

where \( \lambda, \mu \) are constants to be determined later. It is to be noted that the solution of equation (19) is given as follows.

\[
\frac{\theta' \left( \xi \right)}{\theta^2 \left( \xi \right)} = \mu + \lambda \left( \frac{\theta' \left( \xi \right)}{\theta^2 \left( \xi \right)} \right)^2
\]

where \( \lambda, \mu \) are constants to be determined later. It is to be noted that the solution of equation (19) is given as follows.

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\frac{\theta' \left( \xi \right)}{\theta^2 \left( \xi \right)} = \mu + \lambda \left( \frac{\theta' \left( \xi \right)}{\theta^2 \left( \xi \right)} \right)^2
\]
where $\xi_1$ and $\xi_2$ are constants to be determined later.

Here, the term $N$ in equation (19) can be computed taking into account the balancing between the highest order derivative and the nonlinear term in equation (10). Making use of equation (18) with equation (19) into equation (10), combining all the terms of the same power of $(\omega^2(\xi)/w^2(\xi))$, and performing some steps, we can get the values of $a_0$, $\beta$, $\omega$, and $k$. By inserting these values in equation (18) along with general solutions of equation (19), the solutions of equation (9) can be obtained directly.

4.3. New Exact Solutions of the Reduced Equation via $\exp(-\psi(\xi))$ Expansion Function Method. To solve the reduced equation (6), via $\exp(-\psi(\xi))$ expansion, by using the wave transformation $\xi = k(x + y - (\nu t^a/\alpha))$, equation (6) yields

$$
-\nu kR_f C \frac{dv}{d\xi} - k^2 \delta^2 D \left[ (1 - \eta) \frac{d^2 \nu}{d\xi^2} \right] \exp \left[ \psi - (1 + a)\nu^2 + av \right],
$$

$$
-\nu kR_f C \frac{dw}{d\xi} - k^2 \delta^2 D \left[ (1 - \eta) \frac{d^2 \omega}{d\xi^2} \right] \exp \left[ \psi - (1 + a)\omega^2 + aw \right].
$$

(23)

Considering the balance principle to equation (23), we obtain $\lambda = 1$. Then, the solution of equation (23) admits to

$$
V(\xi) = a_0 + a_1 \exp(-\psi(\xi)),
$$

(24)

$$
W(\xi) = b_0 + b_1 \exp(-\psi(\xi)).
$$

(25)

Set 1

Inserting equations (25) and (24) into equation (23) with equation (12), collecting all power of $\exp(-\psi(\xi))$, and using symbolic computation program, it yields as follows.

$$
k = k, \delta = \delta, \nu = \pm \left[ \frac{(-1/(-\lambda^2 + 4\mu))^{1/2}(2\eta - 1)D\delta^2 k(4\mu + 4\lambda a - \lambda^2 - a\lambda^2)}{R_f C (a - 1)} \right], b_0 = a_0,
$$

$$
a_0 = \pm \left[ \frac{\lambda a}{2} \frac{(-1/(-\lambda^2 + 4\mu))^{1/2} + 1}{2} \right],
$$

$$
a_1 = b_1 = \pm \left[ (-1/(-\lambda^2 + 4\mu))^{1/2} (a - 1) \right].
$$

Set 2

$$
k = k, \nu = \sqrt{1-\lambda^2 + 4\mu(2\eta - 1)D\delta^2 k(4\mu + 4\lambda a - \lambda^2 - a\lambda^2)} / R_f C (a - 1),
$$

$$
a_0 = \pm \left[ \frac{\lambda a}{2} \frac{(-1/(-\lambda^2 + 4\mu))^{1/2} + 1}{2} \right],
$$

$$
\delta = \delta, b_0 = a_0, b_1 = a_1 = \pm \left[ \frac{-1}{-\lambda^2 + 4\mu} (a - 1) \right].
$$

(27)

Substituting Set 1 into equations (23) and (24), it gains the new solutions as follows:
thenewexactsolutionofequation(6)asfollows:

\[ V_i(\xi) = \pm \left[ \frac{a}{2} \pm \left( -\frac{1}{ \lambda^2 + 4\mu} \right)^{(1/2)} \lambda a \right] \exp(-\psi_i \xi), \quad i = 1, 2, 3, 4, 5, \]

\[ W_i(\xi) = \pm \left[ \frac{a}{2} \pm \left( -\frac{1}{ \lambda^2 + 4\mu} \right)^{(1/2)} \lambda a \right] \exp(-\psi_i \xi). \]

Substituting Set 2 into equations (25) and (24), it gains the new exact solution of equation (6) as follows:

\[ V_i(\xi) = \pm \left[ \frac{a}{2} + \sqrt{-\frac{1}{ \lambda^2 + 4\mu}} \lambda a \right] \exp(-\psi_i \xi), \quad i = 1, 2, 3, 4, 5, \]

\[ W_i(\xi) = \pm \left[ \frac{a}{2} + \sqrt{-\frac{1}{ \lambda^2 + 4\mu}} \lambda a \right] \exp(-\psi_i \xi). \]

\[ V(\xi) = a_0 + a_1 \left( \frac{\theta'(\xi)}{\theta^2(\xi)} \right), \]

\[ W(\xi) = c_0 + c_1 \left( \frac{\theta'(\xi)}{\theta^2(\xi)} \right). \]

Inserting equations (31) and (32) with equation (19) into equation (23) and collecting same power of \( \psi(\xi)/\psi(\xi) \), equating to zero, we have a set of algebraic equations. By solving it, we obtain

\[ k = \pm \frac{(\beta/(-8D\lambda\mu + 16D\eta\lambda\mu))^{(1/2)} (-1 + a)}{\delta}, \]

\[ \nu = \frac{1}{2} (1 + a) (-1/4\lambda/\mu)^{(1/2)} \beta/\gamma/(\beta/(-8D\lambda\mu + 16D\eta\lambda\mu))^{(1/2)} \delta/\lambda, \]

\[ c_0 = a_0 = \frac{1}{2} + \frac{a}{2}, \]

\[ a_1 = c_1 = \pm \sqrt{-\frac{1}{4\mu}} (-1 + a). \]
Figure 1: Soliton solutions of equation (29) in 3D and contour plots, where \( y = 2; k = 0.2; v = 0.2; \alpha = 0.5; u = 3; \lambda = 4; a = 2; \) and \( c_1 = 2. \)

Figure 2: Soliton solutions of equation (29) in 3D and contour plots, where \( y = 2; k = 0.2; v = 0.2; \alpha = 0.5; u = 3; \lambda = 4; a = 2; D = (\lambda^2) - (4u); \) and \( c_1 = 2. \)

Figure 3: Soliton solutions of equation (34) in 3D and contour plots, where \( y = 2; v = 0.2; a = 3; u = 0.2; k_1 = 3; k_2 = 4; k = 0.02; \lambda = 4; \) and \( \alpha = 0.5. \)
Substituting equation (33) into equations (31) and (32), we get the new exact solutions of equation (6) as follows:

\[ V_j(\xi) = \frac{1}{2} + \frac{a}{2} \pm \frac{1}{4\mu} (-1 + a) \left[ \frac{\theta^\prime (\xi)}{\theta (\xi)} \right], \]

\[ W_j(\xi) = \frac{1}{2} + \frac{a}{2} \pm \frac{1}{4\mu} (-1 + a) \left[ \frac{\theta^\prime (\xi)}{\theta (\xi)} \right], \]

where \((\theta^\prime (\xi)/\theta^2 (\xi))\) is given by equations (20)–(22) and \(\xi = k(x + y - (vt^r/a))\). It is worth noting that, in the limiting case \(r = \mu, q = \lambda\), and \(p = 0\), the results obtained here are the same obtained in [28].

5. Conclusion

In this paper, we introduced new solutions to one of the most important differential equations in biology. In this study, we have proposed a new model of myelinated nerve fibers described by a time fractional nonlinear evolution equation. Two algorithm schemes, namely, \(\exp(-\psi (\xi))\) expansion function method and \((\theta^\prime (\xi)/\theta^2 (\xi))\) expansion method are used for constructing the new soliton solutions and other solutions such as hyperbolic function, trigonometric function, and rational function. To our knowledge, these new solutions have not been reported in former literature, and hence, they may be of significant importance for the explanation of some special physical phenomena. The results as in equations (29) and (34) are plotted in Figures 1–4. The obtained solutions here can be useful for applications in mathematical physics, engineering, and nonlinear optics. The achieved results here show the effectiveness and reliability of the proposed technique.

Data Availability

The data used to support the findings of this study are available within the manuscript.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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